UNESCO Regional Office for
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International hydrological programme

Soil Erosion and Sediment Production on Watershed Landscapes: Processes and Control

ihP - LAC

International Hydrological Programme for
Latin America and the Caribbean

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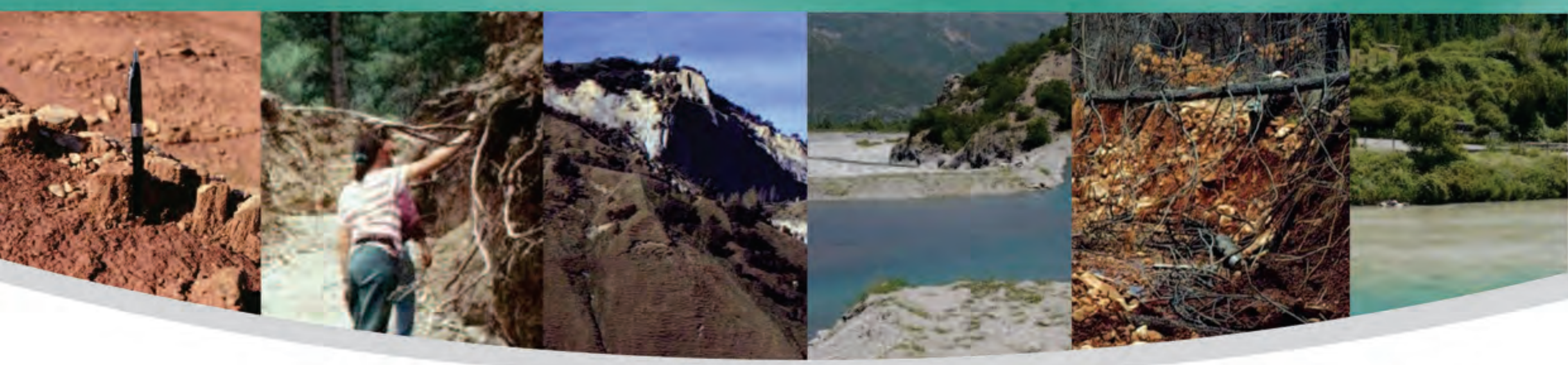

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INTRODUCTION

Charpter One

1. Losses of Soil Resources

Losses of the soil resources from otherwise productive and well-functioning watersheds are often a recurring problem confronting hydrologists and watershed managers. These losses of soil have both *on-site* and *off-site* effects on the watershed impacted. In addition to the loss of inherent soil resources through erosion processes, on-site effects can include the breakdown of soil structure, a decline in organic matter and nutrients in the soil, and a reduction in available soil moisture (Morgan, 1995; Gregersen *et al.,* 2007; Brooks *et al.,* 2013). The net impact of these on-site effects can be a loss of productivity that leads to a decline in the values of the natural resources on watershed landscapes.

Off-site effects, called *externalities* by economists, are reflected mostly by increases in sediment loading and the loss of nutrients such as nitrogen and phosphorus that are adsorbed to the soil particles in the sediment deposited in a stream channel (Dunne and Leopold, 1978; Morgan, 1995; Brooks *et al.,* 2013). The consequent increases in the sediment in the streamflow from an upland watersheds often reduces the capacity of rivers to deliver high-quality water to downstream users, increases the risk of flooding in river basins, reduces or blocks the flow of water through irrigation systems, and shortens the expected operational life of downstream reservoirs.

Increased soil erosion and sedimentation rates can also jeopardize the array of ecosystem services provided by the watersheds. Included among these services are regulation of the climate, purification of water, recharging of groundwater aquifers, effective nutrient cycling, and maintenance of biodiversity (Postel and Carpenter, 1996; National Research Council, 2005; Gregersen *et al.,* 2007). It is imperative, therefore, that efforts are made by hydrologists and watershed managers to prevent unacceptable rates of soil erosion and the resulting increases in sediment yields from occurring by implementing ecologically, environmentally, and economically sound management practices; or, when excessive soil erosion and sediment yields are occurring on a watershed, to control the magnitude of these losses to levels that are likely to occur with natural conditions through effective interventions.

2. The Purposes of This Publication

Keeping the above discussion in mind, the purposes of this publication are three-fold:

- To describe the processes that lead to losses of soil resources through erosion; effective methods of preventing unacceptable soil losses on watersheds; and methods of controlling the losses of soil resources when these losses become excessive.
- To describe the sedimentation that is likely occur with the losses of soil resources on a watershed; methods of reducing the accumulations of sediment in stream channels; and measures of the sediment outflows from a watershed.
- To discuss the economics of selecting economically feasible watershed management practices to prevent or control excessive increases in the loss of soil resources on watershed landscapes.

3. Organization of the Publication

The publication is organized into three parts:

- Soil erosion processes, prevention, and control are described in Part I of the publication that includes chapters on surface erosion, gully erosion, and soil mass movement.
- The focus of Part II is placed on sediment supply, transport, and outflows and consists of chapters on sediment sources and its transport in a stream; and the sediment yield from a watershed.
- Economic considerations of importance in selecting the most feasible watershed management practice to prevent or control of increased soil erosion and excessive sedimentation is the emphasis of a chapter on the economic appraisal of alternative management practices comprising Part III of the publication.

An appendix is presented at the end of the publication to describe the some of the tools and technologies that are available to, and commonly used by, hydrologists and watershed managers to meet the challenges of preventing or controlling unacceptable levels of soil erosion and sedimentation.

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PART I

SOIL EROSION PROCESSES, PREVENTION, CONTROL

Soil losses from a watershed can occur by surface erosion, gully erosion, or soil mass movement. *Surface* erosion involves the detachment and subsequent removal of soil particles and small aggregates from a site by water or wind. In reference to the action of water, the focus of this publication, this type of erosion is caused by the action of raindrops, thin films of flowing water, or concentrated surface runoff. *Gully erosion* is the detachment and movement of individual soil particles or large aggregates of soil in a well-defined channel. This type of erosion is a major form of geologic erosion that is often accelerated under poor land management. *Soil mass movement* refers to erosion in which cohesive masses of soil and rock materials are displaced and moved downslope by gravity. The mass movement of soil can be rapid such landslides or bluff collapse or it can be slow such creep and channel slumps. All of these erosion processes can occur singly or in varying combinations on a watershed. It is often difficult to distinguish the basic types of erosion that is occurring and to determine whether they are natural processes or have been accelerated by poor land-use activities or management practices.

Chapter Two

SURFACE EROSION

1. Introduction

Surface soil erosion requires the expenditure of energy. This energy is imparted to the a soil surface by forces resulting from impulses produced by the momentum (mass x velocity) of falling raindrops or the momentum of eddies in the turbulent flows of surface runoff or the turbulent actions of wind. Soil erosion that is caused by both the impacts of falling raindrops and surface runoff is the focus of this chapter.

2. Processes

The dislodgement of soil particles at the soil surface by falling raindrops is a primary agent of erosion on soils with a sparse vegetative cover. The energy released at the surface of mineral soil in a large rainstorm can be sufficient to splash more than 200 tons of soil into the air on one hectare of bare and loose soil. Furthermore, individual soil particles can be splashed more than 0.5-meter in height and 1.5 meters sideways. A major impact of the impulses imparted to the soil surface by raindrops is a deterioration of soil aggregates (Dunne and Leopold 1978). The subsequent splashing of finer soil particles tends to puddle and close the soil surface that reduces infiltration and increases surface runoff.

Surface runoff combined with the beating action of raindrops causes rills to be formed on the soil surface. *Rill erosion* is the form of surface erosion that produces the greatest amount of soil loss worldwide (Dunne and Leopold, 1978; Montgomery, 2007; Brooks *et al.,* 2013). Sheet *erosion* occurs between rills and, therefore, is also called *inter-rill erosion.* Sheet erosion is the movement of a semi-suspended layer of soil particles over the land surface. However, minute rills are formed almost simultaneously with the first detachment and movement of particles. The constant movement in position of these small rills can obscure their presence leading to the concept of sheet erosion.

Surface runoff quickly becomes concentrated in rills where its erosive power increases as the depth and mass of the runoff become concentrated over a smaller surface area. As the flow increases and carries more eroded soil particles downslope, the abrasive action of the particles adds to the erosive power of the surface runoff (Dunne and Leopold, 1978; Brooks *et al.,* 2013). Soil loss in this manner can become dramatic with high-intensity rains on steep unobstructed slopes. Such losses are common in arid and semi-arid regions of the world where the sparse vegetative cover has often been disturbed by poor land practices.

The momentum gained by surface runoff on an unobstructed slope and the resulting amount of soil that can be lost from a site depend mostly on the length and inclination of a slope. Soil loss per unit length is accelerated initially with increasing slope length but then approaches a constant rate. The steeper and longer the slope, the greater are the problems of control can become. When rills expand and become larger downslope, uncontrolled surface runoff is capable of causing gully erosion. The occurrence of this phenomenon is common on sparsely vegetated slopes in arid and semi-arid regions.

3. Measurement of Surface Erosion

Surface erosion on small watersheds can be measured or estimated by the use of plots, stakes, or natural landscape features such as soil pedestals (Satterlund and Adams, 1992; Morgan, 1995; Brooks *et al.,* 2013). Surface erosion over larger drainages basin can be measured by repeated reservoir surveys of designated transects or through the use of tracers.

3.1. Erosion Plots

A widely used method of quantifying surface erosion is to measure the amount of soil that washes from bounded plots (figure 2.1). In installing these plots, collecting troughs are sunk into the soil surface along the width of the bottom of the plots with walls of plastic, sheet metal, plywood, or concrete are inserted into the soil surface to form the boundaries of the plot (Mutchler *et al.,* 1994; Morgan, 1995; Brooks *et al.,* 2013). The collecting trough empties into a tank or other container in which both the entrained soil particles and surface runoff are collected. These containers can be designed with recording instruments so that the rates of flow can be measured. The total volume of soil particles and water is measured after a rainstorm has occurred in other cases.

Figure 2.1. A bounded plot for quantifying surface erosion by measuring the amount of soil that washes from the plot (photograph by Roberto Pizarro Tapia).

Plots vary in size from micro-plots of 1 to 2 square meters to the standard plot of approximately 2 meters by 22 meters used in applying the universal soil loss equation (see below). Micro-plots are less expensive and more practical than the use of rainfall simulators for multiple comparisons of vegetation, soils, and land-use activities. However, larger plots can provide more realistic estimates of erosion because they better represent the cumulative effect of increasing volume and velocity of surface runoff downslope. Plots larger than the standard plot for the universal soil loss equation can yield large volumes of surface runoff and soil particles that are difficult to store. Devices that split or sample a portion of total water and sediment flow are preferred in these cases.

3.2. Erosion Pins or Stakes

The insertion of pins or stakes into the soil can be used to estimate soil losses and deposition that occur along the hillslopes of a watershed. An erosion pin commonly consisting of a metal nail with a washer welded to the top of the nail is inserted into the soil surface and the distance between the head of the nail and the washer is measured after an erosion-producing event. Surface erosion is measured by the distance from the cap of the pin to the soil surface (figure 2.2) while deposition is measured by the accumulation of soil on the top of the pin. The pins are re-set to be flush with the soil surface after the measurements are taken to facilitate subsequent measurements. A benchmark should be established in close proximity to the stakes as a point of reference and stakes should be clearly marked so that original stakes can be accurately relocated on subsequent surveys.

Erosion stakes are located in a grid pattern on a hillslope with repeated measurements taken over time in which the changes in soil surface are related to soil loss and deposition. This method is inexpensive compared with the plot method but presents more difficulty in converting observations into actual soil losses.

Figure 2.2. An erosion pin consisting of metal nail with a washer welded to the top of the nail inserted into the soil surface to measure surface erosion. The distance between the cap of the pin and the soil surface is a measure of surface erosion (photograph by Peter F. Ffolliott).

3.3. Natural Landscape Features

Surface erosion can sometimes be estimated from natural landscape features such as soil pedestals that form beneath clumps of grass, dense shrubs, stones, or other areas that are protected from rainfall impacts. The distance between the pedestal top and bottom increases as erosion removes soil particles from around the pedestals. Repeated measurements of the height of residual soil pedestals provide estimates as described for stakes or pins. The key to this method is to relate measurements to a point of reference or benchmark.

4. Prediction of Soil Loss by Surface Erosion

Land-use activities and management practices can influence the magnitude of surface erosion. As a consequence, hydrologists and watershed managers frequently often want to predict the amount of soil loss by surface erosion. Several models are available for predicting erosion caused by the action of water including the universal soil loss equation (USLE), the modified universal soil loss equation (MSLE), the revised universal soil loss equation (RUSLE), and the water erosion prediction project (WEPP) model.

4.1. Universal Soil Loss Equation

The need for a widely applicable erosion prediction technique led to the development of the universal soil loss equation (USLE) by the Agricultural Research Service of the U.S. Department of Agriculture. The original USLE was based on the analysis of 10,000 plot-years of data collected mostly on agricultural plots under natural rainfall conditions. Subsequently, surface erosion research has been conducted with simulated rainfall. Rainfall-simulator measurements are used to describe the inherent soil erodibility and provide values for conservation tillage and construction practices for controlling soil erosion.

The term "universal" differentiates the USLE from earlier erosion prediction equations that applied only to specific sites and regions. The USLE was applied on agricultural lands throughout the United States by 1978 and also to non-agricultural landscapes such as forests and grasslands and construction sites. A sub-factor method has been developed to estimate values for the *C* factor because extensive baseline data were not available for all of these applications. This sub-factor method is discussed later as the modified universal soil loss equation.

The English units employed in its original development are used in the following description of the USLE rather than corresponding often cumbersome metric units. The USLE (Wischmeier and Smith, 1965, 1978) is:

$$A = RK\,(LS)\,CP \qquad (2.1)$$

Where *A* = computed soil loss expressed in tons per acre for the time period selected for *R* (usually 1 year); *R* = a rainfall erosivity factor for a specific area expressed in terms of average erosion index (*EI*) units; *K* = a soil-erodibility factor for a specific soil horizon expressed in tons per acre; *LS* = topographic factor, a combined dimensionless factor for slope length and slope gradient, where *L* is the ratio of soil loss from a given field slope length to soil loss from a 72.6-foot length under the same conditions, while S is the slope gradient factor expressed as the ratio of soil loss from a given slope steepness to soil loss from a 9% slope under the same conditions; *C* = a dimensionless cropping-management factor expressed as a ratio of soil loss from the condition of interest to soil loss from tilled continuous fallow (the condition under which *K* is determined); and *P* = an erosion control practice factor expressed as a ratio of the soil loss with the practices (contouring, strip-cropping, or terracing) to soil loss with farming up and down the slope.

Equation 2.1 provides an estimate of sheet and rill erosion from rainfall events on upland watersheds. It does not include predictions of erosion from stream banks, snowmelt runoff, or wind and it does not include eroded soil deposited at the base of slopes and at other reduced-flow locations before surface runoff reaches a stream channel.

A description of the factors comprising the USLE and their respective formulations is presented below.

4.1.1. Rainfall Erosivity Factor

The rainfall erosivity factor (*R*) is an index to characterize the effect of raindrop impact and rate of surface runoff associated with the rainstorm. It is determined by calculating the *EI* for a specified period of one year or one season in a year. The *EI* averaged over a number of these periods (*n*) equals *R*:

$$R = \frac{\sum_{i}^{n} EL_i}{n} \qquad (2.2)$$

The energy of a rainstorm striking a soil surface depends on the amount of rain and the rainfall intensities of the storm. This energy is proportional to velocity squared for mass in motion. Therefore, rainfall energy is related directly to rain intensity by:

$$E = 916 + 331 (\log I_i) \quad (2.3)$$

Where E = kinetic energy per inch of rainfall expressed in foot-tons per acre; and I_i = rainfall intensity in each rainfall intensity period of the storm expressed in inches per hour.

The total kinetic energy of a rainstorm (k_e) is obtained by multiplying E by the depth in inches of rainfall in each intensity period (n) and summing:

$$k_e = \sum_i^n [916 + 331 (\log I_i)] \quad (2.4)$$

The EI for an individual rainstorm is calculated by multiplying the total kinetic energy (k_e) of the rainstorm by the maximum amount of rain falling in 30 consecutive minutes (I_{30}), multiplying by 2 to obtain inches per hour, and dividing the result by 100 to convert from hundreds of foot-tons per acre to foot-tons per acre:

$$EI\ (storm) = \frac{2k_e I_{30}}{100} \quad (2.5)$$

The EI for a year or a season of a year is the sum of the EI values computed for storms greater than 0.5 inch in the specified time period. The R factor is then determined as the sum of the EI values for all such storms that occurred during a 20- to 25-year period divided by the number of years (see Equation 2.2).

4.1.2. Soil Erodibility Factor

The soil erodibility factor (K) indicates the susceptibility of soil to erosion. It is expressed as the soil loss per unit of area per unit of R for a unit plot. A unit plot is 72.6 feet long, on a uniform 9% slope, and maintained in continuous fallow with tillage to break surface crusts and control weeds. These dimensions are selected because they coincide with the erosion plots used in early research in the United States.

The K value can be determined as the slope of a regression line through the origin for source data on soil loss (A) and erosivity (R) once the ratios for L, S, C, and P have been adjusted to unit conditions. Studies with rainfall simulators have been used to produce a soil erodibility nomograph based on soil texture and structure (Wischmeier *et al.,* 1971).

4.1.3. Slope Length and Slope Gradient Factors

The topographic factors (L) and (S) indicate the effects of slope length and steepness on erosion, respectively. Slope length refers to surface runoff from where it originates to where it reaches a stream channel or deposition begins. Slopes are treated as uniform profiles with maximum lengths seldom shorter than 15 to 20 feet or longer than 600 feet. The slope length factor (L) is defined as:

$$L = \left(\frac{\lambda}{72.6}\right)^m \quad (2.6)$$

Where λ = field slope length expressed in feet; and m = an exponent affected by the interaction of slope length with gradient, soil properties, and type of vegetation. The exponent value ranges from 0.3 for long slopes with gradients less than 5% to 0.6 for slopes more than 10%.

An average value of 0.5 is applicable to most cases. The slope gradient factor (*S*) is determined by:

$$S = \frac{0.43 + 0.30s + 0.04s^2}{6.613} \qquad (2.7)$$

Where *S* = slope gradient expressed in percent.

Foster and Wischmeier (1973) adapted the *LS* factors for use on irregular slopes. This adaption is useful on *wildland* sites that are landscapes not set aside for agriculture, urban development, or mining operations. These sites rarely have uniform slopes. These authors describe the combined factor as:

$$LS = \frac{1}{\lambda_e} \sum_{j=1}^{n} \left[\left(\frac{s_j \lambda_j^{m=1}}{(72.6)^m} \right) \left(\frac{10{,}000}{10{,}000) + s_j^2} \right) \right] \qquad (2.8)$$

Where λ_e = overall slope length; *j* = sequence number of segment from top to bottom; *n* = number of segments; λ_j = length (ft) from the top to the lower end of the jth slope segment; 8_j–1 = the slope length above segment *j; Sj* = *S* factor for segment *j* (equation 2.7); and *sj* = slope (%) for segment.

LS for uniform slopes is determined as:

$$LS = \left(\frac{\lambda_e}{72{,}6} \right)^m S \left(\frac{10{,}000}{10{,}000) + s^2} \right) \qquad (2.9)$$

4.1.4. Cropping Management Factor

The cropping management factor (*C*) represents an integration of the factors that affect erosion including vegetative cover, plant litter, soil surface characteristics, and land management. Embedded in this factor is a reflection of how intercepted raindrops that are reformed on a plant canopy affect splash erosion. The binding effect of plant roots on erosion and how the properties of soil change as it lays idle is also considered. The manner in which grazing livestock and other plant-cover manipulations change the magnitude of *C* is not adequately defined.

The value of *C* is not constant throughout the year in most cases. While treated as an independent variable in the formulation of the USLE, the actual value of this factor is likely dependent on other factors. Therefore, the value of *C* should be established experimentally. Runoff plots and fabric dams are useful for this purpose.

4.1.5. Erosion Control Practice Factor

The effect of erosion control practice (*P*) measures is considered an independent variable. As a consequence, it has not been included in the cropping management factor. Soil loss ratios for erosion control practices vary with slope gradient. Management practices characterized by *P* including strip-cropping and terracing are not applicable to most forested and grassland watersheds. Measurements to quantify the *P* factor for non-agricultural management practices on forested and grassland watersheds are not available.

4.2. Modification of the Universal Soil Loss Equation

The USLE has been modified for use in forest and grassland environments (Wischmeier 1975, Environmental Protection Agency 1980). The cropping management (*C*) and the erosion control practice (*P*) factors in the USLE have been replaced by a vegetation management (*VM*) factor in forming the modified universal soil loss equation (MUSLE) represented by the following formula:

$$A = RL(LS)(VM) \tag{2.10}$$

Where *VM* = the vegetation management factor expressed as the ratio of soil loss from watersheds managed under specified conditions of vegetative cover to that from the fallow condition on which the *K* factor is evaluated; and *R, L*, and (*LS*) = as described in the USLE.

Vegetative cover and soil surface conditions of natural ecosystems are accounted for with the *VM* factor. Canopy height and cover, ground cover, and bare ground with fine plant roots are considered as sub-factors in forests. These three sub-factors are multiplied together to obtain the *VM* value. *VM* factors for sites without a forest canopy such as a pasture or grassland sites are presented in Clyde *et al.* (1976).

More studies have determined values for *C* factors for the USLE than *VM* factors for MUSLE. Therefore, there are more published values for *C* factors than for *VM* factors. However, values of *C* can be used as approximations for *VM* values if they represent the similar site conditions. The Soil Conservation Service of the U.S. Department of Agriculture (now the Natural Resources Conservation Service) has published *C* values for pastures, grassland sites, and idle lands (Soil Conservation Service, 1977). Wischmeier and Meyers (1973) provide *C* values for construction sites.

The MUSLE procedure can be used as a guide for quantifying the potential erosion on wildland watersheds if the principal interactions on which the equation is based are well-known. Both the USLE and the MUSLE require an estimate of the *R* factor. Estimates of the *R* factor can be obtained from publications by the Natural Resources Conservation Service of the U.S. Department of Agriculture. Long-term rainfall-intensity records must be analyzed to calculate *R* factors for locations where the *R* factor has not been determined.

The USLE and MUSLE require an estimate for the *R* factor. General estimates for the United States are obtained in publications by the Soil Conservation Service of the U.S. Department of Agriculture. However, long-term rainfall-intensity records must be analyzed to estimate a value for the *R* factor that is applicable to specific regions of the United States and other parts of the world.

4.3. Soil Loss and Conservation Planning

The *soil loss tolerance* needs to be established for conservation planning. Soil loss tolerance, also called the *permissible soil loss,* is the maximum rate of soil erosion that will permit a high level of crop productivity to be economically and ecologically sustained. Soil loss tolerance (T_e) values of 2.5 to 12.5 tons per hectare per year are often used. A single T_e value is usually assigned to each soil series. However, a second T_e value can also be assigned to soils where erosion has reduced the thickness of the effective rooting depth to where the potential of the soil to produce biomass is diminished. Criteria commonly used in determining a T_e value to a soil series are:

- An adequate rooting depth must be maintained in the soil for plant growth.
- Soils that exhibit reductions in plant growth when the surface layer has been removed by erosion are assigned lower T_e values than for soils where erosion has had little impacts.
- Little soil loss is tolerated for shallow soils overlying restrictive layers. Therefore, the Te value should be less on shallow soils than for deep soils or soils with underlying soil materials that can be improved through management.

After establishing the soil loss tolerance, the USLE or MUSLE can be written as:

$$CP \text{ or } VM = Te/[R\ K(LS)] \tag{2.12}$$

A value for the combined effect of *C* and *P* or *VM* that fits the equation can be established by selecting the most appropriate cropping management system and conservation practices.

4.4. Revised Universal Soil Loss Equation

The Revised Universal Soil Loss Equation (RUSLE) predicts long-term average-annual soil erosion for a range of farming practices, conservation measures, mining, construction sites, and other sites where the mineral soil has been exposed to raindrop impacts and increased surface runoff. The Agriculture Research Service of the U.S. Department of Agriculture and their cooperators developed the RUSLE to account for the temporal changes in soil erodibility and plant factors that were not originally considered in the formulations of the USLE (Renard *et al.,* 1997; Weltz *et al.,* 1998). RUSLE has a snowmelt-erosion component and, furthermore, the equation can be applied to single events. Improvements were also made to the rainfall, slope length, and management practice factors in the original USLE model.

The RUSLE technology is computer-based and, therefore, replaces the tables, nomographs, and USLE calculations with a keyboard entry. Other improvements of the RUSLE over the USLE (Renard *et al.,* 1997) include:

- More data from different locations, for different crops and cropping systems, and for erosion in forest and grassland ecosystems are incorporated into the RUSLE.
- Corrections of errors in the USLE analysis of soil erosion have been made and gaps in the original data filled.
- The increased flexibility of the RUSLE allows for predicting soil erosion for a greater diversity of ecosystems and watershed management alternatives.

RUSLE has undergone revisions since its original formulation with the current version, called RUSLE2, a computer program that provides estimates of soil loss, soil-particle characteristics from rill and sheet erosion, and resulting sediment yield. It also uses a graphical-user interface in its application instead of the text-based interface of earlier versions of the program.

4.5. Water Erosion Prediction Project Model

The Water Erosion Prediction Project (WEPP) model is a newer technology for predicting soil erosion by water that has been developed by the Agriculture Research Service of the U.S. Department of Agriculture and their cooperators. The WEPP model estimates soil erosion from single events, long-term soil loss from hillslopes, and soil detachment and deposition in small stream channels and impoundments within a watershed (Weltz *et al.,* 1998). WEPP is a process-oriented family of models that are conceptually superior to the lumped RUSLE model and more versatile as to the conditions that can be evaluated.

The WEPP model operates on a daily time step, allowing the incorporation of temporal changes in soil erodibility, management practices, above- and below-ground plant biomass, litter biomass, plant height, canopy cover, and ground cover into the prediction of soil erosion on agricultural and grassland watersheds. Linear and nonlinear slope segments and multiple soil series and plant communities on a hillslope are also represented. The WEPP technology is intended to apply to all situations where surface erosion occurs including that resulting from rainfall, snowmelt runoff, irrigation, and ephemeral gully formation.

5. Prevention of Surface Erosion

Avoiding sites susceptible to increases in surface erosion in the first place is the most effective and economical means to prevent surface erosion from occurring and, in doing so, to maintain the inherent productivity of a watershed. More specifically, sites most susceptible to increases in surface erosion are those with sloping surfaces, shallow soils, soils with low hydraulic conductivity, and a lack of a protective vegetation cover.

6. Control of Surface Erosion

Implementing varying combinations of vegetative measures often in conjunction with mechanical methods while minimizing the impacts of roads can be required when the control of surface erosion becomes necessary. The key here is to maintain the surface soil in a condition that readily accepts water. The more water that infiltrates the soil, the better is the chance of reducing the erosive effects of raindrops striking the soil surface and the consequent surface runoff. The following section of this chapter describes some of the more common ways to control surface erosion. Much of the information presented in this section is based on publications by Satterlund and Adams (1992), Haan *et al.* (1994), Gray and Sotir (1996), Garcia-Chevesich (2008), Pizarro *et al.* (2008), Brooks *et al.* (2013), and others.

6.1. Vegetative Measures

Maintaining a vegetative cover on the soil surface is the best means of controlling surface erosion. A vegetative cover protects a site against the energy of falling raindrops impacting on the soil surface, decreases the velocity of the resulting surface runoff, and, therefore, reduces the rate of surface erosion. For example, strips of vegetation aligned perpendicular to the slope can slow the velocity of surface runoff. The occurrence of plants on a hillslope also increases the roughness of the soil surface to increase the torturousity of the flow path and, as a consequence, reduces the velocity of surface runoff. Soil erodibility is often reduced by a network of plant roots that enhance soil strength and improve soil structure through the addition of organic matter. However, a protective vegetative cover is not always on a site, and, therefore, a vegetative cover must be must be established on the site.

6.1.1. Direct Seeding or Planting Nursery-Grown Seedlings

Direct seeding or planting nursery-grown seedlings are common approaches to establishing a vegetative cover on a disturbed soil surface. Direct seeding lends itself to either dispersal by hand or machinery. This method of establishing a vegetative cover is often successful with proper site preparation to create a favorable regeneration bed. Fast-growing herbaceous species are typically used in the seeding effort. Direct seeding of landscapes has been practiced to improve the value of livestock grazing lands for decades. Planting nursery-grown seedlings by hand or machine can be successful in establishing a vegetative cover when it is planned and implemented to minimize further erosion of the soil surface. Planting seedlings can result in a protective vegetative cover in less time than direct seeding because the germinated herbaceous plants already have the beginning of a rooting system. The choice of the method to apply depends on the availability of seed or seedlings of the desired species, overall expense and time necessary to establish an effective cover, and chances for success. The method selected must also be applied with a minimum of additional soil disturbance to prevent additional surface erosion on the site in either case.

6.1.2. Hydroseeding

Hydroseeding is a process of applying a seed and mulch slurry on the area designated to be vegetated to control surface erosion with a hydroseeder. The slurry can also include additional ingredients such as a fertilizer to improve growth of the germination of the seed, a soil stabilizer to minimize the possible introduction of non-native plant species, and a colored dye to monitor the effectiveness of coverage. The slurry is either transported in a tank located on a truck or other vehicle to be sprayed on the site (figure 2.3) or it is applied by air from a helicopter or other aircraft on larger areas. The applied slurry should quickly adhere to the soil surface to lessen the subsequent removal of soil particles by the erosive actions of rainfall impacting the soil, surface runoff, or wind.

Figure 2.3. An eroding hillslope to be stabilized by establishing a vegetative cover by hydroseeding. The slurry applied to the site is often transported to the hillslope in a tank located on a truck (image from North American Green at www.nagreen.com).

Hydroseeding is often more effective than seeding or planting nursery-stock by hand or a machine in establishing a vegetative cover on eroding hillslopes. Furthermore, soil disturbance is less with hydroseeding. Favorable results are often quickly realized with high rates of germination obtained within a week or so. Inclusion of fiber in the applied slurry can accelerate the rate of germination by maintaining soil moisture around the seeds. Hydroseeding usually costs less than the more traditional process of establishing a vegetative cover by either direct seeding or planting nursery-grown seedlings.

6.1.3. Erosion-Control Blankets

Erosion-control blankets are blankets of plastic fibers, straw, or other plant residues that are placed on the soil surface to facilitate the establishment of a vegetative cover by protecting the soil surface from the further impacts of rainfall events and resulting surface runoff and, in doing so, retain soil moisture on the site (figure 2.4). There is a variety of erosion-control blankets including:

- Blankets of netting-synthetic or natural fiber mesh installed on disturbed areas to hold organic mulch is place.
- Biodegradable blankets of natural fiber held together by netting to facilitate the temporary control of surface erosion.
- Blankets of synthetic material for more permanent erosion control on slopes with experiencing increased velocities of surface runoff.

Figure 2.4. An erosion-control blanket placed on an eroding hillslope to facilitate establishing a vegetative cover by protecting the soil surface from the impacts of rainfall events and surface runoff (image from North American Green at www.nagreen.com).

Erosion-control blankets are installed after completion of a grading operation, if grading of the site is necessary, or following the initial establishment of a vegetative cover. Manufacturer recommendations should then be followed noting particularly the use of appropriate fastening devices (staples) and the need for a firm contact with the soil surface. Continual inspection of a blanket following installation after every rainstorm is suggested until an adequate cover of vegetation has been established. Erosion-control blankets that have moved downslope or been damaged should be re-positioned or replaced. Temporary blankets degrade naturally while permanent blankets will remain in place for prolonged periods of time.

6.2. Mechanical Methods

Vegetative measures of controlling surface erosion must often be accompanied by mechanical methods when a watershed is experiencing unacceptable rates of surface erosion. The main purpose of the mechanical methods is to reduce surface runoff and soil loss by retaining water on a site until a vegetative cover becomes established. Mechanical methods that shorten the slope length and reduce the slope inclination can reduce the volume and velocity of surface runoff, in doing so, decreases the erosive impacts of the surface runoff. A combination of treatments is often desirable but vegetative measures and subsequent land management should follow treatment as soon as possible if the methods are to have a lasting effect.

6.2.1. Silt Fences

Silt fences are an easy, cheap, and efficient way to temporarily control surface erosion. A typical silt fence consists of a piece of synthetic fiber fabric stretched between a series of either wooden or metal stakes along a contour line (figure 2.5). The stakes are installed on the downhill side of the fence with the bottom of the fabric trenched into the soil surface and backfilled on the uphill side. Surface runoff passes slowly through the fence while depositing the entrained soil particles on the uphill side of the fence. The entrained soil particles are captured primarily through the settling of water rather than filtration by the fabric.

Figure 2.5. A silt fence installed to temporarily control surface erosion on a hillslope. Soil particles entrained in surface runoff are captured on the uphill side of the fence through the settling of water (image from Thomas Carpenter, CPESC).

Silt fences are often used to control an increase in surface erosion following a fire, on large construction sites, and after recently planted agricultural fields. Silt fences should be installed downslope from the disturbed area before the rate of soil erosion has been increased on the site. They are purposely designed to concentrate or channel surface runoff.

6.2.2. Straw Wattles

The placement of straw wattles on a hillslope can increase infiltration, reduce surface erosion, and as a result, retain soil on the slope (figure 2.6). Straw wattles are tubes of compressed weed-free (wheat or rice) straw often 20 to 30 centimeters in diameter and 6 to 8 meters long, encased in a photo degradable material with an weight of about 15 kilograms. They are installed in a shallow trench to form a continuous barrier along the contour, but not across drainages, to intercept surface runoff and the entrained soil particles. Stakes are driven below or through the wattles to hold them in place. They are seated with a backfill of soil on their uphill side such that surface runoff flowing down the slopes will not pass underneath them.

Figure 2.6. Straw wattles placed along the contours of an eroding hillslope to stabilize the slope and control surface erosion (image from BonTerra Iberica at www.bonterrailberica.com).

Straw wattles are an effective alternative to silt fences in controlling surface erosion on severely burned slopes up to 30 percent. Straw wattles have been installed on slopes of 70 percent but their effectiveness diminishes on slopes steeper than 50 percent. Straw wattles are generally effective until permanent vegetation is established to provide long-term erosion control.

6.2.3. Straw Bales

Compressed bundles of straw secured by wire called **bales** can be transported to an eroding site with the straw then spread by hand to control surface erosion. The control of surface erosion is temporary, however, because the straw deteriorates with time. Straw bales can also be ferried to a remote burn area by a helicopter to help control the anticipated increase in surface erosion following the fire. The bales break apart and spread the straw on the area when they strike the ground to reduce the impacts of rainfall events on the bare soil surface.

6.2.4. Hillslope Catchments

Hillslope catchments are constructed to reduce the velocity of surface runoff following on the hillslope, impound the runoff water in the catchments, and, decrease surface erosion by retaining water and entrained soil particles in the catchments. The type of catchment selected for implementation is dependent on several factors including the soils, geology, and anticipated amount of increased surface erosion to occur on the hillslope. Among these types of catchments (Branson *et al,* 1961; Wiedemann, 1988; Morgan, 1995; Robichaud *et al.,* 2000; Brooks *et al.,* 2013) are:

- Contour furrows - small ditches 20 to 30 centimeters deep along the contour of a slope that hold the water in place until it infiltrates into the soil or evaporates. Contour furrows can also promote plant establishment.
- Contour trenches - large trenches on slopes too steep for contour furrows that are constructed to hold greater amounts of runoff water and can have a potential for increased groundwater recharge depending on soil (figure 2.7). Contour trenches are also called *infiltration or percolation trenches*.
- Fallow strips - vegetation strips about 1 meter wide along contours on gently sloping land that breakup the slope length until vegetation is established.
- Pitting - shallow depressions 20 to 30 centimeters wide and 45 to 60 centimeters long that are dug into the soil surface to create storage for surface runoff and, in many instances, provide water for re-vegetative measures.
- Basins - larger pits about 2 meters long, 1.8 meters wide, and 15 to 20 centimeters deep that store greater amounts of water and, furthermore, often create pockets of vegetation. However, basins are more costly to construct and are not as widely used as pitting methods.

Figure 2.7. A contour trench constructed a hillslope to reduce the velocity of surface runoff, impound runoff water, and decrease surface erosion by retaining runoff water and entrained soil particles (photograph by Roberto Pizarro Tapia).

Caution is necessary in constructing hillslope catchments. If not placed along the contours, furrows and trenches can become drainage ditches that concentration surface runoff and accelerate surface erosion rather than control erosion. The failure of a furrow or trench upslope causing downslope furrows and trenches to fail with the resulting surface erosion greater than was occurring initially can be another concern. Regardless of their form, hillslope catchments have a life expectancy that is limited by the amount of surface runoff and consequent soil loss on a hillslope.

6.2.5. Terraces

Terracing is a method of soil conservation where a hillslope is re-formed into a series of successively receding steps that effectively of shorteng the length of the slope and, in doing so, reduce the velocity of surface runoff, increase the infiltration of intercepted water, and, importantly, decrease the rate of surface erosion. Some of the entrained soil particles that are detached by the surface runoff along the slope in the erosion process are deposited on the terrace to improve the quality of water flowing further downhill. Terracing also promotes the production of agricultural crops requiring large quantities of water such as rice.

6.3. Minimizing Impacts of Roads

The potential of roads to impact of surface erosion can be greater than all of the other land-use activities and management practices combined. However, a properly designed system of roads will minimize the amount of mineral soil exposed and, ultimately, reduce the amount of soil erosion produced. One of the more important decisions to be made in planning of a road system is the allowable width and grade of the roads because these standards will affect the area of disturbance within a watershed. Unfortunately, some erosion can result from roads regardless of how careful the layout might be.

Megahan (1977), Dunne and Leopold (1978), Burroughs and King (1989) ,Satterlund and Adams (1992), and others have identified guidelines to follow in reducing impacts of roads and, more specifically, road construction on surface erosion. Among these guidelines are:

- Avoiding erosion-susceptible areas when locating roads.
- Maintaining or establishing a vegetative cover when necessary to protect cutbanks and fill slopes and other critical areas of exposed mineral soil.
- Providing compaction of fill materials and minimizing the amount of side-cast debris.
- Properly sizing culverts with appropriate spacing and providing for their continuous maintenance to avoid road washouts.
- Keep stream crossings at a minimum regardless of whether the stream is crossed by a culvert, bridge, or ford.
- Avoiding steep gradients that tend to be less stable; promoting high velocities of drainage water; and keeping roads away from stream channels to the extent possible.

7. Cumulative Effects on Surface Erosion

The cumulative effects of changing watershed conditions on surface erosion present a challenge to hydrologists and watershed managers While a minimal amount of surface erosion can be expected in most undisturbed ecosystems, inappropriate land-use activities and management practices that remove protective vegetative cover and expose mineral soil lead to increased rate of surface erosion. Such activities and practices include excessive forest harvesting, uncontrolled and excessive livestock grazing, and improper road construction and maintenance. Once again, the most serious erosion problems are often associated with roads. Maintaining a cover of vegetation and litter helps to prevent and control increased surface erosion by reducing the impacts of raindrops on a soil surface while sustaining high infiltration rates. Installation of mechanical barriers perpendicularly to the slope can slow the rate of surface runoff and the downward movement of entrained soil particles.

8. Summary

Surface erosion is caused by the detachment of soil particles from a site by the impact of raindrops striking a soil surface and their transport from the site by surface runoff. Not all of the detached particles will necessarily reach a stream channel to become sediment, however. Some of the particles can be deposited on sites further downslope.

Among the methods of measuring the magnitude of surface erosion are determining the amount of eroded soil particles that washes from bounded plots or measuring the depth of eroded soil on pins or stakes inserted into the soil. Predictions of the amount of surface erosion that might occur on a site can be obtained by application of the universal soil loss equation, the modified soil loss equation, the revised universal soil loss equation, or the Wind Erosion Prediction Project model.

Preventing surface erosion or maintaining the rate of erosion at acceptable levels include retaining a protective cover of vegetation to reduce the energy imparted by falling raindrops and high velocities of surface runoff. However, a cover of protective vegetative is not always present. Therefore, controlling surface erosion when unacceptable rates of surface erosion are occurring often requires establishing the protective vegetative cover. Reducing the rate of surface runoff and soil loss can also be achieved by retaining water on site by mechanical methods such as constructing contour basins or trenches. Minimizing the detrimental impacts of roads is always an important consideration. The most effect way of controlling surface erosion will likely be a combination of these approaches.

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Chapter Three

GULLY EROSION

1. Introduction

A gully is a relatively deep channel that has been formed by flowing water eroding sharply into a hillslope to create a valley from a few meters to tens of meters in depth and width. Gully erosion is initiated when the force of flowing of water exceeds the resistance of the soil on which the water is flowing. Gullies represent severe stages of erosion and, in simple terms, can be thought of as channels that have cut into hillslopes on sites where channels do not normally belong.

2. Processes

Gully development is triggered by tectonic movements or soil mass movement (see Chapter 4) causing a change in the topographic elevations on a landscape that are in dynamic equilibrium with their environment (Dunne and Leopold, 1978; Satterlund and Adams, 1992; Brooks *et al.,* 2013). Gullies are most often formed on hillslopes with highly erodible soils and an absence or low density of vegetation (figure 3.1). The flows of water within a gully channel are almost always ephemeral.

Figure 3.1. A severe gully formed on a hillslope of erodible soils and a low density of vegetation (photograph by Peter F. Ffolliott).

A gully develops when surface runoff is concentrated at a *knickpoint* where an abrupt change of elevation and slope gradient occurs as a result of the differential rates of erosion above and below the knickpoint (Heede, 1976). The differential erosion rates result from a change in the lithology of the channel. The fall of water over a knickpoint causes the gully bed to be undermined with a subsequent bed failure leading to a migration up-gradient called a *headcut.* The force of the falling water simultaneously dislodges soil particles below the fall and transports these particles downhill to lengthen and deepen the gully in the downhill direction referred to as a *downcut.* The gully bed has a stair-step configuration in a *discontinuous* gully where both processes are equally important (Heede, 1967). A *continuous gully* in comparison generally gains depth rapidly from the headcut and then maintains a relatively constant gradient to the mouth of the gully, where the most active changes take place. A series of discontinuous gullies can frequently coalesce into a continuous gully later.

While gully formation is commonly the result of excessive surface runoff, a subsurface flow of water can also dissolve, dislodge, and transport entrained soil particles (Brooks *et al.,* 2013). When large subterranean voids occur in the soil, the subsurface flow can become turbulent as opposed to laminar-matric flow and is called *pipeflow.* Soil pipes attain diameters of more than 1 m in some cases. Soil pipes can increase in diameter until the soil above them collapses. This process can lead to the further formation of gullies that result in greater erosion than the actual pipeflow itself.

3. Prevention of Gully Erosion

Gully formation can be initiated by forces causing a change in the level of the base datum of a site or, often commonly, on sites that are characterized by a low density of vegetative cover and highly erodible soils. The rapid expansion and deepening of older gullies or the development of new gullies is often the consequence of excessive removal of the vegetative cover on sites of highly erodible soils through mostly non-sustainable land-use activities. The best way to prevent gully erosion from occurring, therefore, is linked to connecting people to the conservation and sustainable use of the natural resources on the watershed.

4. Control of Gully Erosion

A strategy for gully control developed by Heede (1982) incorporates physical factors and parameters to establish priorities for treatment. The most critical locations in controlling gullies are at the gully head and its mouth. Gully widening occurs and creates an inherently unstable situation if deposition occurs at the mouth. Headcut areas, therefore, are always a high priority for stabilizing a gully. Priority should also be given to areas that yield the highest return for the least investment because of the high costs of controlling gullies.

4.1. Establishment of Vegetation

Channel gradients can be stabilized sometimes without resorting to mechanical methods on a site where a vegetative cover can be established (Heede, 1982; Brooks *et al.,* 2013). Vegetation that grows rapidly at a high density with deep and dense root systems is the most effective in controlling gully erosion. However, the selection of the appropriate type of plants to favor is important.

Trees and tall shrubs can restrict high water flow volumes and velocities and cause diversion against the stream bank. New headcuts often form where the water flow re-enters the original channel and, as a result, new gullies can develop. However, trees and shrubs along channel banks and on low gradients in wide gullies can form dams that can accumulate deposits of entrained soil particles by reducing flow velocities. Furthermore, trees can be thinned to allow greater light penetration to increase the growth of understory plants that protect the site.

But, grasses that lie down on the gully bottom under a flow of water form a smooth interface between the flow and original bed and, in doing so, can increase flow velocities that are not suitable for gully stabilization. The resulting higher flow can widen the gully even though the gully bottom is protected.

4.2. Mechanical Methods

Vegetation alone rarely stabilizes progressing headcuts because of the concentrated flow of water at these locations. Mechanical methods can be required if the site conditions do not permit the establishment of vegetation. The use of mechanical methods is often required at critical locations along a gully channel such as at knickpoints on the gully bed, at headcuts, and on gully reaches close to the gully mouth where changes in the flow of water cause frequent changes in deepening, widening, and deposition. Because the construction of large dams can be undesirable or uneconomical, other mechanical structures must often be considered.

Structures in the form of check dams, headcut control measures, vegetation-lined waterways, or gabions on the side-slopes can be necessary to stabilize a gully channel. However, in no case should mechanical structures be considered an end in themselves or permanent solutions despite how well they are constructed and function (Toy and Hadley, 1987). Permanent gully control requires the establishment of a protective cover of vegetation on both the eroding site and upland of the gully where surface runoff originates.

4.2.1. Check Dams

A *check dam* is a barrier that is placed in an eroding gully to trap the entrained soil particles that are carried down t he gully in periodic flow events (Heede, 1976; Morgan, 1995; Brooks *et al.,* 2013). The deposit of soil particles behind a check dam function to:

- Develop a new channel bottom with a gentler gradient than the original gully bottom and, therefore, reduce the velocity and the erosive force of gully flow.
- Stabilize the side slopes of the gully and encourages their adjustment to their natural angle of repose to further reduce erosion of the channel banks.
- Promote the establishment of vegetation on the slope and bed of the gully.
- Store soil water so that the water table can be raised to enhance vegetative growth outside the gully.

Check dams are either *nonporous* or *porous.* Nonporous check dams such as those dams built from earth, concrete, or sheet metal receive heavy impact from the hydrostatic forces of gully flow. These forces require effective anchoring of the dam into the gully banks where most of the pressure is transmitted. In only the exceptional cases should earthen dams be used to control gully erosion because it was likely the failure of earth materials that caused the gully to form in the first place.

Porous check dams have holes in an otherwise impermeable structure that allows water to seep through and drain the structure to create less pressure to the banks of gullies than do nonporous dams. Because gullies generally form on erodible soils, constructing porous dams is easier, cheaper, and often more effective than nonporous dams. Loose rocks, rough stone masonry, gabions, old car tires, logs, and brush have been used successfully to construct porous dams. An effective check dam consists of the following:

- An anchor to fasten the check dam to sides and bottom of the gully.
- A spillway to carry the designed flow of water.
- An apron to absorb the impact of water from the spillway and prevents undercutting of the structure.
- A sill at the lower end of the apron to provide a hydraulic jump that reduces the impact of falling water on the unprotected gully bottom.
- Protective armoring on the gully banks on the downstream side of the structure to help prevent undercutting on the sides of the dam.

Proper spacing between a series of check dams is critical to stabilizing the gully bottom, preventing further down-cutting and head-cutting and, therefore, extension of the gully. Each check dam in a series should be spaced upstream at the toe of the expected sediment wedge formed by the dam below. The first dam should be constructed where downcutting has not occurred, that is, where eroded soil particles have been deposited at the mouth of the gully. The spacing of subsequent dams constructed upstream from the base dam depends on the gradient of the gully floor, the gradient of the wedges of eroded soil deposited upstream of the dams, and the effective height of the dams as measured from the gully floor to the bottom of the spillway.

Heede and Mufich (1973) developed the following formula for the spacing between successive check dams:

$$S_p = \frac{H_e}{K_c G_{cos\theta}} \qquad (3.1)$$

Where S_p = spacing of check dams; H_e = effective height of the dam from gully bottom to spillway crest; θ = angle corresponding to gully gradient; G =gully gradient as a ratio (G = tangent of u); and K_c = a constant related to the gradient of the sediment deposits (S_s) that is assumed to be $(1 - K_c)G$.

The spacing of a check dams calculated by the above formula (figure 3.2) is largely a guide. The final spacing should be made in the field taking into consideration the local topography and other conditions such as:

- Placing the dam at a constriction in the channel rather than at a widened point if there is a choice of one or the other location within a short distance of the calculated position.
- Placing the dam such that it does not receive the impact of flowing of water from a tributary gully that enters the main gully.
- Placing the dam below a site where the flow of water in the gully has meandered within the channel.

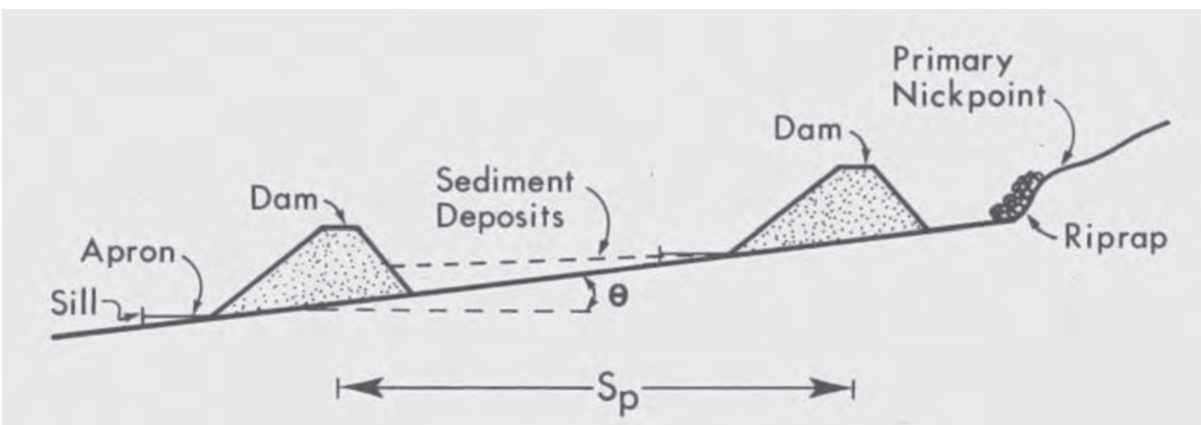

Figure 3.2. Diagram of the placement of successive check dams: Sp = spacing, θ = angle of gully gradient (from Heede and Mufich, 1973).

The spacing and effective height for a series of check dams is depend largely on the gradient and local conditions and the principal objective of the gully control (Brooks *et al.,* 2013). The dams should be spaced farther apart and have a greater effective height when the intention is to achieve the greatest possible deposition of soil (Morgan, 1995). However, the dams can be lower and placed closer together if the main concern is to stabilize the gully gradient while deposits of eroded soil particles are not of interest. A general rule to follow is to keep the dam height at or below the elevation of the bankfull flow.

4.2.2. Straw-Bale Check Dams

Check dams constructed from straw bales (see Chapter 2) can be placed on eroding hillslopes to temporarily control the formation of gullies following a fire. Goldman *et al.,* (1986) recommend that the drainage area behind a straw-bale check dam be less than 10 hectares. The effectiveness of the bales of straw in comprising the dam is usually less than three months, the surface runoff flowing into the dam should not be greater than 0.35 cubic meters per second, and the dam should be removed when the accumulation of soil particles upstream of the dam reaches one-half of the height of the dam. More damage can result from a failed check dam than if no barrier had been installed initially.

4.2.3. Headcut Control Measures

Structures to stabilize headcuts should be designed with sufficient porosity to prevent excessive pressures and, therefore, eliminate the need for large structural foundations. A reverse filter to promote gradual seepage of water from smaller to larger openings in the structure is also needed. Reverse filters can be constructed if the slope of the headcut wall is sufficient to allow a layering material beginning with fine to coarse sand and onto fine and coarse gravel. Erosion cloth can be used effectively.

Loose rock can provide effective headcut control when the flow of water through the structure must be controlled. The shape (preferably angular) and the size distribution of the rock should be selected to avoid openings that allow the flow velocity to become too great. Furthermore, it is important that the toe of the rock fill be stabilized to prevent the fill from being eroded. Loose rock dams can dissipate energy and, in doing so, trap entrained soil particles that can facilitate the establishment of a protective vegetative cover to help stabilize the toe of the rock fill.

4.2.4. Vegetation-Lined Waterways

The gully control measures described above are designed to reduce flow velocity within the channel and aid in the establishment of vegetation (Morgan, 1995; Brooks *et al.,* 2013). Vegetation-lined waterways are designed to reduce the flow of water in the gully by:

- Modifying the topography.
- Lengthening the watercourse to create a gentler bed gradient.
- Increasing the cross-section of the flow to attain a gentle channel side slopes.

Shallow flows of water over a rough surface with a large wetted perimeter reduce the erosive power of flowing water.

A rapid establishment of vegetation-lining of the waterway is essential for successful erosion control. Sufficient precipitation, favorable temperature, and soil fertility are all necessary for quick plant growth. Other requisites specified by Heede (1976) are:

- The gully should not be larger than the available fill volumes.
- The valley bottom must be wide enough to accommodate a waterway that is longer than the gully.

- The soil must be deep enough to permit shaping of the topography.
- The topsoil must be deep enough to permit later spreading on all disturbed areas. Waterways are more susceptible to erosion immediately following construction than are check dams. Therefore, vegetation-lined waterways require careful monitoring and maintenance in the first years after construction.

4.2.5. Gabions

The placement of gabions as a retaining wall along the side-slopes of a gully or stream channel can help to stabilize the gully or stream channel (figure 3.3). Gabions are cages, cylinders, or boxes collectively called baskets that are filled with rocks, pieces of concrete, or occasionally sand. The fill materials in a *basket* are bound together with corrosion-resistant wire. Gabion baskets have an advantage over loose riprap because of their modularity and ability to be stacked in varying shapes to meet the needs of erosion control. However, the gabions forming the retaining wall are often angled backward toward the side-slope of the gully rather than stacked vertically. Gabions have an advantage over more rigid structures because they conform to ground movement, dissipate much of the energy from surface runoff, and drain freely.

The efficiency of a gabion structure improves with time as soil particles and vegetation fill the interstitial voids to reinforce the structure. However, retaining a porosity of about 30 percent among the fill materials provides the necessary permeability. A gabion structure is mostly maintenance-free with the structure providing a useful life cycle when properly designed and constructed. The life expectancy of a structure depends mostly on the life span of the wire holding the gabions together rather than the contents of the baskets. That is, the structure will fail when the wire fails.

Figure 3.3. The side-slope of a stream channel is by gabion baskets. The gabions baskets form a retaining wall to stabilize a gully or stream channel to prevent further erosion (image from Modular Gabion Systems at www.grabions.new).

5. Cumulative Effects on Gully Erosion

Gully formation results in a transport of water, soil, and chemicals (nutrients) from a watershed. It is important, therefore, that hydrologists and watershed managers appreciate the relationships between gully formation and land-use activities on the watershed. Gullies often form where surface runoff is diverted by roadside ditches and culverts onto slopes not having a protective vegetative cover. Ditches concentrate the flow of water while culverts can block and divert the flow over roadbeds.

Most of the increases in gully erosion are closely associated with changes in the hydrology of a watershed. For example, excessive surface runoff originating from inappropriate land-use activities or management practices can cause increased erosion power and the channel networks on the watershed can be modified to expose susceptible sites to erosion. The latter occurs where subsurface flows of water discharge into a stable ravine.

6. Summary

Gully erosion can reduce the otherwise productive areas on a watershed and result in large quantities of eroded soil to move from upland site to downstream areas. Gullies are formed by tectonic movements or soil mass movement (see Chapter 4) causing a change in the topographic elevation on a landscape. Knickpoints where an abrupt change in elevation and slope gradient occurs also play a role in initiating the formation of gullies. Once a gully has developed, however, controlling the consequent soil erosion is difficult and often expensive.

Permanent gully control is achieved only by returning the effected site to a good hydrologic condition. The most critical locations in controlling gullies are at the gully head and mouth. Therefore, headcuts are generally a high priority for stabilizing a gully. Establishment of vegetation alone rarely stabilizes headcuts, however, because of the concentrated flow of water at these locations. Mechanical methods of control are often required for this purpose. Among these methods are check dams, headcut control measures, vegetation-lined waterways, and placement of gabions on the side-slope of the gully.

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Chapter Four

SOIL MASS MOVEMENT

1. Introduction

Soil mass movement is the instantaneous downslope gravity-driven movement of finite masses of soil, rock, and debris. Landslides, debris avalanches, slumps and earthflows, creep, and debris torrents are examples of this movement (Hutchinson, 1968; Dunne and Leopold, 1978; Brooks *et al.,* 2013). *Landslides* are often used as a generic term to include all forms of soil mass movement that exhibit perceptible motion (Satterlund and Adams, 1992). However, large amounts of imperceptible soil mass movement also occur.

Soil mass movement occurs on slopes where forces promoting failure become large compared with the resistance of soil to failure (Swanston and Swanson, 1980; Satterlund and Adams, 1992; Brooks *et al.,* 2013). These conditions are pronounced in steep, mountainous areas that experience high-intensity and often prolong rainfall events or rapid snowmelt.

2. Processes

The stability of soils on hillslopes can be evaluated in terms of a safety factor (*F*). That is:

$$F = \frac{\text{resistance of the soil to failure (shear strength)}}{\text{forces promoting failure (shear stress)}} \qquad (4.1)$$

A value of *F* = 1 indicates imminent failure while larger values indicate a little risk of failure.

Forces promoting failure (shear stress) increase as the inclination of a slope increases or as the weight of the soil mass increases. The presence of bedding planes and fractures in underlying bedrock can cause sites of weakness on a hillslope. Earthquakes or activities such as blasting for construction can augment the sheer stress. The addition of large amounts of water to the soil mantle and the removal of downslope material by undercutting in road construction are also common causes of movement due to increased stress.

Cohesion of soil particles and frictional resistance, a function of the angle of internal friction of the soil and the effective weight of the soil mass between the soil mass, are the major factors affecting the resistance of the soil to failure (shear strength). Pore water-pressure in saturated soil tends to reduce frictional resistance of the soil. Rock strength is affected by cleavage planes, fractures, jointing, bedding planes, and strata of weaker rocks.

Vegetation has a pronounced influence on soil mass movement. The elimination of soil water by transpiration of the plants results in lower pore water pressures, reduced chemical weathering, and reduced weight of the soil mass (Hutchinson, 1968; Hicks and Smith, 1981; Brooks *et al.,* 2013). Tree roots increase the frictional resistance of a sloping soil mass and, as a result, can stabilize thin soils up to 1 meter in depth by vertically anchoring into a stable substrate. Root systems can also provide lateral strength and improve slope stability.

3. Factors Affecting Hillslope Stability

Physical and biological factors influence slope stability and the potential for soil mass movement (O'Loughlin, 1985; Sidle *et al.,* 1985; Satterlund and Adams, 1992; Brooks *et al.,* 2013). Among the more important of these factors that act singly or in combination are:

- Climate and weather conditions including rainfall intensity and duration and temperature changes.
- Soil strength, particle size distribution, clay content, clay type, infiltration capacity, soil drainage condition, porosity, organic content, depth, and stratification, and lithic contacts.
- Slope steepness, slope length, and slope roughness.
- Vegetation type and density, litter thickness, root distributions, and strength of plant roots.
- Water erosive forces, for example, excessive surface runoff and the flow of water from snowmelt.
- Clearing of forests for lumber or other land uses.
- Over-grazing by livestock or over-browsing by wildlife populations.
- Road construction activities including loading slopes with fill material.

4. Evaluating Hillslope Stability

Methods have been developed to evaluate hillslope stability, assess soil mass movement hazards, and determine the potential for the delivery of soil particles to channels (Hicks and Smith, 1981; Fannin *et al.,* 1997; Rosgen, 2006). Terrain-evaluation procedures that are based on topographic and geologic information provide broad categories of the hazard of soil mass movement that are related to forest cutting, road construction, and other land-use and management activities (Sidle, 2000). Many of these procedures are based on the factors responsible for slope stability. Among the other components of these procedures (Swanston and Swanson, 1980) are:

- Land features such as landform, slope configuration, and slope gradient.
- Soil characteristics including parent material, occurrence of compacted, cemented, or impermeable subsoil, and clay mineralogy and angle of internal friction.
- Bedrock lithology and structure such as the type of rock of hillslopes of volcanic ash and silty sandstone is susceptible to soil mass movement, degree of weathering, and fracturing.
- Distribution of plant roots and degree of root penetration into the subsoil.
- Hydrologic characteristics such as saturated hydraulic conductivity and pore water pressure.

5. Reducing Soil Mass Movement

Natural events such as large- and high-intensity rainstorms, earthquakes, and wildfire have a profound effect on the potential for soil mass movement. These events can trigger landslides and debris flows on forest landscapes by increasing soil saturation on steep slopes that are normally unsaturated. Unfortunately, little can be done to prevent soil mass movement when natural events such as excessive rainfall amounts occur on terrain that is susceptible to slope failure (Satterlund and Adams, 1992; Brooks *et al.,* 2013).

Occurrences of soil mass movement can increase when poorly planned forest cutting activities, vegetative conversions, or road construction is carried out on sensitive sites. However, these actions need not take place. Careful planning and implementation of these and other human-induced land-use activities help to mitigate their often compounding impacts on soil mass movement. Guidelines to achieve this goal are considered within the context of the following cumulative effects on soil mass movement.

6. Cumulative Effects on Soil Mass Movement

Modification of the vegetative cover, the soil system, or the inclination of a hillslope can affect the occurrence of soil mass movement (Sidle *et al.,* 1985; Hagans and Weaver, 1987; Fannin and Rollerson, 1993; Brooks *et al.,* 2013). Impacts of these modifications can be estimated by relating them to factors affecting shear strength and resistance to shear. Removal of trees on a steep slope, conversion of a forest to agricultural crops, and road construction activities can have the greatest effect on soil mass movement.

The reduced evapotranspiration rates that accompanies the removal of trees or the conversion of a forest to pasture or agricultural crops often leads to wetter soils. Shear resistance is also reduced by the loss and deterioration of tree roots in areas where the roots had penetrated into the soil mantle and are anchored into the subsoil (Trustrum *et al.,* 1984). In many instances, therefore, maintaining tree cover on steep slopes to reduce the hazard of soil mass movement is desirable.

Undercutting a slope in road construction and improper drainage from a road once it has been constructed are major factors that accelerate mass movement (Burroughs and King, 1989). However, proper road layout, design and control of drainage, and minimizing cut-and-fill can help prevent the problems of soil mass movement. Areas that are susceptible to soil mass movement should simply be avoided when building a road.

7. Summary

Soil mass movement occurs most frequently where the forces promoting hillslope failure are greater than the resistance to failure. The factors affecting hillslope stability include climate and weather; soil conditions; slope steepness, length, and roughness, and human-induced activities such as excessive forest cutting, clearing of the protection of forests for other land-uses, and improper road construction. While there is little that an be done to prevent soil mass movement when natural events such as prolonged rainfall on terrain that is susceptible to slope failure, the occurrence of landslides, debris avalanches, and other forms of soil mass movement can often be prevented through careful planning of the anthropogenic factors that increase the likelihood that soil mass movement will occur.

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PART II

SEDIMENT SUPPLY, TRANSPORT, YIELD

Sediment is derived from soil erosion on the hillslopes and in the stream channels of a watershed. However, there is not necessarily a direct correlation between the amount of soil erosion that has occurred on a watershed and the amount of sediment deposited in a stream channel. Not all of the soil particles that have been eroded from an upper hillside site on a watershed will necessarily be deposited in a channel. Depending on the velocity of the surface runoff and size of the entrained soil particles, some of the particles can be deposited on downslopes sites before reaching the stream channel. The particles that become deposited in the channel as sediment are transported continuously downstream in perennial systems or accumulate in the channel to move downstream episodically in intermittent or ephemeral systems.

All watersheds produce some amount of sediment because soil erosion is a natural geologic process. However, the natural level of sediment production can often increase with the occurrence of a wildfire, a flooding event, or changes in land-use activities or watershed management practices such as the cutting of a forest, converting from one type of vegetative to another or constructing roads.

Chapter Five

SEDIMENT SUPPLY AND TRANSPORT

1. Introduction

The amount of sediment deposited in a stream, river, lake, or reservoir is indicative of the amount of soil erosion from the hillslopes and stream channels of the contributing watershed. Excessive sediment adversely affects water quality characteristics and aquatic habitats. To determine what constitutes excess sediment in a stream it is necessary to recognize that soil erosion and the sedimentation processes occur naturally and, therefore, that the levels of the sediment loads in streamflow can vary by region and from one time period to another. The relationships between erosion sources and sedimentation involve the stream channel processes related to sediment supply, transport, and fluvial mechanics.

The term *sediment* generally refers to the soil particles that are deposited in a stream channel and then transported by streamflow. *Sedimentation*, in turn, is the process of deposition and transportation of soil particles in the streamflow.

2. Classification of Sediment

Sediment is generally classified by its basic components, that is, suspended sediment and bed load. However, sediment can also be classified by size of the soil particles, for example, clay, silt, sand, gravel, cobble, and boulder. Approximations of these size categories are:

Soil particles	size (millimeters)
Clay	< 0.0040
Silt	0.0040 - < 0.065
Gravel	0.065 - < 2.0
Cobble	2.0 - < 256.0
Boulder	256.0 - 5000

The lithology of the soil particles in a sediment deposit can be described by rock or mineral names. Quartzite, sandstone, and basalt are examples of the mineral names.

3. Sediment Supply

Sediment is the product of soil erosion whether it has occurred as upland surface erosion, gully erosion, soil mass movement, or channel erosion. The amount of sediment that is deposited in a stream channel (Brooks *et al.,* 2013) is dependent on:

- The proximity of the erosion site to the channel.
- The shear forces acting on soil and rock.
- The size and distribution of sediment particles (see below).
- The efficiency by which eroded soil particles are transferred from one part of the watershed to another and into the stream channel.

Only a portion of eroded soil particles that accumulates as sediment in a stream channel is passed through and out of a watershed as sediment in storm events. Much of the eroded soil is deposited at the base of hillslopes, on terraces, or within stream-side (riparian) strips of vegetation before reaching a stream channel to become sediment (Comerford *et al.,* 1992; Neary *et al.,* 2010; Brooks *et al.,* 2013). However, while soil erosion occurring on a watershed can be measured, it is more difficult to determine how much of the sediment in a stream will be transported.

4. Energy Relationships in Streams

Once surface runoff reaches a stream channel, the rate and type of flowing water in the channel are determined by gravity and the resistance forces of friction. Gravity forces are expressed as a continuous energy gradient called the *hydraulic gradient.* The hydraulic gradient is a potential energy gradient, however, because the overall hydraulic gradient in a channel is determined by the change in elevation from the highest to the lowest elevations on a watershed. The gradient is steeper at the upper part of a watershed and diminishing as the channel nears the outlet of the watershed.

Water in the soil body of the upper part of a watershed has a high potential energy but cannot perform work until it is released. Water drains from the soil into a stream channel through the force of gravity and then flows from its higher energy state to a lower energy state downstream. The potential energy of a stream is converted to kinetic energy by the velocity of the flowing water.

4.1. Water Flow in a Stream Channel

Water flow in a stream channel is governed by energy relationships that are based generally on the Bernoulli equation:

$$(P/pg) + (V^2/2g) + z = \text{constant} \qquad (5.1)$$

Where P = pressure expressed in units of bars (newtons) per square meter; p = density of fluid expressed in kilograms per meter; g = acceleration as a result of gravity expressed in meters per second; V = velocity of the stream expressed in meters per second; and z = elevation above a datum in meters.

The three components in Equation 5.1 have units of length and, therefore, can be considered as pressure head, velocity head, and elevational head, respectively.

For a specified streamflow discharge (Q), it is known from the conservation of mass principle that even though the dimensions of a stream channel can change from one section to another, the products of A_1V_1 at section 1 = A_2V_2 at section 2. Therefore, if the first term in equation 5.1 is equivalent to water depth in the channel, the depth and velocity of the streamflow will change for a specified discharge in response to changing width and bottom configurations of the channel dimensions. As a result, the overall change in the energy status of a stream relates to the change in the elevation of the water surface in the stream, that is, the slope.

The Bernoulli equation is a one-dimensional equation that illustrates the energy relationships outlined above for a section of stream channel from its upstream location (subscript 1) to its downstream location (subscript 2):

$$z_1 + D_1 + (V_1^2/2g) = z_2 + D_2 + (V_2^2/2g) + h_L \qquad (5.2)$$

Where D = mean water depth expressed in meters; and h_L = the head loss due to energy losses association largely with friction.

The specific energy (Es) for a section of a stream channel with a small slope and a selected streamflow discharge is a function of water depth:

$$E_s = D + (V^2/2g) \qquad (5.3)$$

These energy relationships in a stream channel effect fluvial processes and are the basis for subcritical and supercritical flow and laminar and turbulent flow.

4.2. Subcritical and Supercritical Flow

The Froude number (F_r) is a dimensionless parameter representing a quantitative measure of whether *subcritical* or *supercritical flow* will occur. This number is calculated by:

$$F_r = V/(gD)^{1/2} \qquad (5.4)$$

Where V = the average velocity in the cross-section of measurements; g = the acceleration due to gravity; and D = the average water depth.

Subcritical flow occurs if $F_r < 1$, critical flow occurs when $F_r = 1$, and supercritical flow occurs if $F_r > 1$.

A more or less stable relationship occurs between a specified depth of flow and the ensuing rate of streamflow at and below critical flow. The most accurate measurements of a streamflow are obtained with this relationship because the critical flow is tranquil and exhibits relatively low energy and shear stress on the channel banks and beds. Supercritical flow has high energy and, as a consequence, can damage stream channels through shear stress on the beds and sides of channels.

4.3. Laminar and Turbulent Flow

Streamflow can also be characterized by the movement of individual fluid elements that results in *laminar* or *turbulent flow.* Each element moves in a straight line with a uniform velocity and little mixing among the layers in laminar flow. Turbulent flow has complicated patterns of eddies that exhibit random velocities in multiple directions. Turbulent flow is the normal condition in streams.

The Reynolds number (R_e) is a dimensionless measure to quantitatively distinguish laminar from turbulent flow. It is determined by:

$$R_e = (Vd)/v = (\text{inertial force})/(\text{viscous force}) \qquad (5.5)$$

Where V = the average velocity in the cross-section of measurement expressed in meters per second; d = the average water depth in meters; and v = the kinematic energy expressed in square meters per second.

A Reynolds number < 2,000 usually indicates laminar flow while numbers ≥ 2,000 turbulent flow in natural stream channels. Reynolds numbers are related to the energy gradient (slope) and rate of streamflow discharge. A steeper slope for a short distance will produce turbulent flow.

5. Sediment Transport in a Stream

Water and entrained sediment comprise the flow of a stream. Energy is released as water and sediment move from a higher to a lower elevation. A stream dissipates this energy as heat from friction and by performing work on the channel and sediments (Morisawa 1968, Brooks *et al.,* 2013). It is this process of work by the flow of water and sediment that forms the stream channel and changes the slope of the channel through erosion.

Channel erosion is not the only way that a stream can dissipate excess energy, however. It can also be dissipated internally through turbulent flow. When the stream losses energy to its channel, momentum is transferred from the flowing water to the channel and the stream loses energy in its channel (Rosgen, 2006; Brooks *et al.,* 2013). This change in momentum is a *force.* Sediment will be eroded and carried away when a sufficient force is applied to the channel. The energy that is lost in a section of channel (h_L) is a function of channel roughness (n), the hydraulic radius (R_h), and velocity (v) of the stream as shown below:

$$h_L = n\,(1/(4\,R_h))\,v^2/(2g) \qquad (5.6)$$

The resisting force exerted by the channel is a shear stress (τ), referred to here as shear resistance. The shear resistance is the shear stress that is generated on the bed and banks or the wetted perimeter of a channel in the direction of flow. Expressed as per unit of wetted area, shear resistance (τ_o) can be defined as:

$$\tau_o = \gamma\,(R_h)\,s_b \qquad (5.7)$$

Where γ is the specific weight of the fluid; and sb is the slope of the channel bed.

The sediment discharge of a stream is the rate of the sediment transported through a specified cross section of the stream. It is generally measured in kilograms per cubic meter, milligrams per liter, or parts per million. Sediment discharge contains fine particles that are transported in *suspension* and larger particles as *bed load.* Part of the suspended load is often called the *wash load.* The wash load is comprised of silt and clay while suspended sediment also includes sand-sized particles. The bed load consists of sand, gravel, or larger cobbles and is transported along the stream bottom by traction, rolling, sliding, or saltation. Sediment particles are moved in a stream when eddies formed by turbulent flow dissipate part of their kinetic energy into mechanical work.

5.1. Suspended Load

Soil particles are transported as a suspended load if their settling velocity is less than the buoyant velocity of the turbulent eddies and vortices of the water. The settling velocity depends largely on the size and density of the particle. A settling velocity of particles <0.1 millimeters in diameter is proportional to the square of the particle diameter, while the settling velocity of particles >0.1 millimeters is proportional to the square root of the particle diameter. However, little energy is needed for transport once particles are in suspension. A “heavy load” of suspended sediment decreases turbulence and makes the stream more efficient. Concentrations are highest in shallow streams where velocities are high.

The concentration of suspended sediment in a stream is lowest near the water surface and increases with stream depth. Silt and clay particles less than 0.005 millimeters in diameter are generally dispersed uniformly throughout the stream depth but large grains are more concentrated near the bottom.

There is a general correlation between suspended concentrations and streamflow discharge in most streams. As the peak passes and the rate of streamflow discharge drops, the amount of sediment in suspension also diminishes rapidly and aggradation occurs (Brooks *et al.,* 2013). When measurements of the suspended sediment concentrations and streamflow discharge are available, a relationship can be developed for use as a sediment rating curve (see Chapter 6).

5.2. Bed Load

Bed load particles transported singly or in groups can be entrained if the vertical velocity of eddies creates sufficient suction to lift the particle from the bottom. These particles are placed in motion if the force exerted by the water is greater on the top of the grain than on the lower part (Brooks *et al.,* 2013). The particles move by saltation when the hydrodynamic lift exceeds the weight of the particle. The particles will be re-deposited downstream if not re-entrained. Both large and small bed load particles can roll or slide along the bottom of a stream channel depending on the velocity of the streamflow. Rounded particles are more easily moved. The largest particles are generally moved in the steeply sloping channels of headwater streams.

The largest grain size that a stream can move as bed load determines the *stream competence.* The competency of a stream varies throughout its length and with time at any point along its length. Stream competence is increased during high peak streamflow discharges and flood events. The force required to entrain a given grain size is the *critical tractive force. Erosion velocity* is the velocity at which entrainment of bed particles occurs. DuBoy’s equation (Dunne and Leopold, 1978; Satterlund and Adams, 1992; Brooks *et al.,* 2013) can be used to calculate the tractive force for low velocities and small grains as a function of stream depth and gradient:

$$T_f = W_w DS \tag{5.8}$$

Where T_f = tractive force; W_w = specific weight of water; D = depth of water; and S = stream gradient.

Stream velocity is more important than depth and slope for high velocities and large particles. This situation has given rise to the sixth-power law that is:

$$\text{competence} = CV^6 \tag{5.9}$$

Where C is a constant.

Doubling the stream velocity means that particles 64 times larger can be moved. However, the exponent is only approximate and varies with other conditions of flow.

Stream power expresses the ability of a stream to transport bed load particles. It is the combined product of streamflow discharge, water surface slope, and the specific weight of water (Dunne and Leopold, 1978; Brooks *et al.,* 2013). Relationships similar to a sediment rating curve can be developed between unit stream power and unit bed load transport rate for a stream.

Another important concept in sediment transport is the *stream capacity,* which is the maximum amount of sediment of a given particle size and smaller that a stream can carry as bed load. Increased channel gradient and streamflow discharge rate can result in increased stream capacity (Dunne and Leopold, 1978; Brooks *et al.,* 2013). The stream capacity for both large and small particles is increased if small particles are added to predominantly coarse streambed material. However, when large particles are added to small-size grain material, the stream capacity is reduced. Small particles increase the density of the suspension and, therefore, the carrying capacity. The carrying capacity also decreases with increasing grain size. All of the variables affecting stream capacity are interrelated and vary with channel geometry.

6. Channel Degradation and Aggradation

The supply of sediment to a stream depends mostly on the climate, topography, geology and soils, vegetation, and land-use activities on the watershed. The relationships among the supply of sediment material to the channel, characteristics of the channel, the physical characteristics of the sediment, and the rate and amount of streamflow discharge are among the factors that determined the amount of sediment carried by a stream (Rosgen, 2006; Brooks *et al.,* 2013). Channel characteristics of importance are the morphological stage of the channel, roughness of the channel bed, bed material, and steepness of the channel slope. Soils and geological materials of the watershed and stream channels and the state of their weathering largely determine the physical characteristics of the sediment particles.

The relationships among these factors also determine the amount of energy available for the stream to entrain and transport the particles. When stream energy exceeds the sediment supply, *channel degradation* occurs. The removal of sediment materials from the channel bed by flowing water is called *channel scour.* On the other hand, *aggradation* occurs within the channel when sediment supply exceeds stream energy. A relationship between transport capability or capacity and supply can be developed for a specified stream and flow condition (Dunne and Leopold, 1978; Rosgen, 2006; Brooks *et al.,* 2013). The sediment supply limits total sediment transport for smaller particles but total sediment transport is more likely to be limited by transport capability as the material gets larger.

The processes of degradation and aggradation are important when considering streamflow dynamics because these are the primary mechanisms for sediment storage and release within a stream channel, respectively. When aggradation occurs, excess material is deposited and, eventually, a new channel slope that equals the upstream slope is established. The equilibrium of the new slope can carry the incoming sediment but the downstream slope has likely not adjusted accordingly and, therefore, deposition occurs. This latter deposition occurs above and below the reach of a stream to raise the channel bed to a position that is parallel to the equilibrium of the new slope. The rate of this deposition decreases with time or its advance downstream and, in doing so, the rate of aggradation. The channel upstream and downstream from the aggrading front behaves like two different reaches with different flows until the aggradation ceases and the status of dynamic equilibrium is restored (see below).

Degradation involves the removal of sediment. While naturally occurring degradation is a relatively slow process, rapid degradation can occur when the equilibrium of a stream system is disturbed (Rosgen, 2006; Brooks *et al.,* 2013). However, this initially rapid degradation diminishes slowly through time. The profile of a degrading stream is typically concave with the channel cross-section V-shaped. Soil particles are picked up from the channel bed until the load limits are reached in the degradation process. The carrying capacity for sediment is normally lower near the stream banks than in the center of the stream channel because of bank roughness. Therefore, more material is picked up in the center of the stream to cause the V-shaped cross-section of the stream.

Aggradation generally creates a convex-longitudinal profile of a stream where coarse materials are deposited first with the finer material moving farther downstream. Particle size decreases downstream as a consequence (Dunne and Leopold, 1978; Rosgen, 2006; Brooks *et al.,* 2013). The streambed rises slowly and there is a tendency for the water to flow over the stream banks when aggradation occurs. This process can lead to natural levee formation. The continual deposition and aggradation can lead to a braided river.

7. Dynamic Equilibrium

Stream channels are constantly in a state of change because of the processes of degradation and aggradation (Lane, 1955; Rosgen, 1980, 2006; Brooks *et al.,* 2013). However, a channel is in *dynamic equilibrium* when it is sufficiently stable so that compensating changes can occur without significantly altering this equilibrium (figure 5.1). This resilience or resistance to rapid change is caused by internal adjustments to a change in streamflow or sediment movement in the stream that are made by several factors including vegetation, channel depth, and stream morphology operating simultaneously in the system (Heede, 1980; Schumm, 2005).

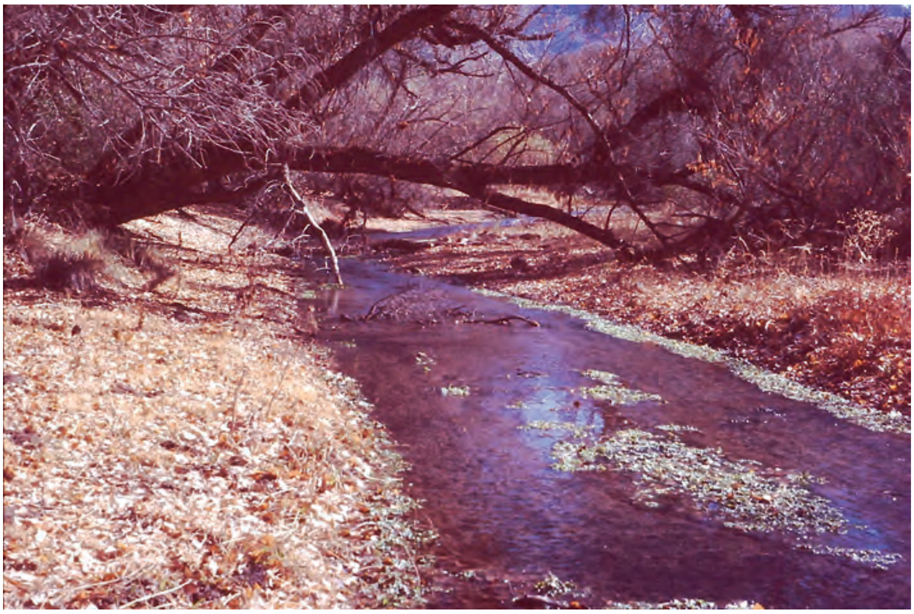

Figure 5.1. A stream channel in dynamic equilibrium between the forces acting to produce a change and the resistance of vegetative, geomorphic, and structural features to the change (photograph by Peter F. Ffolliott).

Dynamic equilibrium can also be explained in terms of hydraulic geometry. Hydraulic geometry relationships suggest that the spatial variation in stream power is caused by equal spatial adjustments between streamflow depth and width (Dunne and Leopold, 1978; Singh *et al.,* 2003). As flow depth increases within limits, the width of the stream channel must also increase assuming that the friction or roughness is constant enough to allow equilibrium conditions to occur in the channel. The concept of dynamic equilibrium under steady-state conditions tends to maximize entropy (Jaynes, 1957). Maximum entropy of a system occurs when the change in stream power is distributed among the changes in:

- Streamflow velocity and depth.
- Channel width, slope, and friction factors or resistant materials as determined from particle size.

These processes are illustrated by the principle of tractive force theory expressed in the continuity equation by Lane (1955) where sediment size and sediment load are proportionally balanced by streamflow discharge and channel slope. Streams in dynamic equilibrium:

- Lack headcuts.
- Have watercourses that begin high on the watershed to form a smooth transition between the non-channelized area and the stream channels.
- Possess bed scarps that are not well developed and are concave in longitudinal profile.

Streamflow velocity, depth, and width tend to increase downstream while the channel gradient and sediment particle size decrease if watershed conditions remain constant over relatively long stream reaches (Rosgen, 2006; Brooks *et al.,* 2013). Sediment production is negligible as a consequence.

Streams that are not in dynamic equilibrium are characterized by:

- Channel headcuts.
- Underdeveloped drainage networks with one-half or less of the watershed area having channelized watercourses.
- Frequent bed scarps.
- An absence of a concave-longitudinal profile where watershed conditions are relatively constant.

Channel headcuts are sources of soil erosion and, furthermore, indicate that the stream length and gradients have not allowed an equilibrium condition to develop. Bed scarps develop at knickpoints to indicate marked changes in longitudinal gradients. These bed scarps move upstream until a smooth transition between upstream and downstream gradient is attained.

8. Reducing Sediment Depositions in Stream Channels

The best way to reduce the amount of sediment that accumulates in a stream channel is to control the magnitude of soil erosion in the first place. However, soil erosion is a geologic process that can increase as a result of land-use activities or management practices on a watershed as discussed earlier. But, the eroded soil particles that are entrained in surface runoff are often trapped on the hillslopes of the watershed before entering a stream channel.

The entrained eroded soil particles in stream water can also be trapped in buffer strips of vegetation, behind contoured-felled trees, or within contour trenches (Goldman *et al.,* 1986; Satterlund and Adams, 1992; Brooks *et al.,* 2013). As implied earlier, these barriers are most effective where the surface runoff carrying the entrained soil particles is dispersed and its velocity reduced to the point where the particles are deposited before reaching the channel to become sediment.

Maintaining the integrity of a buffer strip of vegetation on a stream bank or establishing such a barrier when one is missing is a particularly effective of dispersing and reducing the surface runoff from the surrounding watershed and, in doing so, depositing some of the entrained soil particles before reaching a stream channel (Comerford *et al.,* 1992; Neary *et al.,* 2010). A buffer strip placed in the streamside management zone is effective in functioning as a filter of the soil particles entrained in surface runoff occurring as rills and inter-rill flows (figure 5.2). Buffer strips are not effective when gullies that intersect the strips to discharge the surface runoff directly into the channel, however. There is also little opportunity for a buffer strip to disperse and reduce the velocity of surface runoff and the loading of sediment in a stream when a culvert or drainpipe transports surface runoff through the strip.

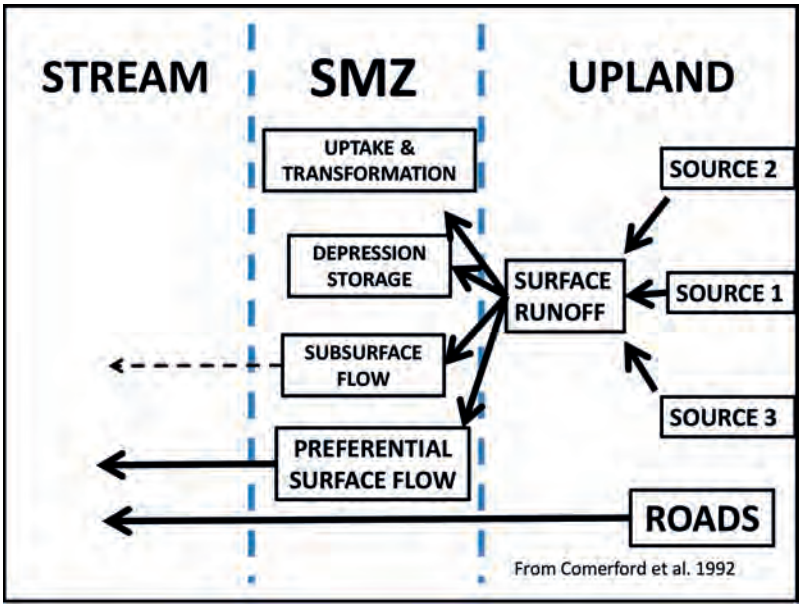

Figure 5.2. A diagram illustrating the movement of soil particles entrained in the surface runoff originating from varying sources passing through a buffer strip located in the streamside management zone (SMZ) acting as a filter of the surface runoff (from Comerford *et al.,* 1992).

9. Summary

Surface erosion, gully erosion, soil mass movement, stream bank erosion, and stream channel scour combine to produce sediment depositions in the channel. Fluvial and hydraulic processes are involved with aggradation and degradation of the channel in the deposition and storage of sediment in a stream channel. It is the interrelationship among these processes that determine the amount of sediment that will be deposited in the channel and the energy that is available for a stream to transport the deposited sediment downstream.

Streams transport sediment downstream as suspended particles and bed load on a continuous basis in perennial streams and episodically in ephemeral or intermittent flows. In either case, the movement of sediment in the channel decreases with time or its advance downstream and, as a consequence, the rate of aggradation in the channel decreases. The channel upstream and downstream from the aggrading front functions as two different reaches with different flows of water until the aggradation ceases and a status of dynamic equilibrium is restored.

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Chapter Six

SEDIMENT YIELD

1. Introduction

Sediment yield is the total sediment outflow from a watershed for a specified period of time and at a defined point in a stream channel. It is normally quantified by obtaining sediment measurements and relating these measurements to streamflow discharge. Conducting sediment deposit-surveys in reservoirs (Dunne and Leopold, 1978; Rausch and Heinemann, 1976) is another approach. Streams discharging large quantities of sediment are those that drain areas undergoing active geologic erosion or intensive land-use activities that cause high rates of erosion on the hillslopes and in the stream channels of the watershed. Sediment yields in relation to streamflow discharge are generally higher in arid and semi-arid regions than more humid areas because of their lower vegetation densities of protective vegetation and the consequent higher rates of soil erosion.

2. Measurement of Sediment Yield

Measurement of sediment yield to relate to streamflow discharge can be obtained by a number of methods. Some of these methods are also used to collect samples to analyze for other water-quality constituents.

2.1. Suspended Sediment

Obtaining "grab samples" by hand is a common procedure of measuring suspended sediment in small streams. However, this method of collecting samples is not always reliable because of the variability in suspended sediment concentrations in the streamflow (Brooks *et al.,* 2013). Single-stage samplers consisting of a container with an inflow and outflow tube at the top are used on small fast-rising streams. A single-stage sampler begins its intake when the water level exceeds the height of the lower inflow tube and continues until the container is full. Therefore, the use of such measurements is limited because only the rising stage of the hydrograph is sampled.

Depth-integrating samplers minimize the sampling bias encountered with single-stage samplers. A depth-integrating sampler (such as a DH-48 or DH-49 sampler) has a container that allows water to enter the sampler as it is lowered and raised in the streamflow at a constant rate (figure 6.1). A relatively uniform sample of a vertical section of a stream is obtained as a result. Measurements are obtained by the observer standing in smaller streams or sitting in a car suspended above larger streams. Depending upon the size of the stream, a series of measurements of suspended sediment are taken at specified intervals across the channel (Brooks *et al.,* 2013). Each measurement should also be accompanied by a measurement of streamflow discharge through the channel cross section.

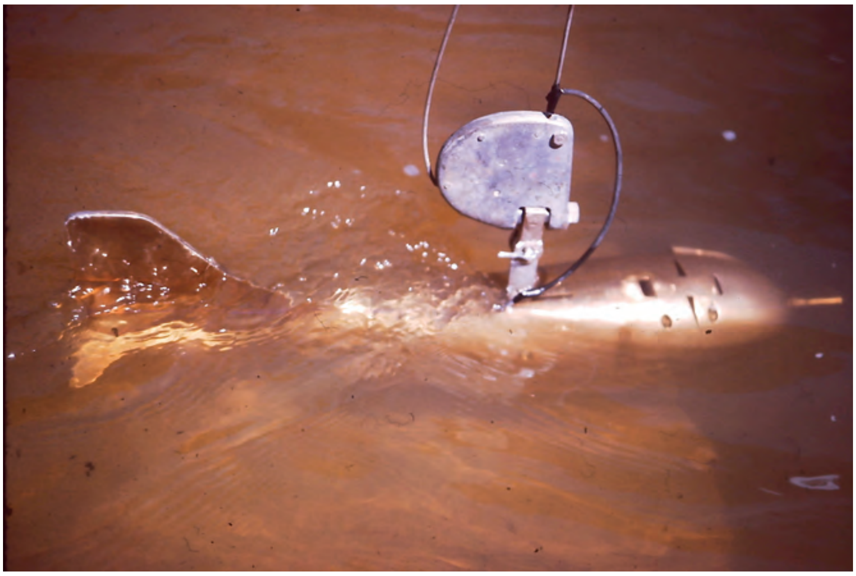

Figure 6.1. A depth-integrating sampler suspended by a cable from car above the stream. Streamflow enters the sampler as it is lowered and raised at a constant rate (photograph by Peter F. Ffolliott).

A variety of pumping samplers that automatically collect a sample of water at a specified time interval a selected point in a stream are also available to collect suspended sediment concentrations for analysis (Hansen, 1966). Components of a pumping sampler are:

- An intake or series of intakes to collect the sample.
- A pump to activate the sampler.
- A splitter device to draw-off a specified volume of water.
- A circular table to hold the containers in which the samples are pumped.
- A water supply for priming the pump and flushing sediment out of the intake(s) before each sample is taken.
- A clock and control box with a timer that initiates the sequence of operations in the proper order.

With the exception of the intakes that are positioned at a point in the stream channel, these components are housed in a shelter. The pumping sampler should be located adjacent to a continuous water-level recorder to obtain a measure of the water level in the stream when each sample is collected. One advantage of a pumping sampler is that samples of streamflow are collected for specified time periods.

Regardless of the method of measurement, once a suspended sediment sample has been collected, the liquid portion of the sample is removed in a laboratory by evaporating, filtering, or centrifuging and the amount of sediment remaining weighed. The dry weight of the sample is typically expressed as a concentration in kilograms per cubic-meter, millimeters per liter, or parts per million of water.

Once the weight of the suspended sediment has been determined, the sample can then be expressed as a concentration by:

$$C = A \left[\frac{\text{weight of suspended sediment}}{\text{weight of water-sediment mixture}} \right] \qquad (6.1)$$

Where C = suspended sediment concentration expressed in kilograms per cubic-meter, milligrams per liter, or parts per million; and A = a factor that corrects for the differences in the specific weights of water and the water-sediment mixture. Values for this factor correction are found in references on hydraulics and hydrology.

2.2. Bed Load

Bed load is more difficult to measure than suspended sediment because there is no device for measuring bed load particles that is reliable, economical, and easy to use. While many bed-load samplers are available, the hand-held Helley-Smith bed-load sampler is one of the most widely used on small streams in the western United States (Leopold and Emmett, 1976; Brooks *et al.,* 2013). Estimates of bed load can also be obtained by measuring the amount of material deposited in sediment traps, settling basins, porous sediment-collecting dams, or reservoirs (figure 6.2). These volumetric measurements can then be partitioned into sands, gravels, and cobbles to determine the contributions by particle size.

Figure 6.2. Deposition of bed load particles in a settling basin following the cessation of streamflow from a watershed (photograph by Peter F. Ffolliott).

2.3. Total Sediment

Measurements of total sediment can be obtained in an installation consisting of a low dam and basin to trap the coarse sediments in a bed load (see above) and a splitter or a series of splitters that collect a known portion of the suspended sediment passing over a spillway in the dam. Low streamflow volumes that do not spill over the dam deposit their sediment load in the basin. However, smaller sediment particles pass over the spillway in intermediate streamflow events with increasing larger particles passing through the spillway in still larger flows and, as a consequence, these sediment particles are not sampled. It is necessary that the basin be designed so that it does not completely fill with sediment for the anticipated streamflow regimes from the watershed. Following cessation of streamflow, the basin is drained of the remaining water and the bed-load particles collected for analysis (see figure 6.2). This procedure is best suited for ephemeral or intermittent streamflow regimes because of the need to drain the basin.

Continuous measurements of suspended sediment are obtained with the use of a splitter (Jones *et al.,* 1981) or a series of splitters that are positioned to collect the streamflow passing through the spillway of the dam (Brown *et al.,* 1970). As water flows through the spillway of the dam or through a weir, a small fraction is separated from the flow by the splitter. The flow obtained can be further sampled with a second and even a third splitter when large streamflow discharges occur. An intermediate storage tank is often placed between the second and third splitter with the third split from this tank transporting water into a storage tank (figure 6.3). A screen is placed at the outlet of the intermediate tank to prevent trash from reaching the third splitter. The water collected in the final storage tank is then sampled for measurement and analysis.

Figure 6.3. A series of splitters established to sample suspended sediment in the streamflow passing through the spillway of a dam (photograph by Peter F. Ffolliott).

The fraction of the total suspended sediment that is sampled by a series of splitters is determined through a calibration of the splitters. For example, the proportion of the water flowing through the spillway and entering the final storage tank is 1:60,000 if the proportion split by the first splitter is 1:600, the proportion of the split by a second splitter is 1:10, and the proportion of split by a third splitter is also 1:10. The suspended sediment sampled in the final storage tank would be multiplied by 60,000 to obtain an estimate of the total suspended sediment in the streamflow for the period of data collection.

Assumptions that are made in the analysis of a sample of suspended sediment obtained by a splitter or series of splitters are:

- That the respective proportions of the splits are constant for all streamflow discharges.
- That the splitters divert an unbiased sample of the average suspended sediment concentrations of the water flowing over the spillway for all concentrations encountered.

The weight of the bed load collected in the basin is added to the weight of the suspended-sediment load that has passed through the spillway to determine the total sediment outflow from the watershed. If the bed-load deposition is small, it can be weighed directly and adjustments made for its moisture content (Brooks *et al.,* 2013). The dry weight of large depositions of bed-load materials is determined by volumetric surveys and measurement of the weight per unit volume of the material. The suspended sediment computations require that:

- The weight of the sediment in the intermediate and final storage tanks be divided by the volumetric split-proportion entering the respective tanks.
- The calculated total loads for each tank are additive.

3. Prediction of Sediment Yield

Prediction of sediment yield is a more difficult task than predicting soil erosion. While it is often convenient to distinguish suspended sediment from bed load in predicting sediment yield, soil particles that are transported as suspended sediment in one reach of a stream channel can become bed load further downstream where the flow conditions are different or within a single reach of the channel as the flood wave increases. For example, sediment comprised of coarse silts, sand, and fine gravel can change from one mode of transportation to another depending on the streamflow conditions. Nevertheless, formulas have been developed by hydrologists and watershed managers to provide predictions of the sediment yield from a watershed.

3.1. A Modification of the Universal Soil Loss Equation

One approach to predicting sediment yield is by applying a modification of the universal soil loss equation. Assuming that the volume of the stormflow and the peak stormflow discharge resulting from a rainstorm is dependent on the amount, duration, and intensity of the storm, Williams (1975) modified the USLE by replacing the R factor with a runoff factor to predict the sediment yield attributed to the storm. The modified equation is:

$$S_s = 95q_{pq}QK(LS)CP \qquad (6.2)$$

Where S_s = sediment yield in tons; q_p = peak discharge expressed in cubic feet per second; Q = volume of stormflow expressed in acre-feet; and $K(LS)CP$ = as described in the USLE (see Chapter 2).

Equation 6.2 was developed to predict sediment yield on a storm-by-storm basis. Satisfactory predictions of sediment yield have been obtained by solutions of the equation for a wide range of watershed conditions. However, the equation tends to over-estimate sediment yields from small storms and under-estimate sediment yields from large storms.

Stochastic modeling of future rainstorm events based on the knowledge of past events and then projections of the past events into the future can facilitate the prediction of future sediment yields with equation 6.2.

3.2. Engineering-Based Formulas

There has been a tendency by some hydrologists and watershed managers to apply bed load or total load formulas to predict total sediment yield from a watershed because of the changing mechanisms of sediment transport in a stream channel (Nakato, 1990). Importantly, the predictions obtained by solving these formulas must be interpreted within this context. Largely engineering-based formulas for predicting bed load and total sediment yield have been developed for use in the United States and Europe. However, obtaining solutions for these formulas often require the availability of detailed input variables that are not routinely available or readily obtained on an operational-scale.

Summaries of many of the available bed load and total-load formulas have been compiled by Vanoni (1975), Alonso (1980), Brownlie (1981), Yang and Molinas (1982), and Bathurst (1985), and others. It is beyond the scope of this publication to describe the mathematical structures and applications of these formulas, however. Therefore, the cited summaries should be reviewed for this information before considering the use of the formulas for a specified situation.

4. Modeling Sediment Yield

Modeling of sediment yield generally incorporates a module representing soil erosion processes into the simulation structure because of the linkages between these hydrologic processes. Much of the modeling of sediment yield has focused on one of two approaches (Lopes, 1991). The first approach assumes steady-state flow conditions even though the sedimentation process is largely unsteady. Among the contributions made to this modeling approach are those reported by Meyer and Wischmeier (1969), Foster and Meyer (1972), Meyer *et al.* (1983), and Rose (1985). The second modeling approach focuses on features of the sediment-flow system without the steady-state assumption made with the first approach. Kinematic wave approximations to dynamic flow equations are used in this approach to describe the hydraulics of the sedimentation processes. These latter models frequently use the continuity equation for simulating advective sediment transport and empirical relationships for estimating the detachment of soil particles by rainfall impact and hydrologic shear. The flow and coupled sediment equations are solved analytically by the method of characteristics or numerically by finite difference methods. Bennett (1974), Lane and Shirley (1982), Singh (1983), and Lopes and Lane (1988) have made contributions to this approach of modeling sediment yield. Models embedding kinematic wave approximations into their structure can be restricted, however, because of the assumptions of constant rainfall intensity and infiltration rates required to solve these equations.

A general framework for simulating sediment processes has been proposed by Lopes and Ffolliott (1996) as a basis to modeling sediment yield. Sediment processes are described in terms of *broad shallow-flow* and *concentrated flow* within this framework. However, while many of the governing equations for these flow processes have been formulated for use in this modeling framework, formulations of the boundary conditions and scales at which solutions to these governing equations require further refinement.

5. Analysis of Sediment Data

Sediment data can be interpreted by developing a sediment budget, sediment delivery ratio, sediment hydrograph, or sediment rating curve from the data. Analysis of these descriptors is helpful in evaluating the impacts of land-use activities and management practices on the soil resources of a watershed.

5.1. Sediment Budget

The transport of sediment from source areas on the hillslopes of a watershed where active soil erosion takes place to downslope stream channels involves many complex processes. However, a *sediment budget* is a general accounting of the sediment input, output, and changes in storage for a stream system or channel reach and, therefore, is a simplification of the collective processes that affect sediment transport (Brooks *et al.,* 2013). Development of a sediment budget requires consideration of the following:

- The sources of the sediment, that is, surface erosion, gully erosion, soil mass movement, or channel-bank erosion.

- The rate of episodic movement of sediment in intermittent or ephemeral streams from one temporary storage area in a stream channel to another.
- The amount of sediment and its time in residence at each storage site in a stream system.
- The linkages among the processes of transfer and storage sites in a stream.
- The changes in sediment as the sediment moves through the system.

A sediment budget is a quantitative statement on the rates of production, transport, and discharge of sediment. However, to properly account for the spatial and temporal variations of sediment accumulation in a stream channel, its storage in the channel, and its transport in streamflow can require the use of a hydrologic simulation model (see Appendix).

5.2. Sediment Delivery Ratio

A common method of relating soil erosion rates on a watershed to sediment yield is through a *sediment delivery ratio* that is calculated by:

$$D_r = Y_s / T_e \tag{6.3}$$

Where (D_r) is the sediment delivery ratio; Y_s = sediment yield at a point expressed in weight per area per year; and T_e = total erosion from the watershed above the point also expressed in terms of weight per unit area per year.

A sediment delivery ratio is affected by the prevailing climate, texture of sediment particles, land-use conditions, local stream environment, and physiographic characteristics. As the size of the watershed increases, the sediment delivery ratio will generally decrease (Reohl, 1962; Jones *et al.,* 1981; Morgan, 1995). However, such relationships should only be used to provide approximations of sediment yields because sediment concentrations for a watershed can vary significantly.

5.3. Sediment Hydrograph

A *sediment hydrograph* is a graphical representation of the suspended sediment concentrations is relation to time. The relationship between the transport of suspended sediment and stormflow discharge becomes apparent after superimposing a sediment hydrograph on a stormflow hydrograph (Brooks *et al.,* 2013). A *stormflow hydrograph* is the hydrograph or that part of a hydrograph that is generated in direct response to a rainfall event. The higher concentrations of suspended sediment correspond generally with the rising limb of the hydrograph. After the peak of the stormflow passes and the hydrograph is receding, the suspended sediment concentrations also decrease indicating that there is less suspended sediment in the flow. Once developed for a watershed, a sediment hydrograph can be used to estimate the total yield of suspended sediment from the watershed for a stormflow event by integrating the values shown on the sediment hydrograph through the duration of the stormflow.

5.4. Sediment Rating Curve

It is difficult to combine all of the factors affecting concentrations of suspended sediment into one meaningful expression to estimate the sedimentation processes on a watershed or isolate the effects of the factors on these processes (Dunne and Leopold, 1978; Brooks *et al.* 2013). However, one approach to analyzing the effects of land-use activities and management practices on suspended sediment concentrations is through interpretations of a *sediment rating curve.* Such a curve is often expressed in the form of a power function. That is:

$$SS = kq^m \tag{6.4}$$

Where *SS* = suspended sediment concentration in milligrams per liter; *q* = streamflow discharge expressed in cubic meters per second; and k and *m* = constants for the stream.

A sediment rating curve will change as a result of changes in the magnitude of suspended sediment concentrations, the streamflow discharge regime, or the stream-channel morphology (Brooks *et al.,* 2013). With respect to the changes in suspended sediment concentrations, a sediment rating curve such as obtained by equation 6.3 can be used for estimating the effects of land-use activities and watershed management practices on these concentrations (Piest, 1963; Sidle and Campbell, 1985; Lopes *et al.,* 2001). However, a stable sediment rating curve is necessary for this purpose with observed changes in the rating curve attributed to natural phenomena taken into account. A shift in the sediment rating curve following some action that increases suspended sediment concentrations such as cutting a forest or the conversion of vegetative cover from one type to another can then be quantified.

The measurements obtained to develop a sediment rating curve can be partitioned into the streamflow-generation mechanism, that is, either rainfall or snowmelt-runoff, to compare the suspended sediment concentrations to the mechanisms of streamflow-generation (Lopes *et al.,* 2001). These measurements can also be separated into the rising and receding stages of a hydrograph to investigate the effect of hydrograph stage on the suspended sediment concentrations-streamflow discharge relations.

6. Cumulative Effects on Sediment Yield

Sediment yield from a watershed is altered by changes on the watershed that influence sediment deposition in a stream channel, streamflow discharges, or both. Furthermore, changes to the stream channel itself that affect stream slope, channel roughness, and channel morphology can alter aggradation-degradation processes and, therefore, sediment yield. Among the land-use activities and management practices that can affect these relationships on a watershed (Dissmeyer, 2000) are:

- Altering vegetative cover
- Urbanization.
- Road construction and maintenance activities.
- Loss of stream-side (riparian) plant communities.
- Drainage of wetlands.
- Ditching or stream channelization.

These changes generally occur piecemeal on a watershed and are often implemented incrementally through time. Nevertheless, the cumulative effect of the changes can impact the dynamic equilibrium of a stream. While sediment yield can be an indicator of land use and management impacts, they are difficult to interpret in terms of their causal effects without information on how the sediment was produced. It is important, therefore, that sediment measurements be carried out within the framework of statistically valid sampling schemes.

The general diversity of land use and management changes that occur spatially and temporally on a watershed can cause significant changes in the sediment yield from the watershed (Brooks *et al.,* 2003). Increases in streamflow resulting from reduced time of concentration can lead to changes in stream-channel dimensions to accommodate the modified flow. Channel erosion, primarily lateral extension that increases channel width, adds to sediment supply. Reductions in streamflow can also lead to channel adjustments and alterations of sediment yield.

7. Summary

Watersheds with large outflows of sediment, that is, large sediment yields, are those experiencing active geologic erosion or inappropriate land-use activities or management practices. While measurements of suspended sediment and bed load are possible, prediction of the sediment yield from a watershed is a more difficult task. A modification of the universal soil loss equation and engineering-based formulas are available for this purpose. Efforts to model sediment yield are also presented in a conceptual framework.

Sediment budgets, sediment delivery ratios, and sediment rating curves can be useful in characterizing the nature of sediment yields from a watershed and the effects of land-use activities and watershed management practices on the watershed, however.

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PART III

ECONOMIC CONSIDERATIONS

While hydrologists and watershed managers are often mostly with biophysical processes, they should also have an understanding of the economic implications of what they might be proposing. Furthermore, it is important that they know the economic values that are associated with the alternative watershed management practices that are considered to be feasible in preventing or controlling increased soil erosion and sedimentation processes. Hydrologists and watershed managers should also know who is responsible for obtaining and then allocating the financial resources necessary for management practices considered for implementation. Therefore, the economic aspects of watershed management practices are considered in Part III of this publication. More specifically, an overview of the procedures by which economic analysts assign values to inputs and outputs and compare the benefits and costs of the alternative watershed management practices is presented.

Chapter Seven

ECONOMIC APPRAISALS OF WATERSHED MANAGEMENT PRACTICES

1. Introduction

Economic appraisals of alternative watershed management practices to prevent or control soil erosion and excessive sedimentation rates are made to assist decision-makers in selecting which of the alternative management practices is the most economically efficient. *Economic efficiency* relates to the relationships between benefits and costs that are valued by either a market price or economic values when market prices are not appropriate. If only one management practices is considered, an economic appraisal will help to indicate the economic value of the practice.

The economic appraisal process is generally iterative with the analyst moving through increasingly detailed stages of evaluation (Gregersen *et al.,* 1987, 2007; Dixon *et al.,* 1994). Each of the sequential steps is discussed below.

2. Identifying and Quantifying Physical Inputs and Outputs

Obtaining information on the physical inputs and outputs of each of the alternative watershed management practices and the relationships between these inputs and outputs is one of the major tasks in the economic appraisal process. It is in this first step of the appraisal process and represents the initial interaction between a hydrologist or watershed management manager and an economic analyst often takes place. However, it is the responsibility of the hydrologist or watershed manager to identify and quantify most of the inputs and associated outputs in physical terms and define the management alternative(s) to be evaluated. This information is needed in terms of:

- The physical units in which the inputs and outputs have been measured.
- The source of the inputs.
- When the inputs will be needed and when the outputs will occur.

It is essential that the inputs be related to the outputs from which they are derived. This information can be summarized in a *physical-flow table* that shows the flows of the physical inputs and outputs through time. A point emphasized here is that the input and output quantities in the physical-flow table should reflect the differences *with-and-without* the implementation of the watershed management practice evaluated. That is, reference should be made to the differences in prevention or control of soil erosion and sedimentation with and without the watershed management practice when referring to preventing or controlling soil erosion and sedimentation.

Many outputs of watershed management are expressed in the form of losses prevented through either preventing or controlling soil erosion and sedimentation rates. Even though some of the outputs can be difficult to quantify in reference to the with-and-without principle, the relevant outputs should be included in the appraisal process because they are important in human-value terms. As a consequence, the tons of soil loss prevented by implementing an erosion-control practice is not an adequate output measure because people normally do not put a value on the soil loss. Therefore, the soil loss prevented must be related to a human-value such as the losses in food production or other losses prevented by the control practice.

The values of some of the outputs of watershed management are not easily measured in the marketplace. However, even if these outputs cannot be quantified and valued in the market, they should be qualitatively described to the extent possible. Many non-quantifiable benefits such as ecosystem preservation relate to the issues that are associated with the sustainability of human-values. Benefits such as these are important and, therefore, should be quantified and valued in a descriptive manner.

3. Valuing Inputs and Outputs

Prices established at the marketplace are used to value the inputs and outputs of alternative watershed management practices that are traded in the market whenever possible (Hufschmidt *et al.,* 1983). This process is relatively straightforward and, therefore, there is little need for a further discussion on this approach. Instead, the focus here will concentrate on the valuation of nonmarketable benefits and costs with measures of economic value and methods of shadow pricing.

3.1. Measures of Economic Value

A basic measure of economic value is the *willingness to pay.* The willingness to pay (WTP) is a measure that reflects the willingness of people to pay for goods and services at the margin, that is, if an additional unit of the good or service is made available. The WTP reflects a scarcity value in that the more that is made available, the less an individual is willing to pay for the good or service at the margin.

Another common measure of economic value is the *opportunity cost,* which is a measure of value of the opportunity foregone when a resource is used for one purpose rather than another. An example would be the opportunity cost (OC) of establishing a watershed protection area to prevent the extraction of resources such lumber because this action might result in increased soil erosion and sediment yield. The OC applied to the land set aside for this purpose would be the value of the benefits foregone by not being able to harvest the lumber. There is a relationship between the WTP and OC with OC values used in measuring the WTP for the goods and services foregone.

One can assume that market prices reflect the WTP at the margin in a competitive economy with no constraints on the movement of prices. It is for this reason that market prices are used widely in economic appraisals. However, the WTP and OC can diverge from market prices when regulations are placed on the market prices such as when subsidies or taxes affect them (Gregersen and Contreras, 1992). Market prices are adjusted to reflect true scarcity in the economy when this divergence occurs. These adjusted prices are called *shadow prices.* Shadow pricing is required is when the goods and services do not have observable market prices. Many environmental services obtained in a watershed management practice are of this type. The economic analyst attempts to derive shadow prices that reflect the WTP for the good or service in this case.

3.2. Shadow Prices

One of three approaches is used in developing shadow prices for the costs (inputs) and benefits (outputs) of a watershed management practice. These approaches are *market prices, surrogate market prices,* or *hypothetical valuation approaches.*

3.2.1. Market Prices

The market price itself can be adjusted to reflect the value of the good or service at the margin when a market price is considered to adequately reflect the WTP for a good or service (Gregersen *et al.,* 1987). Reasons for this are:

- Market prices are accepted more readily by decision makers than artificial values that are derived by an economic analyst.
- Market prices are easy to observe at a point in time and through time.
- Market prices reflect the decisions of many people acting as buyers and not only the judgment of the economic analyst that is the case with subsidized prices.
- The procedures for calculating shadow prices are imperfect, and, therefore, estimates of these prices can introduce larger discrepancies than the simple use of even imperfect market prices.

3.2.2. Surrogate Market Price

Surrogate market prices are used where the benefits and costs are not themselves valued in the market but for which clear substitutes exist in the marketplace. The market prices of the substitutes are often used to develop surrogate values for the benefits or costs to be valued (Gregersen *et al.,* 1987, 2007). For example, there is no market for the amount of soil that is eroded from an upstream watershed or the amount of sediment that is deposited in a downstream reservoir. However, one approach to placing a value on the eroded soil or the deposited sediment is to examine the market prices of the eroded uplands or the silted lowlands and then compare these prices to the market prices of comparable lands that are not affected by soil erosion or sedimentation. The difference in respective land values can be a surrogate price for the damage caused by the erosion or sedimentation.

3.2.3. Hypothetical Valuation Approaches

Hypothetical valuation approaches apply when it is not possible to derive acceptable market price measures of value. In such cases, an economic analyst might derive some information about value through local surveys or expert judgment to estimate the minimum values for some of the benefits of a watershed management practice through an analysis of the cost of obtaining these benefits. This approach is a cost-price analysis since it uses costs to derive information to estimate the minimum value of the benefits that would be required to break even with costs (Gregersen *et al.,* 1987). However, that these estimates represent a lower value of the good or service in question must be remembered.

The results obtained in applying either surrogate or hypothetical market prices to place a value on goods and services must be interpreted carefully because neither is based on actual market prices (Gregersen *et al.,* 1987). Surrogate or hypothetical market prices should only be used in an economic appraisal when market-based approaches are impractical or impossible to apply.

4. Comparing Benefits and Costs

Once the physical-flow tables and the associated values are formulated, the two are brought together to develop an *economic value-flow table.* An *economic value-flow table* presents the flows of economic benefits and costs through the expected life of the alternative watershed management practices. Implications of risk and uncertainty in the development of an economic value-flow table are considered through a sensitivity analysis (Gregersen *et al.,* 1987). A sensitivity analysis indicates how the measures of worth (value) might change with changes in assumptions concerning the identified input and output values.

The main purpose of developing an economic value-flow table is to organize information to compare and evaluate the relative feasibility of the alternative watershed management practices. Two questions are always of interest to decision-makers in evaluating the feasibility of implementing a watershed management practice. These questions are:

- Is the proposed watershed management practice worth implementation?
- Is the practice better than alternative watershed management practices and often scarce resources?

Additional questions concerning benefits and costs that are relevant in the economic appraisal of a watershed management practice include:

- What is the budget impact likely to be?
- Is the management practice that is selected for implementation attractive to all of the people who will be required to put resources into the various managerial tasks to make the practice work?
- What are the income-distribution impacts of the proposed management practice?
- Are the economic benefits greater than costs, that is, is the practice selected for implementation an economically efficient use of resources?

Answers to these questions help to place an economic appraisal of alternative watershed management practices into a proper perspective for evaluation.

Once the economic value-flow table has been developed, an economic-efficiency analysis is undertaken to compare the streams of benefits and costs for the alternative watershed management practices. There are three value measures that can be used in an analysis of economic efficiency (Gregeren *et al.,* 1987). These measures are the *net present worth,* the *economic rate of return,* and a *benefit-cost ratio.* Importantly, all of these measures are calculated with the same benefit and cost data and underlying assumptions.

4.1. Net Present Worth

Net present worth (NPW), also known as net present value, is based on a need to determine the present value of net benefits from a watershed management practice. The use of the NPW criterion will provide a ranking of alternatives if the goal is to determine the total net benefits of a management practice to society. The formula for the NPW calculation is:

$$NPW = \sum_{t=1}^{n} \left[\frac{B_t - C_t}{(1+r)^t} \right] \tag{7.1}$$

where B_t and C_t = the benefits or costs in year t; and r = the selected discount rate.

4.2. Economic Rate of Return

The economic rate of return (ERR) is also used to evaluate alternative watershed management practices. Unlike the NPW or a benefit-cost ratio (see below), the ERR does not use a predetermined discount rate in its calculation. Rather, the ERR represents the discount rate that sets the present value of benefits equal to the present value of costs. The ERR is the discount rate, r, such that:

$$\sum_{t=1}^{n} \left[\frac{B_t - C_t}{(1+r)^t} \right] = \sum_{t=1}^{n} \left[\frac{C_t}{(1+r)^t} \right] \tag{7.2}$$

or

$$\sum_{t=1}^{n} \left[\frac{B_t - C_t}{(1+r)^t} \right] = 0 \tag{7.3}$$

Although a discount rate is not prescribed but is determined as a result of the ERR calculation, this does not eliminate the use of a discount rate in its analysis. The calculated ERR is compared to a predetermined discount rate to decide whether a management practice is economically efficient. For example, if the ERR calculated is 15% and the OC of the funds necessary to implement the practice represent 10%, the practice would be economically attractive. However, the practice would be financially unattractive if funds available for the project cost 18%.

4.3. Benefit-Cost Ratio

A benefit-cost (B/C) ratio compares the present value of benefits to the present value of costs:

$$B/C\ Ratio = \frac{\sum_{t=1}^{n} \left[\frac{B_t}{(1+r)^t} \right]}{\sum_{t=1}^{n} \left[\frac{C_t}{(1+r)^t} \right]} \tag{7.4}$$

If the *B/C* ratio is greater than 1, the present value of benefits is greater than the present value of costs and the management practice is an economically efficient use of financial resources assuming that there are no lower-cost means for achieving the same benefits.

4.4. Deciding Which Value Measure to Use

Maximum total NPW is the economic objective that people seek for the investment of available but scarce resources. Therefore, the NPW measure should always be a part of any ranking scheme for accepting or rejecting a watershed management practice (Dixon and Hufschmidt, 1986; Dixon *et al.,* 1994). The ERR and the B/C ratio are measures of benefits per unit of cost. However, these two value measures provide little indication of the total magnitude of the net benefits. Since net benefit is what is necessary to maximize for a specified investment budget, reliance on just the ERR or B/C ratio could lead to the selection of a management practice that provides total net benefits that are smaller than those resulting when projects are selected using the NPW criterion (Gittinger, 1982).

In cases where alternative watershed management practices are not mutually exclusive and there are no constraints on costs, all of the management practices that result in a positive NPW can be accepted. Where not all of the practices can be selected for implementation because of a cost constraint, the goal is to select the practices that provide the greatest total NPW. For mutually exclusive projects, that is, when two or more practices that would use the same site, the NPW measure is the only value measure that will always lead to the correct selection.

5. Nonmonetary Benefits and Costs

In spite of all the advances that have been made in the economic appraisal of non-marketed goods and services, there are likely to be some of the effects of a watershed management practice that are impossible to either quantify or value (Gregersen *et al.,* 1987, 2007). For example, the construction of a large dam to prevent the movement of sediment further downstream can have a negative aesthetic impact to society in that the impacted view is not as natural or pleasing as it previously was. This kind of aesthetic effect is almost impossible to quantify because there are no widely accepted measurement or expressions of value for scenic beauty.

A watershed management practice that requires a change in the lifestyle of the people would have a cultural impact. The impacts of these nonmonetary benefits and costs are also difficult to quantify. Nevertheless, these nonmonetary effects should still be recognized and described within the analysis, evaluated qualitatively, and presented to the decision-maker for consideration. These effects can be ignored by the decision-maker even though the effects cannot be entered directly into the economic analysis in this way.

6. Summary

Economic appraisals of watershed management practices require identifying, quantifying, and valuing inputs and outputs to determine the monetary and non-monetary benefits and costs of alternative management practices to control increasing soil erosion and excessive sedimentation processes. An economic-efficiency analysis involving the respective value measures of the alternative practices is then conducted. These measures are the present net worth, economic rate of return, and the benefit-cost ratios of the practices. The most economically feasible management practice to prevent or control soil erosion and excessive sedimentation rates within an array of alternative management practices is then selected for implementation.

The economic appraisal procedure presented in this chapter has been applied in selecting a watershed management practice to satisfy a variety of goals and objectives in Morocco (Brooks *et al.,* 1982), Taiwan (Wang *et al.,* 1998), and People's Republic of China (Shuhuai *et al.,* 2001). It is concluded, therefore, that this appraisal procedure is applicable elsewhere where the necessary input and output data and valuation information are available or can be easily obtained.

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APPENDIX

Appendix

TOOLS AND TECHNOLOGIES

1. Introduction

Some of the tools and technologies that are available to hydrologists and watershed managers to improve their understanding of soil erosion and sedimentation processes and then preventing or controlling these processes when they become excessive are reviewed in this appendix. These tools and technologies can help in making management tasks easier and providing analytical capabilities not necessarily available in the past. Hydrologic simulation models, remote-sensing technologies, geographic information systems, the global positional system, decision-support systems, and Internet applications are among the tools and technologies available to hydrologists and watershed managers.

2. Hydrologic Simulation Models

Hydrologic simulation models are used to address the questions related to the analysis of past, present, and future hydrologic processes. These models are also helpful in extending hydrologic data and other information for predicting what might happen when a change occurs on a watershed landscape (Larson, 1973; Dingman, 2002). Hydrologic simulation models are continuously undergoing improvement with increased advances in computer technology that facilitate their capability to interface with emerging technologies to provide more powerful tools for operational applications.

The utility of hydrologic simulation models is their capacity to generate acceptable predictions within the context of the available input data. *Deterministic models* are often the focus because they are better able to predict the hydrologic effects of a change in climate, vegetation, or land use rather than *stochastic models* that are best used for stationary watershed conditions. Criteria for assessing the utility hydrologic simulation models to predict soil erosion and sedimentation processes and to evaluate the effectiveness of their prevention or control measures include their spatial representations, temporal resolutions, and conceptual basis.

2.1. Spatial Representation

Hydrologic simulation models are either *lumped* or *spatially distributed* in their structure. Lumped models assume no spatial heterogeneity in the modeling domain and do not allow for spatially variable inputs. Spatially distributed models allow the user to designate varying precipitation, temperature, and other climatic variables and the spatial occurrence of vegetation, soils, and slope characteristics. Hydrologic processes such as surface and subsurface water flow, streamflow regimes, and soil erosion rates and sedimentation are represented as varying on the landscape on a landscape in spatially distributed models.

2.2. Temporal Resolution

Hydrologic simulation models are either *single event* or *continuous simulators.* Single-event models simulate the response, for example, to a specified precipitation event while continuous simulation models predict hydrologic responses a range of precipitation events. Continuous simulators keep track of hydrologic responses such as antecedent moisture conditions of a watershed and, furthermore, are suited to predict high and low surface runoff and the corresponding soil erosion and sediment transport in hourly, daily or seasonal time steps or steady-state or longer-term average conditions.

2.3. Conceptual Basis

Hydrologic simulation models also range from *empirical* to *physically-based* in structure. Empirical models relate hydrologic outputs to hydrologic inputs without simulating the hydrologic processes that are involved (Larson, 1973). The parameters in empirical models are developed from a synthesis of field studies, published or unpublished information, or earlier modeling outputs. These parameters are modified when necessary by comparing simulated to observed outputs with adjustments made until the best fit is achieved.

Physically-based models are the most conceptually correct models in which the mathematical relationships (algorithms) represent soil, vegetation, and topographic characteristics and precipitation and temperature inputs that are obtained from site measurements. Often embedded in physically-based models are empirical relationships that require a lumping of characteristics because there are limitations in mathematically representing all of the hydrologic processes of a watershed.

2.4. Selection of a Hydrologic Simulation Model

The hydrologic simulation model selected for application must be able to facilitate the scaling-up of hydrologic processes and prediction from small to large watersheds to larger river basins while addressing long-term scenarios of hydrologic responses to changing land-use activities and management practices. This requirement means that a model be more physically-based than empirical with a capacity to simulate hydrologic changes within a framework of cumulative watershed effects (Reid, 1993; MacDonald, 2000).

A hydrologic simulation model might have to be formulated for a specific site or hydrologic condition when the available models do not meet the application purposes. Among the criteria considered for formulating a hydrologic simulation model or evaluating a hydrologic simulation model that is available are:

- Accuracy of prediction - models with minimal bias and error variance are superior Simplicity – this criterion refers to the number of parameters that must be estimated and the ease with which the model can be explained to the user.
- Consistency of parameter estimates - this requirement is important in models that use input parameters estimated by optimization techniques. Models are unreliable when optimal values of the parameters are “sensitive” to the period of record in the simulation exercise or where the values vary widely among similar watershed conditions.
- Sensitivity of results to changes in parameter values - it is desirable that models not be sensitive to input variables that are difficult to measure and costly to obtain.

The formulation or evaluation of hydrologic simulation models has been, and continues to be, on an iterative process. This process has resulted in a large assemblage of hydrologic simulation models in which there is no single model that is suitable for all possible applications. However, a listing of the hydrologic simulation models that have been, and continue to be, applied in varying hydrologic situations is beyond the intent of this publication. The reader is referred to Feldman (1981), Haan *et al.* (1982), Singh (1995), or Singh and Frevert (2009) for more detailed descriptions of these simulation models.

3. Remote-Sensing Platforms

Many remote-sensing platforms are operational, others have completed their usefulness, and still others are currently in design or early production phases. There are many types of imaging that are applied in earth-science observations, modeling, and the management of land, water, and other natural resources including visual, ground- and aerial-based photography, satellite observations, radar, and sonar. While advances have been made in nearly all phases of these remote-sensing technologies, the emphasis has often been placed on the electromagnetic (EM) spectrum. The two types of EM sensing most commonly used in studying the features of watershed landscapes are *optical remote sensing and radar.*

3.1. Optical Remote Sensing

Optical remote sensing focuses on the short wavelengths of the EM spectrum from ultraviolet to the infrared spectra. Optimal remote sensing has advantages over more traditional land-surface studies that are often limited by point-based estimates of the parameters of interest and constrained by sample size. Optimal remote sensing provides a unique and useful perspective of the earth's surface that is suitable for large-scale investigations of surface patterns. Many mathematical relationships are available for case-specific applications in classifying vegetation, geomorphology, and soil analysis (Guertin *et al.,* 2000; National Research Council, 2008). One such algorithm is the normalized difference vegetation index (NDVI) that is a spectral ratio between the infrared and red spectra to predict biomass. However, there are constraints that limit the use of NDCI and, more generally, optimal remote sensing including operational limitations to daylight hours and the masking of surface signals from the sensors by clouds and smoke.

3.2. Radar

Radar (Radio Detection and Ranging) uses the microwave (long-wave) portion of the EM spectrum that is orders-of-magnitude longer than those sensed in the optical range. Most radar applications involve the emission of a microwave signal from an aircraft or satellite toward the object of interest with the aircraft or satellite recording the signal upon its return. Synthetic aperture radar (SAR) facilitates the mapping of surface characteristics through processing radar signals such that the azimuth resolution is improved in proportion to the system's aperture size (Dobson, 2000). Inteferometric SAR, where a target is sensed multiple times from different orientations, can be used to prepare detailed maps that detect changes in the surface of a watershed.

3.3. New Technologies

Airborne and satellite remote-sensing techniques and light detection and ranging (LiDAR) are two remote-sensing technologies that continue to emerge in development and application. Airborne and satellite remote-sensing technologies have reduced the time and costs of monitoring the storage of water in the atmosphere and changes in vegetation and soil characteristics on large watersheds, river basins, and geographic regions (National Research Council, 2008). Satellites such as Terra and Aqua that carry the Moderate Resolution Imaging

Spectroradiometer (MODIS) sensor view the surface of the earth every one or two days to acquire source data in 36 spectral bands. Daily estimates of ET losses at 1 kilometer resolution are available with this imagery. MODIS with scaling techniques to reconcile differences in resolution is also used to provide water-balance information at fine spatial and temporal scales (Singh *et al.,* 2004). Other satellites operating in the optical and microwave parts of the spectrum are useful in mapping areas of inundation and saturation on boreal landscapes (Sass and Creed, 2007) and the features of wetland ecosystems (Toyra *et al.,* 2001).

LiDAR is a rapidly developing optical remote-sensing technology that measures the properties of scattered light to facilitate the analyses of topographic features and land-use characteristics of a watershed and the climatic and precipitation regimes affecting the watershed landscape (Lefsky *et al.,* 2002). The primary difference between LiDAR and radar is that LiDAR uses shorter wavelengths (ultraviolet, visible, or near infrared) in the EM spectrum than radar. LiDAR is highly sensitive to cloud particles and, therefore, has applications in atmospheric investigations, meteorology, geomorphology, and seismology.

High-resolution digital maps that are generated by stationary and airborne LiDAR have led to advances in hydrology and watershed management. For example, scientists from the National Oceanic and Atmospheric Administration (NOAA) and National Aeronautics and Space Administration (NASA) in the United States have been able to study changes in the erosion of stream banks and shorelines with this technology. The topographic information obtained by LiDAR has also been used for establishing stream-gauging networks on watersheds in remote locations and supporting dense tree overstories (Poff *et al.,* 2008). LiDAR can provide details of the forest structures on watershed landscapes that are comparable to the information obtained from field inventories but on a much larger scale (Hummel *et al.,* 2011).

4. Geographic Information Systems

Geographic information systems (GISs) are capable of capturing, storing, analyzing, and retrieving geographically references data in a format that meets the informational needs of a hydrologist or watershed manager (Star and Estes, 1990; Guertin *et al.,* 2000). GIS data sets can represent objects including waterways, trees, roads, elevations, and land-use activities with digital data stored in either a *raster* or *vector* form. The data layer can be an array of rectangular or square cells each of which has an assigned value in a raster (cell-based) system; line work in a vector (line-based) system is represented by a set of connected points with a line segment between two points a vector (van Roessel, 1986). The choice of data layers is dependent on the needs of the user.

GISs have applications in hydrology and watershed management including up-dated inventory information such as the quantities of a natural resource that is available, where it is located, and whether it is increasing, decreasing, or stable in character (Benda *et al.,* 2007). Incorporating information from a GIS into a hydrologic simulation model provides an element that other hydrologic models often lack, that is, an ability to analyze combinations of slope, aspect, and hydrologic-response units in the simulations. More detailed input information can also be included in the models such as vegetation types, terrain roughness, and soil characteristics that can influence surface runoff, streamflow regimes, and erosion and sedimentation processes (Heywood *et al.,* 2006). These added data layers can result in more accurate models.

Advanced GIS technologies when combined with spatial modeling methods have enhanced the collection and analysis of enlarged spatial and temporal data sets to predict water flows, soil erosion, and sediment transport from small and large watersheds. For example, the NetMap system can be used to estimate hillslope failures, soil-erosion potentials, and sediment supplies (Benda *et al.,* 2007). GIS with models of terrain-analysis features can facilitate the planning of stream restoration following excessive soil erosion.

GIS systems continue to progress in allowing predictions of the effects of land-use activities and watershed management practices at increasingly finer resolutions and for larger watershed areas than were possible only a decade ago.

5. The Global Positioning System

The global positioning system (GPS) is a space-based global-navigational satellite system that provides location- and time-related information on weather almost everywhere on, or near, the earth where there is an unobstructed line of sight to four or more GPS satellites. While it is maintained by the United States government, GPS is freely accessible to anyone with a GPS receiver (Guertin *et al.,* 2000). Originally a military project, GPS technology is advancing land surveying by providing absolute locations to determine boundaries and prepare maps. The location coordinates obtained by a GPS can be linked to digital objects such as photographs and other documents to create map overlays for inclusion in a GIS when appropriate.

A GPS satellite can fix the locations of weather stations, remote precipitation gauges and other monitoring devices, flumes and weirs, cross-sections of stream channels, and research study plots. GPS-referenced multiple-resource data sets can also be incorporated into database management systems to facilitate interpretations of watershed characteristics for managing land and water resources (Habraken, 2000). These characteristics can be used as watershed descriptors such as its size and orientation, streamflow networks and physiographic characteristics, streamflow regimes, and soil erosion and sedimentation patterns.

GPS satellites are limited in their ability to fully characterize the spatially distributed characteristics of a watershed, however. Errors in GPS applications are affected mostly by geometric dilution of precision. Other problems include atmospheric effects, signal arrival-time errors, numerical errors, ephemeris errors, and multipath errors.

6. Decision-Support Systems

The complexity of the questions asked, the extensive information available, and the often decreasing availability of land, water, and other natural resources are why better decision-making procedures have become necessary). Therefore, planning and implementing management practices that sustain or often increase the availability of these natural resources should be based on multiple-use and ecosystem-based principles. Fortunately, a diversity of decision-support systems is available to help in making better decisions about watershed management (Lane and Nichols, 2000). *Linear programming* and *multiple-criteria* or *multiple-objective* decision-support systems are examples of these methods.

Linear programming is the basis of relatively simple decision-support systems. For example, a watershed manager might want to reduce the costs of a management practice that is represented by a linear-objective function and a set of linear constraints. However, in this example, the one and only objective function and all of the constraints must be linear for the range of values permissible. This basic requirement of linearly is inappropriate or unsuitable for many watershed management problems.

Decision-making problems confronted by hydrologists and watershed managers more commonly involve several objectives and constrains that are nonlinear. Reducing the costs of management while simultaneously optimizing the total benefits obtained from soil, water, and other natural resources might be necessary. Such a set of objective functions are likely to be subject to several linear and nonlinear constraints. More realistic problems such as this can be analyzed by multi-criteria decision-making (MCDM) or multi-objective decision making (MODM) techniques (Szidarovzky *et al.,*1986). That is, the preferred solutions to a management-related problem in which the discrete alternatives are evaluated against specified acceptance criteria can often be obtained with MCDM or MODM techniques (Yakowitz *et al.,*1993; El-Swaify *et al.,*1998).

Care needs to be taken in selecting the appropriate MCDM or MODM technique for use in solving a decision-making problem in watershed management to avoid a mismatch between the problem confronted and selection of the technique to solve the problem (Tecle, 1992; Tecle *et al.,* 1994). Otherwise, the result obtained from a poorly matched technique can be misleading with costly consequences in wasted time, money, and other decision-making resources. Incorporating fizzy logic and stochastic technologies can often help in selecting the most appropriate decision making technique (Tecle and Jibrin, 2012).

7. Internet Applications

The Internet is a network of networks linking computers to computers. The Internet itself does not contain information but it provides a user with access to information that is readily available on a worldwide basis. It is more correct, therefore, to state that the information was found by using the Internet. Internet communication used most frequently is electronic mail (email), which is an easy-to-use way of delivering content and receiving feedback. A collection of email addresses allows a user to deliver a set of messages of specified interest to many people with a similar interest.

The World Wide Web (the Web) is the largest and fastest growing activity on the Internet. While incorporating all of the Internet services available, the Web is also a system of servers that supports formatted documents with links to other text materials, graphics, audio, and video files. Users can find publications, data sets, images, and software related to hydrology and watershed management on many Web listings. Subject guides and search engines are available to help people to effectively collect and distribute this information.

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