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CHAPTER 17

Watershed Sediment Yield

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17.1 INTRODUCTION

17.1.1 General

Watershed sediment yield is the total amount of sediment generated within a watershed and delivered at its outlet during any given time. It starts with soil erosion, which is defined as the removal (detachment) of soil particles from the earth's surface. A portion or all of the eroded soil is then transported by flowing water as sediment. Sediment yield is defined as the amount of sediment that is delivered to a point remote from its origin. In a watershed, sediment yield includes erosion from land surface slopes, gullies, streams, and mass wasting, minus sediment that is deposited after it is eroded but before it reaches the point of interest.

Estimation of watershed sediment yield is critical in planning soil conservation and sustainable development of natural resources. Erosion is an important and pervasive watershed process that sculpts all aspects of watershed topography and affects all terrestrial and aquatic ecosystems. It reflects the interactive factors of climate, geology, biology, time, and topography and the influence that these exert on watersheds. Planners of human watershed activities must be cognizant of current erosion from all pristine and human-impacted watershed elements, as well as how the planned watershed activities themselves may influence erosion. Erosion can also affect those planned activities and can cause major damage to the environment. Sediment generated from erosion can pollute streams, rivers, and estuaries, fill reservoirs and navigation channels, and cover valuable floodplain lands and properties.

Agricultural, mining, forestry, and construction activities often involve clearing of vegetation and massive movement of soil, exposing it directly to the erosive actions of rain and flowing water. As a result, enormous amounts of soil can be lost from these sites, degrading the environmental quality and soil fertility of such highly eroded land surfaces. Sediment is also generated from streambeds, stream banks, and floodplains by the erosive actions of flowing water. As reported by Gianessi et al. (1986), the percentages of eroded soil in the United States attributable to various sources are as follows: cropland (37%), forests (16%), rangeland (11%), stream banks (11%), gullies (6%), pasture (4%), and other sources, including roads, construction sites, mines, and rural lands (15%).

In addition to its direct impact on waterways and aquatic ecosystems, sediment is a major contributor to non-point-source pollution. It can carry nutrients (particularly phosphates) to waterways, and it contributes to eutrophication of lakes and streams. This can severely affect aquatic habitat in streams, rivers, lakes, and wetlands. Adsorbed pesticides and toxic substances are also carried with sediment, and can adversely affect surface-water quality.

Proper land use and planning can greatly reduce the erosion potential during the periods of serious erosion hazard before the land is stabilized by vegetation growth or permanent structures. A good understanding of the complex processes of soil erosion, sediment transport, and sediment deposition (sedimentation or siltation) provides a sound basis for developing improved prediction and control methods. This chapter will discuss these processes and available methodologies for predicting the amount of sediment reaching a point collectively from different sources (sediment yield) and for evaluating the impacts of current or potential land-use changes and management practices. All of the erosion and sedimentation processes contributing to sediment yield take place within the boundary of a watershed. Therefore, watershed sediment yield from all watershed sources, managed and unmanaged, is the primary topic of interest.

This chapter deals only with sediment from rain and water erosion. In arid, semiarid, and some humid regions, wind causes considerable erosion of soil and damage to crops and infrastructure (fences, buildings, highways, etc.). The impact of wind erosion is generally not described or delimited by watershed boundaries, and although it does cause significant soil degradation, whether it has any impact on aquatic systems depends on the specific situation. Wind erosion is therefore not covered here, though much information is available elsewhere in the literature (Schwab et al. 1993).

The remainder of this section discusses soil erosion, sedimentation processes, and physical factors affecting those processes. The remaining sections describe available methodologies, ranging from simple empirical equations to more comprehensive watershed models, for estimating soil erosion generated from different sources (upland slopes, gullies, and streambeds and banks) and finally computing sediment yield.

17.1.2 Soil Erosion and Sedimentation Processes

From a plan (bird's-eye) view, erosion begins on the relatively planar hillslopes that slope down from the watershed divides, and from ridges or other divides between subwatersheds. The runoff from these hillslopes concentrates in the lower portions of the local topography where the warped planar surfaces converge, defining the beginning of a concentrated-flow channel system. Though exceptions may exist—as when a steep channel empties onto a floodplain and forms an alluvial fan and poorly defined channel—most channels are ultimately linked together in a dendritic network. The smaller upland channels may be poorly defined broad swales, and generally have flow only when there is runoff from a storm event. Further down the watershed, larger drainage areas contribute flow, so channels generally become better defined and are more likely to have flow from subsurface baseflow even when there is no runoff. The channel system itself usually makes up a very small portion of the entire watershed area, with the planar hillslopes feeding runoff and any associated sediment into the channel system along most of its length.

Soil erosion and sedimentation by water include detachment from the soil mass, transport of some or all of the eroded soil as sediment downslope, and during its transit depositing some of the sediment or picking up more eroded soil. In following a droplet of runoff down the hillslope, three distinct forms of erosion are seen in the upland areas. These are sheet erosion, rill erosion, and gully erosion. Sheet erosion, also known as interrill erosion, takes place uniformly between rills or gullies and results primarily from raindrop impact. The erosive potential of this impact depends on raindrop size, fall velocity, and total mass at impact, but can be devastating. In the absence of vegetation, mulch, or other cover to absorb the impact, raindrops can detach tremendous quantities of soil. For that detachment to result in erosion, the detached particles must then be transported downslope. In sheet erosion areas, this is accomplished by the resulting shallow surface flow, which does not have enough power to detach particles but does have enough power to transport them.

In moving downslope, additional runoff water collects as the contributing area grows. The runoff soon (usually within 1-3 m of slope length) reaches a depth at which it has sufficient energy to begin detaching soil particles. This in turn lowers the soil surface at that point, causing even more runoff to flow in that direction. This ultimately forms a rill, which is defined as a small concentrated flow channel in the generally planar hillslope. Rills may be very shallow or very deep, but generally form parallel channels running downslope on the planar surface. Their location is controlled somewhat randomly by small irregularities in the microtopography, so if they are destroyed by tillage they will reform in different places.

Rill erosion is much more noticeable than interrill erosion. These small channels carry runoff and sediment from interrill areas, the rain that falls directly on them, and any sediment produced from erosion within the rill. Rill erosion increases rapidly as the slope steepens or lengthens and as the runoff rate increases.

Gully erosion is massive removal of soil by large concentrations of runoff. These occur in the low portions of the macrotopography where the planar hillslopes converge, so they are best thought of as the uppermost portions of the watershed channel system. When the gullies are small the erosion in them occurs primarily through the erosive action of the concentrated flow acting on the bottom and to a lesser extent the sides of the channel. Such gullies are referred to as ephemeral gullies, and are usually small enough so that they can be crossed by vehicles and can be erased by normal tillage operations. If precautionary measures are not taken, gullies will grow, and soon the erosive action of the flow is augmented by headcutting and sidewall sloughing, at which point the channels are defined as classical gullies. These may yield tremendous volumes of sediment. Timeliness of implementation and maintenance of erosion-control practices is all-important to keep this from occurring.

These processes take place primarily in the upland areas and upper channels of a watershed. Once the flow has reached the watershed channel system, sediment may also be generated from streams or channels as a result of streambed and bank erosion, in which case the channel is said to be degrading. On the other hand, if more sediment is added from the upland areas than the channel flow can transport, significant deposition and storage of upland sediment may occur within the channel system, in which case the channel is said to be aggrading. In a stable channel, very little net erosion occurs because of equilibrium between the sediment transported out of the channel system and that added by the upland erosion processes. When instability is introduced within the channel by removing vegetation along the banks, increasing the channel slope, or changing other channel characteristics, those influences on the channel can result in the production of significant amounts of sediment from erosion of streambed and/or bank.

The quantity and size of sediment material transported by channel flow are functions of runoff (or flow) velocity and turbulence, both of which increase as the slope steepens and

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the flow increases. The larger the eroding material, the greater the flow velocity and turbulence must be to transport it. When velocity or turbulence decreases, some of the sediment may deposit. The largest and densest particles settle first, whereas the finer particles are carried farther downslope or downstream. The overall result depends on the balance between the flow's transport capacity and current sediment load. If the transport capacity is higher than the current sediment load, the potential exists for additional erosion. If the converse is true (sediment load > transport capacity), deposition will result. Though this is conceptually simple, both factors are constantly changing temporally and spatially as water and sediment are added to or removed from the flow and as the channel and flow characteristics change the flow velocity and degree of turbulence and therefore the transport capacity.

17.1.3 Factors Affecting Erosion by Water

The major factors affecting soil erosion are climate, soil, vegetation, topography, and time. Of these, vegetation—and to a lesser extent soil and topography—may be controlled through normal management. For our purposes, climatic factors are assumed to be beyond human control. The important climatic factors are precipitation, temperature, wind, humidity, and solar radiation. Temperature and wind are most evident through their effects on evaporation and transpiration, but wind also changes raindrop velocity and angle of impact. Humidity and solar radiation are recognized as being somewhat less directly involved, in that they are associated with temperature and rate of soil-water depletion, although humidity affects raindrops in that very dry conditions may prevent precipitation from ever reaching the ground.

Physical properties of the soil affect infiltration, detachment of soil particles, and transport of the sediment. In general, soil detachability increases as the size of soil particles and/or aggregates increases, and soil transportability increases with decrease in particle and/or aggregate size. For example, clay particles are more difficult to detach than sand, but clay is more easily transported. Other general soil properties that influence erosion include soil structure, texture, organic matter, water content, clay mineralogy, and density (or compactness), as well as chemical and biological characteristics of the soil. No single soil characteristic or index has been identified as a satisfactory means of predicting erodibility, so it is usually measured directly through field studies. However, it can generally be said that human activities that loosen and pulverize soil often promote accelerated erosion.

Vegetation has the major impact on resisting or reducing soil erosion. Vegetation intercepts rainfall and absorbs the raindrop energy, thus reducing soil detachment. It retards erosion by decreasing surface-water velocity and by physically restraining sediment movement. Vegetation improves soil aggregation and porosity through the impact of its roots and plant residues. These increase biological activity in the soil, and through transpiration decrease soil water, resulting in increased storage capacity and less runoff. Vegetation effects vary with season, crop, degree of maturity, and soil and climate interactions with the vegetation and with the nature of the vegetative material, i.e., roots, plant tops, and plant residues. Residues from vegetation protect the surface from raindrop impact and improve soil structure. Residue and tillage management practices used in growing the vegetation can have a dramatic effect on soil erosion.

Soil erosion is also controlled by topographic features, such as slope steepness, length, and shape, and the size and shape of the watershed. On steep slopes, runoff water is more erosive and can more easily transport detached soil downslope. On longer slopes, increased accumulation of overland flow tends to increase rill erosion and the potential for gully formation. Concave slopes, with lower slopes at the foot of the hill, are less erodible than are convex slopes.

17.2 UPLAND SOIL EROSION

Upland soil erosion consists mostly of sheet or interrill and rill erosion, the basic forms of erosion. Predictions of upland soil erosion and sediment yield are needed to guide the making of rational decisions in conservation planning. The prediction equations enable the planner to predict the average rate of soil erosion for alternative combinations of cropping systems, management techniques, and erosion-control practices on any particular site.

17.2.1 Soil Loss Tolerance

The term "soil loss tolerance" (T) denotes the maximum rate of soil erosion that can occur and still permit crop productivity to be sustained economically. A deep, medium-textured, moderately permeable soil that has subsoil characteristics favorable for plant growth has a greater tolerable soil loss rate than do soils with shallow root zones or high percentages of shale at the surface. For the soils of the United States, T values of 1 to 5 tn/acre/year were derived by soil scientists and conservationists, agronomists, engineers, geologists, and federal and state researchers at regional workshops around the country. These recommended T values may be obtained from the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS).

As part of the conservation planning process, if the predicted soil erosion rate exceeds the T value, various combinations of management practices, as discussed below, can be tested through application of a soil loss prediction equation until the predicted soil loss erosion rate is at or below the T value.

17.2.2 Soil Loss Equation

As discussed above, the rate of upland soil erosion depends on rainfall erosivity, soil erodibility, the length, steepness, and shape of the slope, cultural practices used, stage of vegetation growth, and supporting conservation practices applied to the area. Factors representing these erosion-influencing characteristics have been combined in the Universal Soil Loss Equation (USLE), developed originally by Wischmeier and Smith (1965; 1978). Thousands of plot-years of data from runoff plots and small watersheds were used to develop the relationships in the USLE. This equation predicts soil loss from sheet (or interrill) erosion and rill erosion from the roughly planar hillslope areas. It enables land management planners to estimate average annual soil erosion rates from upland slopes for a wide range of rainfall, soil, slope, cover, and management conditions. It also enables planners to select from alternative cropping as cover and management combinations that would limit erosion rates to acceptable (T-value) levels.

A revised version of the USLE, called the Revised Universal Soil Loss Equation (RUSLE), was developed and documented by Renard et al. (1997) for computer applications, allowing more detailed consideration of farming practices and topography for erosion prediction. Both USLE and RUSLE use the following equation to compute average annual soil erosion expected on upland (field) slopes:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \tag{17-1}$$

where

- A = spatial and temporal average soil loss (erosion) per unit area, expressed in the units selected for K and for the period selected for R. In practice, these are usually selected so that A is annual soil erosion rate expressed in tn/acre/year or t/ha/year.
- R = rainfall-runoff erosivity factor—the rainfall erosion index plus a factor for any significant runoff from snowmelt.
- K = soil erodibility factor—the soil-loss rate per erosion index unit for a specific soil as measured on a standard plot, which is defined as a 72.6-ft (22.1-m) length of uniform 9% slope in continuous clean-tilled fallow.
- L = slope length factor—the ratio of soil loss from the field slope length to soil loss from a 72.6-ft length under identical conditions.
- S = slope steepness factor—the ratio of soil loss from the field slope gradient to soil loss from a 9% slope under otherwise identical conditions.
- C = cover-management factor—the ratio of soil loss from an area with specified cover and management to soil loss from an identical area in tilled continuous fallow.
- P = support practice factor—the ratio of soil loss with a support practice such as contouring, stripcropping, or terracing to soil loss with straight-row farming up and down the slope.

These factors and their representative values for different geographic locations in the United States, and for different soils, topography, covers, and practices, are given and extensively described for the USLE by Wischmeier and Smith (1965; 1978), and more recently for RUSLE by Renard et al. (1997). Brief descriptions and recently updated values from Renard et al. (1997) are given here. Since the release of Renard et al. (1997), additional work has been done on RUSLE. A version released in 1998 (RUSLE1.06) includes features that allow the RUSLE hillslope to be carried all the way down to a concentrated flow channel (Toy et al. 1999). A new version, RUSLE2, is currently under testing and implementation by USDA-NRCS, but is based primarily on the science found in RUSLE1.06, with several enhancements.

Other significant differences exist between the USLE and the most recent version of this technology as found in RUSLE2. Perhaps the greatest of these is that in the USLE the factors could be considered relatively independent. This meant that simple comparison of the C factors could usually be used to compare management systems. This is no longer the case in the later version of RUSLE1 or in RUSLE2, because these recognize that many of the factors are interrelated. In RUSLE2, therefore, comparisons of management alternatives must be made on the basis of overall erosion estimates rather than on the basis of individual factors.

17.2.3 Rainfall-Runoff Erosivity Factor (*R*)

The rainfall-runoff erosivity factor R quantifies the effects of raindrop impact and reflects the amount and rate of runoff likely to be associated with rain. Field data indicate that when factors other than rainfall are held constant, soil losses from cultivated fields are directly proportional to the total storm energy (E) times the maximum 30-min intensity (I_{30}). The R factor used to estimate average annual soil loss A (Eq. (17-1)) must include the cumulative effects of the many moderate-sized storms as well as the effects of the occasional severe ones. The average annual total of the storm EI_{30} values in a particular locality is the R for that locality. Local values of R in the United States are calculated from rainfall data around the country and are plotted in isoerodent maps (Renard et al. 1997) as shown in Figs. 17-1 to 17-5 for the eastern United States, western United States, California, Oregon and Washington, and Hawaii, respectively. Isoerodents are lines of equal R values. R values for locations between the lines can be obtained by linear interpolation.

Although the R factor is assumed to be independent of slope, splash erosion is less on flatter slopes, where raindrops tend to be more buffered by water ponded on the soil surface. A correction factor (Renard et al. 1997) as shown in Fig. 17-6 may be used to adjust R values for various flatter slopes and 10-year-frequency EI_{30} values.

In the dry-farmed cropland areas of the northwestern U.S. wheat and range region (Washington, Oregon, and Idaho),

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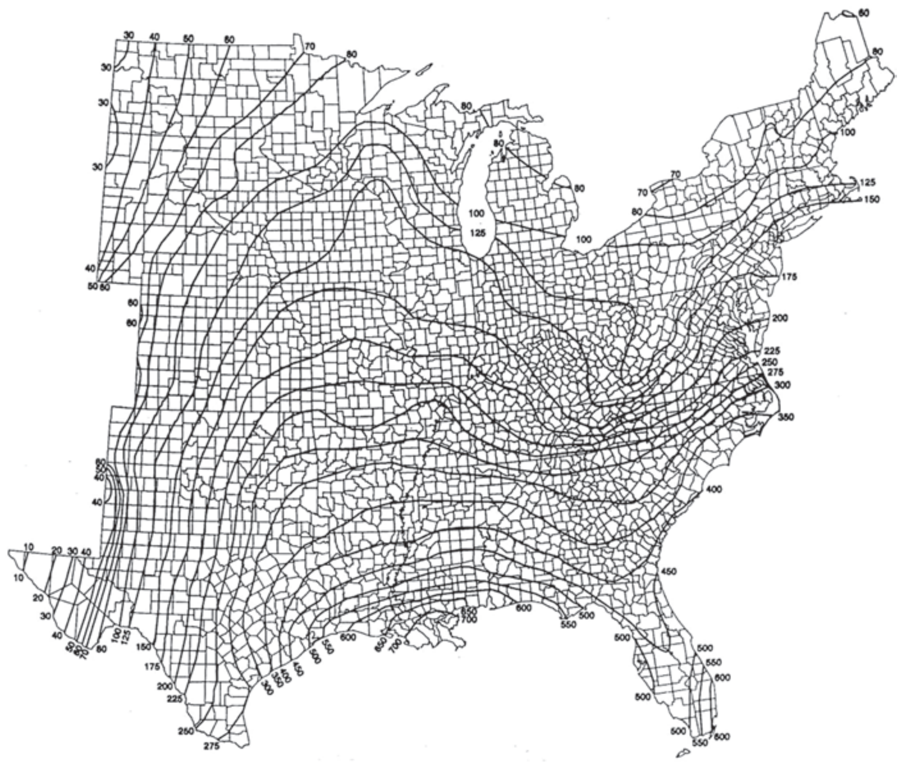

Fig. 17-1. Isoerodent map of eastern United States. Units are hundreds ft tnf in (ac h year)$^{-1}$. After Renard et al. (1997).

melting snow, rain on snow, and/or rain on thawing soil accelerate soil erosion resulting from higher R values. Renard et al. (1997) present a procedure to compute "R Equivalent (R_{eq}) for Cropland in the Northwestern Wheat and Range Region" and the R_{eq} isoerodent maps for estimating soil loss under these conditions.

17.2.4 Soil Erodibility Factor (K)

The soil erodibility factor (K) is the rate of soil loss per rainfall erosion index unit for a specific soil as measured on a unit plot, which is defined as being 72.6 ft (22.1 m) long, with a minimum width of 6 ft (1.83 m), 9% slope, and in a continuously clean-tilled fallow condition with tillage performed up and down slope (Wischmeier and Smith 1978). These factors are best obtained from direct measurements on natural-runoff plots. Guidelines for preparation and maintenance of natural-runoff plots in the United States were issued in 1961 by D. D. Smith (Romkens 1985). Renard et al. (1997) lists the soils and the locations in the United States on which natural-runoff plots for K-factor determinations were established, along with the resulting K-factor values. Rainfall simulation studies may also be used to determine K factors, but these short-term results are generally less accurate.

Soil erodibility is related to the integrated effect of rainfall, runoff, and infiltration on soil loss. The K factor accounts for the influence of soil properties on soil loss during storm events on upland areas. It is the average long-term soil and soil-profile response to the erosive powers of rainstorms and is a lumped parameter that represents an integrated average annual value of the total soil and soil profile reaction to a large number of erosion and hydrologic processes. These processes consist of soil detachment and transport by raindrop impact and surface flow, localized deposition due to topography and tillage-induced roughness, and rainwater infiltration into the soil profile. There is some interdependency of the K factor with the other USLE or RUSLE factors, specifically the topographic (LS), rainfall erosivity (R), and cover-management (C) factors.

The soil erodibility K can also be estimated by a variety of relationships. The most widely used relationship between the K factor and soil properties is the soil erodibility nomograph (Wischmeier et al. 1971; Wischmeier and Smith 1978; Renard et al. 1997). The nomograph comprises five soil and soil-profile parameters: percent modified silt (0.002–0.1 mm), percent modified sand (0.1–2.0 mm), percent organic matter (OM), and classes for structure (s) and permeability (p). The structure and permeability classes and groups of classes were taken from the *Soil Survey Manual* (USDA 1951). Structure (s) values are 1 for very fine granular, 2 for fine granular, 3 for medium or coarse granular, and 4 for blocky, platy, or massive structure. Permeability (p) values

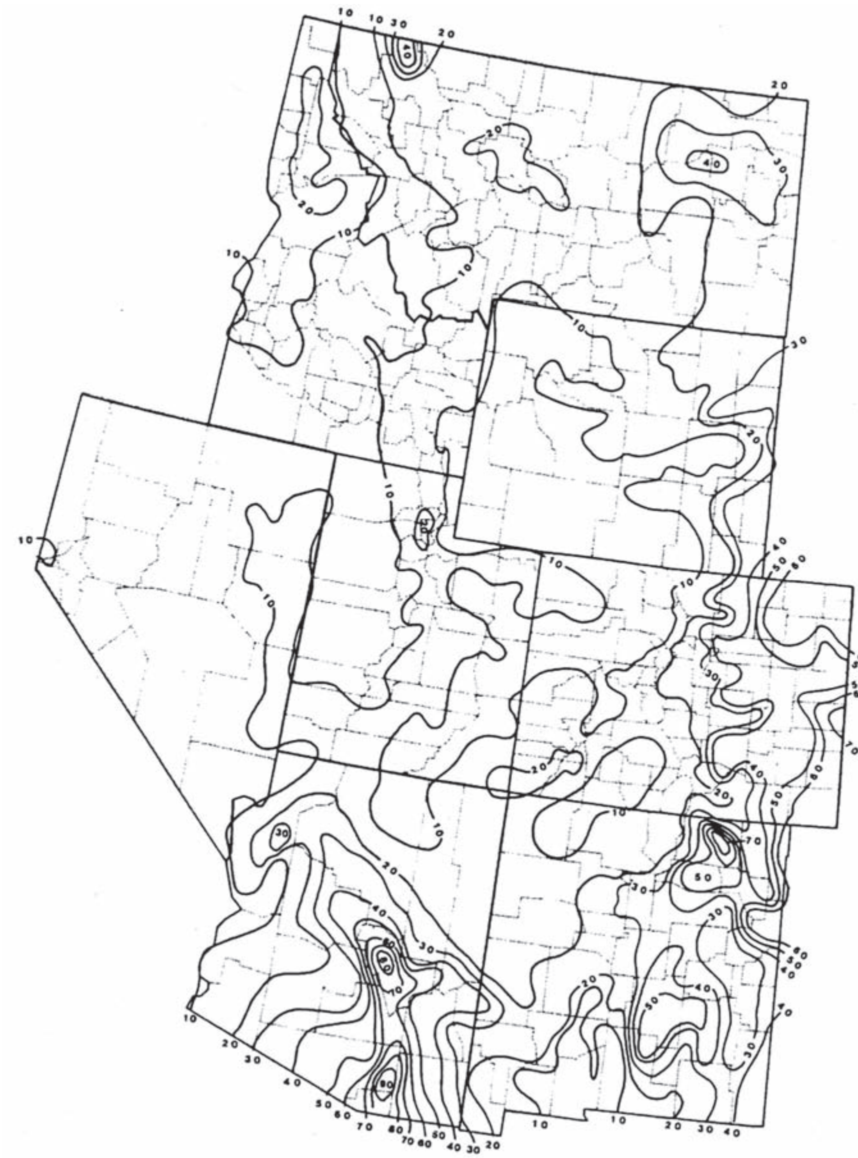

Fig. 17-2. Isoerodent map of western United States. Units are hundreds ft tnf in (ac h year)$^{-1}$. After Renard et al. (1997).

are 1 for rapid, 2 for moderate to rapid, 3 for moderate, 4 for slow to moderate, 5 for slow, and 6 for very slow. A useful algebraic approximation (Wischmeier and Smith 1978) of the nomograph for those cases where the silt fraction does not exceed 70% is

$$K = [2.1 \times 10^{-4}(12 - \mathrm{OM})\, M^{1.14} + 3.25(s - 2) + 2.5(p - 3)]\,/\,100 \tag{17-2}$$

where M is the product of the primary particle size fractions (% modified silt or the 0.002–0.1 mm size fraction) $\times$ (% silt + % sand) and K is expressed as tn/acre per erosion index unit. For example, a soil having 65% modified silt, 5% modified sand, 2.8% OM, fine granular structure ($s = 2$), and slow to moderate permeability ($p = 4$) will have a computed K value of 0.31.

The nomograph relationship was derived from rainfall-simulation data from 55 U.S. Midwest surface soils, mostly (81%) medium-textured surface soils. It is well suited for the less aggregated and medium-textured surface soils of the Midwest. Renard et al. (1997) present more relationships based on other soil types and soils from other locations, including Hawaiian volcanic soils (El-Swaify and Dangler 1976), soils from the upper Midwest (Young and Mutchler 1977), and Midwest clay subsoils (Romkens et al. 1977).

The presence of rock fragments in the soil may significantly affect soil detachment by rainfall. When present in a coarse-textured-soil profile (sands and loamy sands), the

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Fig. 17-3. Isoerodent map of California. Units are hundreds ft tnf in (ac h year)$^{-1}$. After Renard et al. (1997).

fragments can appreciably reduce infiltration, whereas in a fine-textured soil the fragments may actually increase infiltration. The effect of rock fragments on the soil surface is included in the *C* factor. However, the effect of rock fragments within the soil profile is included with the *K* factor insofar as it affects infiltration and runoff. These effects are discussed and quantified in Renard et al. (1997).

Seasonal variation of *K* values is also discussed and quantified in Renard et al. (1997). Soil freezing and thawing are major causes of these variations, because such processes change the effective soil texture and soil-water content, thereby increasing the *K* factor. The greater the number of freeze-thaw cycles, the longer the erosion resistance of a soil is at a minimum, resulting in higher erosion and *K* factor. In locations where frozen soil is not a problem, the *K* factor gradually decreases over the course of the growing season until it reaches a minimum near the end of growing season. Then it gradually increases until it reaches the maximum. For many locations this pattern follows rainfall patterns.

17.2.5 Slope Length and Steepness Factors *(LS)*

The slope length factor (L) and the steepness factor (S) account for the effects of topography on upland soil erosion. Erosion increases as slope length and/or steepness increases. Slope length for the USLE and early RUSLE versions was defined as the horizontal distance from the origin of overland flow to the point where either the slope gradient (steepness) decreases enough so that deposition begins or runoff becomes concentrated in a defined channel (Wischmeier and Smith 1978). In later versions, including RUSLE1.06 and all versions of RUSLE2, process-based deposition routines have been added, so the slope length extends down to a concentrated flow channel, which will normally be part of the watershed channel system. Surface runoff usually enters such a concentrated flow channel in less than 400 ft (122 m), which is a practical slope-length limit in many situations, although longer slope lengths of up to 1,000 ft (305 m) are occasionally found, most often when the surface has been carefully graded into ridges and furrows that maintain flow for long distances.

The factors L and S are usually evaluated together as the topographic factor LS, which represents the ratio of soil loss on a given slope length and steepness to soil loss from a slope that has a length of 72.6 ft (22.1 m) and steepness of 9%, where all other conditions are the same. The value of LS is 1.0 at the 72.6-ft slope length and 9% steepness. Values of LS for horizontal slope lengths from less than 3 ft (0.9 m) up to 1,000 ft (305 m), with steepness values ranging from 0.2% to 60%, and low, moderate, and high ratios of rill to interrill erosion are given in tabular form in Renard et al. (1997). These tables also present LS values for thawing soils where most of the erosion is caused by surface runoff. All of those values can also be computed using separate relations for L and S as given from Renard et al. (1997):

$$L = (\lambda/72.6)^m \tag{17-3}$$

where

λ = horizontal slope length (ft) and
m = a variable slope-length exponent (Wischmeier and Smith 1978).

The slope-length exponent m is related to the ratio of rill erosion (caused by flow) to interrill erosion (principally caused by raindrop impact), and is expressed (Foster et al. 1977) as

$$m = \beta/(1+\beta) \tag{17-4}$$

where

β = ratio of rill to interrill erosion.

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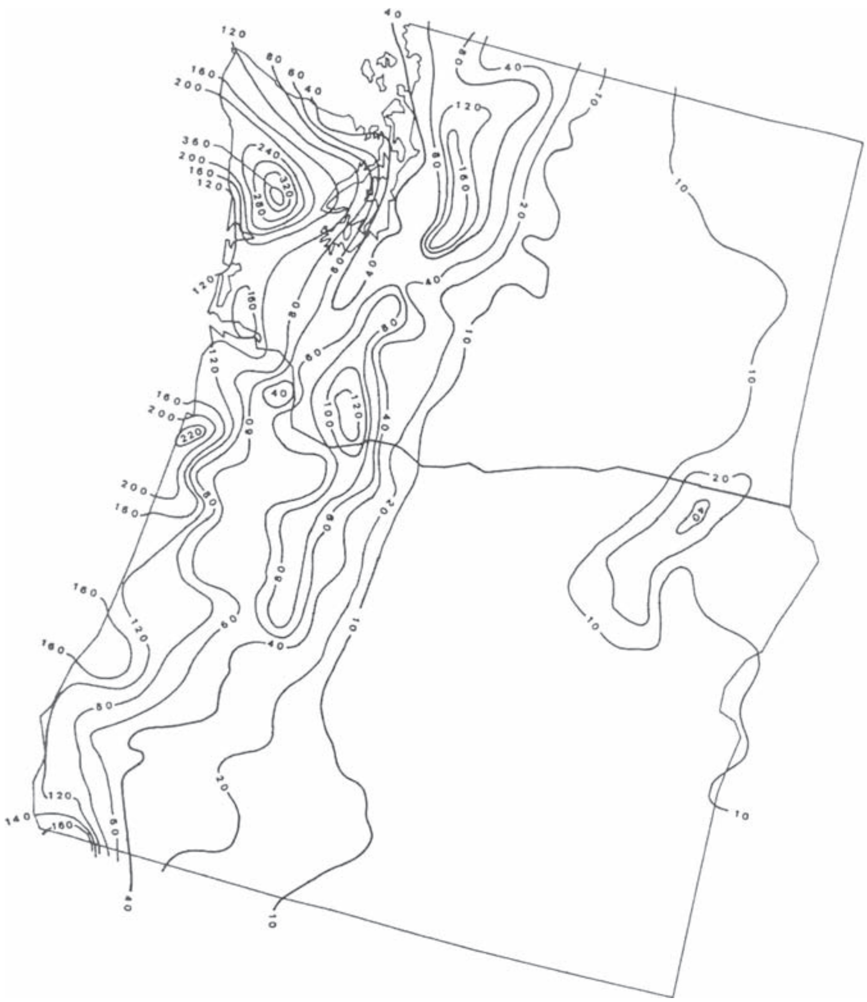

Fig. 17-4. Isoerodent map of Oregon and Washington. Units are hundreds ft tnf in (ac h year)$^{-1}$. After Renard et al. (1997).

For conditions where the soil is moderately susceptible to both rill and interrill erosion, β is expressed (McCool et al. 1989) as

$$\beta = (\sin\theta \;/\; 0.0896) \,/\, [3.0(\sin\theta\,)^{0.8} + \;0.56] \qquad (17\text{-}5)$$

where

θ = slope angle.

Equation (17-5) gives β values for conditions that are typical of agricultural fields in seedbed condition, where the soil is moderately susceptible to both rill and interrill erosion.

When runoff, soil, cover, and management conditions indicate that the soil is highly susceptible to rill erosion, a condition most likely to occur on steep, freshly prepared construction slopes, the β value is doubled from that calculated by Eq. (17-5). Conversely, when the conditions favor less rill erosion than interrill erosion, a condition common to rangelands, β values are taken as half of those calculated from Eq. (17-5).

For the erosion of thawing, cultivated soil by surface flow, a condition common in the Northwest U.S. Wheat and Range Region, a constant value of 0.5 is used for the slope length exponent *m* (McCool et al. 1989; 1993). When runoff on thawing soil is accompanied by rainfall sufficient to cause significant interrill erosion, the β value is taken as half of that calculated from Eq. (17-5). To ease these calculations, RUSLE2 automatically calculates the β value based on the presumed soil, management, and climatic conditions.

Soil loss increases more rapidly with slope steepness than it does with slope length. The slope steepness factor *S* is computed using the following relations (McCool et al. 1987):

$$S = 10.8 \sin\theta + 0.03 \quad s < 9\% \qquad (17\text{-}6)$$

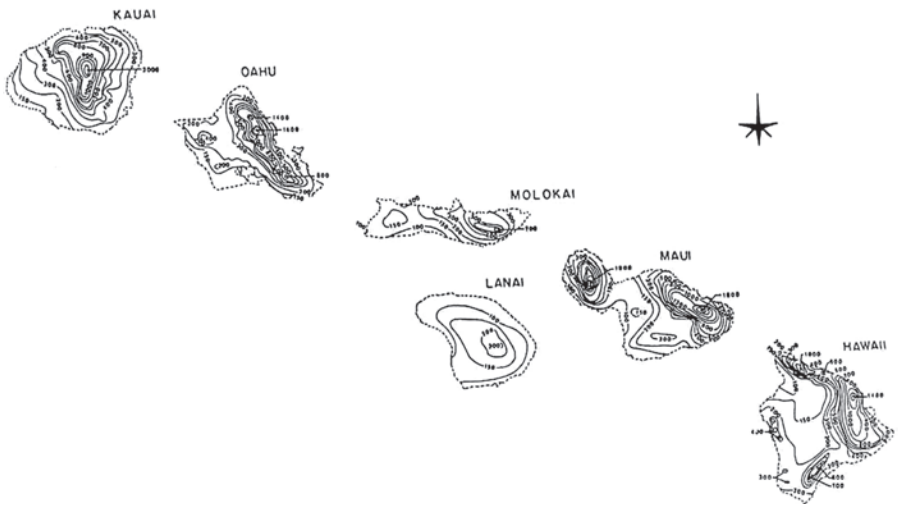

Fig. 17-5. Isoerodent map of Hawaii. Units are hundreds ft tnf in (ac h year)[-1]. After Renard et al. (1997).

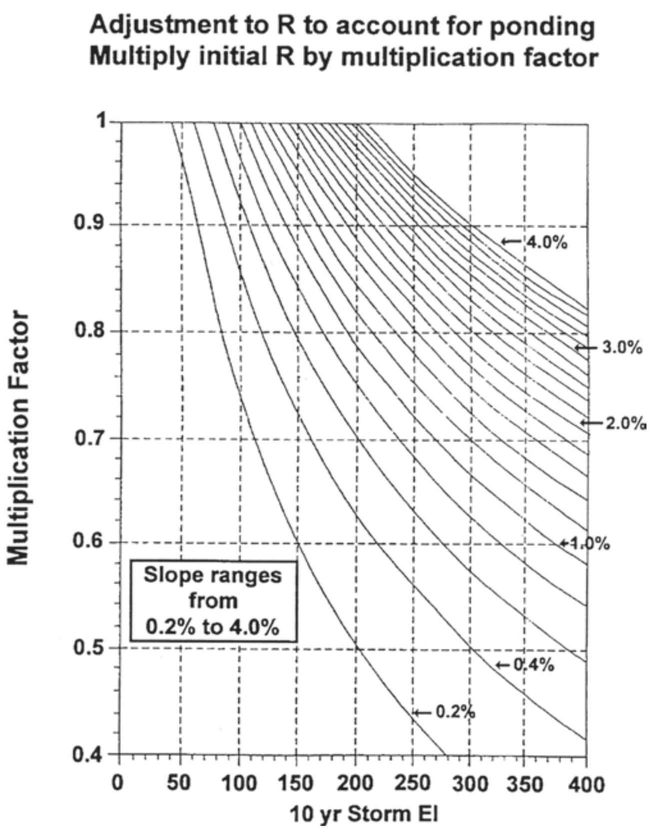

Fig. 17-6. Correction for R factor for flat slopes and large R values to reflect amount of rainfall on ponded water. After Renard et al. (1997).

$$S = 16.8 \sin\theta + 0.5 \qquad s \geq 9\% \quad \lambda \geq 15 \text{ ft} \qquad (17\text{-}7)$$

$$S = 3.0 (\sin\theta)^{0.8} + 0.56 \qquad s \geq 9\% \quad \lambda < 15 \text{ ft} \qquad (17\text{-}8)$$

where s = ground slope in percent. Equation (17-8) assumes that rill erosion is insignificant on slopes shorter than 15 ft (4.6 m), and therefore this equation should not be used on such slopes where rill erosion is expected to occur. Rill erosion usually begins with a slope length of 15 ft; however, it may take longer slope lengths on soils that are consolidated and resistant to detachment by flow.

For recently tilled soil under thawing, in a weakened state and subjected primarily to surface flow, Eq. (17-7) is rewritten as (McCool et al. 1993)

$$S = (\sin\theta / 0.0896)^{0.6} \qquad s \geq 9\% \quad \lambda \geq 15 \text{ ft} \qquad (17\text{-}9)$$

These relations are applicable to uniform slopes where steepness is the same over the entire length. Procedures of accounting for nonuniform or irregular concave, convex, or complex slopes in the erosion computations are outlined in Renard et al. (1997). They can also account for changing soil type along the slope. Within limits, they can be further extended to account for changes in the C and P values. These adjustments are all done automatically in RUSLE2. Renard et al. (1997) provides extensive guides for choosing slope lengths.

17.2.6 Cover-Management Factor (C)

The C factor is designed to reflect the effect of cropping and management practices on erosion rates, and is the factor used most often to compare the relative impacts of management options on conservation plans. The C factor is essentially a soil loss ratio (SLR), which is defined as the ratio of soil losses under actual conditions to losses

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experienced under the clean-tilled continuous fallow reference conditions. The C factor depends on previous cropping and management, vegetative canopy, surface cover and roughness, and, in some cases, soil moisture, each of which is assigned a subfactor value. These subfactor values are multiplied together to yield an SLR (Laflen et al. 1985), expressed as

$$\mathrm{SLR} = \mathrm{PLU} \cdot \mathrm{CC} \cdot \mathrm{SC} \cdot \mathrm{SR} \cdot \mathrm{SM} \tag{17-10}$$

where

SLR = soil-loss ratio for the given conditions;
PLU = prior-land-use subfactor;
CC = canopy-cover subfactor;
SC = surface-cover subfactor;
SR = surface-roughness subfactor; and
SM = soil-moisture subfactor.

PLU incorporates the influence of subsurface residue effects from previous crops and the effects of previous tillage practices on soil consolidation. PLU values range from 0 to 1. Renard et al. (1997) provide an extensive discussion and procedure to estimate PLU.

The CC subfactor value ranges from 0 to 1 and incorporates the effectiveness of vegetative canopy in reducing the energy of rainfall striking the soil surface. It is expressed as

$$\mathrm{CC} = 1 - F_c \cdot \exp(-\,0.1 \cdot H) \tag{17-11}$$

where

F_c = fraction of land surface covered by canopy, and
H = canopy height (ft), which is the distance that raindrops fall after striking the canopy.

The SC subfactor incorporates the effects of surface cover, including crop residues, rocks, cryptogams, and other nonerodible materials that are in direct contact with soil surface, on soil erosion. These affect erosion by reducing the transport capacity of runoff water, by causing deposition in ponded areas, and by decreasing the surface area susceptible to raindrop impact. It is perhaps the single most important factor in determining the SLR. The SC subfactor is expressed as

$$\mathrm{SC} = \exp\left[-b \cdot S_p \cdot (0.24/R_u)^{0.08}\right] \tag{17-12}$$

where

b = an empirical coefficient;
S_p = percentage of land area covered by surface cover; and
R_u = surface roughness (in.).

The b value in Eq. (17-12) ranges from 0.030 to 0.070 for row crops, and from 0.024 to 0.032 for small grains. In the Northwest U.S. Wheat and Range Region, b values may be greater than 0.050. For rangeland conditions with the impact of subsurface biomass removed, a b value of 0.039 is recommended. The b value can be also chosen based on the dominant erosion process. When rill erosion is the primary mechanism of soil loss (such as for irrigation or snowmelt or for highly disturbed soils), b values should be about 0.050. Fields dominated by interrill erosion have a b value of around 0.025. For typical cropland erosion conditions, a b value of 0.035 is suggested. Calculation of the b value is done automatically in RUSLE2, based again on the estimated soil and management conditions.

In RUSLE2 and recent versions of RUSLE1, the SC and CC subfactors are linked, so that canopy cover with a very low canopy height essentially becomes surface cover. In other words, a 50% canopy cover with a height of 0 will give combined SC and CC subfactors providing the same erosion reduction as 50% surface cover, not the CC = 0 value indicated by Eq. (17-11).

An R_u value of 0.24 in. (0.61 cm) is typical of a field in seedbed condition. An R_u value of 4 in. indicates more roughness than from most primary tillage operations. R_u values for various tillage operations in croplands, ranging from 0.30 to 1.9 in., and various conditions in rangelands, ranging from 0.25 to 1.30 in., are given in Renard et al. (1997).

Surface roughness directly affects soil erosion by reducing flow velocity and by decreasing transport capacity and runoff detachment. It also indirectly affects soil erosion by causing ponded water and reducing raindrop impact, as incorporated into Eq. (17-12). The direct impact of surface roughness on erosion is incorporated into the SR subfactor. Its baseline condition (SR = 1) is established in a unit plot of clean cultivated conditions smoothed by extended exposure to rainfall of moderate intensity. These conditions yield a random roughness of 0.24 in. The SR subfactor for random roughness greater than 0.24 in. is computed using the expression

$$\mathrm{SR} = \exp\left[-\,0.66\,(R_u - 0.24)\right] \tag{17-13}$$

The SM subfactor incorporates the influence of antecedent soil moisture on infiltration and runoff and hence on soil erosion. In general, antecedent moisture effects are an inherent component of continuously tilled fallow plots, which are reflected in variation in soil erodibility throughout the year, and are already taken into account in the derivation of soil erodibility factors. Therefore, the SM subfactor is kept at 1 without any adjustment for changes in soil moisture. However, it is recommended that SM subfactor in the Northwest U.S. Wheat and Range Region be adjusted between 1.0 on April 1, indicating response equivalent to that of a continuous fallow with soil moisture near field capacity,

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and 0.0 from September 1 to October 1, indicating no runoff and erosion with soil moisture in soil profile near wilting point to a 6-ft (1.8-m) depth. SM values between these dates are linearly interpolated: 0.0 to 1.0 for October 1 to April 1, and 1.0 to 0.0 for April 1 to September 1.

For areas such as pasture or rangeland that have reached a relative equilibrium, the subfactors used in computing SLR values may change very slowly with time. In these cases, the PLU, CC, SC, and SR subfactor values are assumed to be annual averages, and are simply multiplied together to yield C-factor value (SM = 1.0), as

$$C = \mathrm{PLU} \cdot \mathrm{CC} \cdot \mathrm{SC} \cdot \mathrm{SR} \tag{17-14}$$

In almost all cropland scenarios and in many cases where rangeland or pasture are being managed, the crop and soil characteristics change over time. This demands that the SLR values be calculated frequently enough over the course of a year or a crop rotation to provide an adequate measure of how they change. These values depend on tillage type, elapsed time since a tillage operation, canopy development, and date of harvest. An individual SLR value is calculated for each time period over which the subfactors can be assumed to remain constant. Each of the SLR values is then weighted by the fraction of rainfall and runoff erosivity (EI) associated with the corresponding time period, and these weighted values are combined into an overall C-factor value (Wischmeier and Smith 1978), expressed as:

$$C = (\mathrm{SLR}_1 EI_1 + \mathrm{SLR}_2 EI_2 + \ldots \mathrm{SLR}_n EI_n)/EI_t \tag{17-15}$$

where C = average annual or crop C factor value, SLR_i = soil-loss ratio for time period i, EI_i = percentage of the annual or crop EI occurring during that time period, n = number of periods used in the summation, and EI_t = sum of the EI percentages for the entire period. For RUSLE1 these calculations were performed for half-month periods; in RUSLE2 they are performed on a daily time-step.

17.2.7 Support Practice Factor (P)

The P factor represents support practice effects on soil erosion. These practices generally modify the amount, rate, flow pattern, or direction of surface runoff. For cultivated land, support practices include contouring (tillage and planting on or near the contour), stripcropping, terracing, and subsurface drainage. On dryland or rangeland areas, soil-disturbing practices oriented on or near the contour that result in storage of moisture and reduction of runoff are also used as support practices. For construction and mine reclamation areas, this includes such practices as contour plowing and diversions. Note, however, that improved tillage practices such as no-till and other conservation tillage systems, sod-based crop rotation, fertility treatments, and crop-residue management are not included in support practices, but rather are included in the C factor. The P-factor value is a product of P subfactors for individual support practices, some of which are used in combination. For example, contouring generally accompanies stripcropping and terraces.

The P-factor value for farming upslope and downslope is 1.0. Other P-factor values given in Renard et al. (1997) were obtained from experimental data, supplemented by analytical experiments involving scientific observation of known cause-and-effect relationships in physically based models such as CREAMS (Knisel 1980). Such an extensive discussion and procedure development are beyond the scope of this chapter, but the P-factor values for three major support practices in cultivated lands, as given earlier by Wischmeier and Smith (1978), are shown in Table 17-1. Within a practice type, the P factor is most effective for the 3 to 8% slope range, and effectiveness decreases as the slope increases. As the slope decreases below 2%, the P-factor value increases, due to the reduced effectiveness of the practice when compared to up-and-down-hill cultivation. The P factor for terracing in Table 17-1 is for prediction of total off-the-field soil loss. If within-terrace interval soil loss is desired, the terrace interval distance should be used for the slope length factor (L) and the contouring P value for the practice factor.

17.3 GULLY EROSION

Gully erosion is defined as the erosion process whereby runoff water accumulates and often recurs in narrow channels and, over short periods, removes soil from these narrow areas to considerable depths (Poesen et al. 2002). Gullies are often defined for agricultural land in terms of channels that occur in the low areas of the macrotopography and that are too deep to ameliorate easily with ordinary farm tillage equipment, typically ranging from 0.5 m to as much as 25 to 30 m (Soil Science Society of America 2001). In the 1980s, the term "ephemeral gully erosion" was introduced to include

Table 17-1 Support Practice Factor *P* for Cultivated Lands[a]

Land slope, %	Contouring	Contour, strip cropping, and irrigated furrows	Terracing[b]
1–2	0.60	0.30	0.12
3–8	0.50	0.25	0.10
9–12	0.60	0.30	0.12
13–16	0.70	0.35	0.14
17–20	0.80	0.40	0.16
21–25	0.90	0.45	0.18

[a]From Wischmeier and Smith (1978).

[b]For prediction of contribution to off-field sediment yield.

concentrated flow erosion larger than rill erosion but smaller than classical gully erosion. According to the Soil Science Society of America (2001), ephemeral gullies are small channels eroded by concentrated overland flow that can easily be filled by normal tillage, only to be reformed in the same location by additional runoff events. In the United States, the sediment contribution from ephemeral gullies has been estimated to average about 80% of that contributed by sheet and rill erosion (Bennett et al. 2000b). A study in Kenya (Wijdenes and Bryan 1994) reported that 50% of the eroded sediment in their study watershed was produced from gullies, with the other half resulting from sheet and rill erosion.

Numerous field and modeling studies on gully erosion are reported in the literature (Woodburn 1949; Beer and Johnson 1963; Thompson 1964; Piest et al. 1975; Bocco 1991; Wijdenes and Bryan 1994; Bennett et al. 2000a; 2000b; Nachtergaele et al. 2002; Poesen et al. 2002; 2003; Torri and Borselli 2003). Sources and references for many other studies may be found in these publications. However, there is still a lack of understanding of the processes that form gullies, including headcut migration. Understanding and quantification of gullies lag behind those for other forms of water erosion. One reason is scale. Gully erosion tends to operate on a larger scale than the runoff plot scale, where the vast majority of water erosion research has been conducted. Gully development also operates over longer time periods than is common for water erosion research studies. Finally, because of these scale and temporal issues it is very difficult to replicate scientific field studies of gullies, because no two gullies are found in exactly the same place in the landscape and because gullies are dependent on everything that happen upslope over long periods. In spite of these difficulties, there are some commonly used relationships describing gullies. A few of the key empirical relations discussed in Thompson (1964), United States Soil Conservation Service (1966), and Nachtergaele et al. (2002) are presented here.

Leopold and Maddock (1953) and Wolman (1955) described the hydraulic geometry of river channels by a set of empirical relations (as presented in Nachtergaele et al. 2002):

$$W = a\,Q^{b} \tag{17-16}$$

$$d_m = c\,Q^{f} \tag{17-17}$$

$$u_m = k\,Q^{l} \tag{17-18}$$

where

W = channel width (m);
Q = flow discharge ($m^3\ s^{-1}$);
d_m = mean flow depth (m);
u_m = mean flow velocity ($m\ s^{-1}$); and
a, b, c, f, k, and l = empirical constants.

The empirical constants are related as follows:

$$a \cdot c \cdot k = 1 \tag{17-19}$$

$$b + f + l = 1 \tag{17-20}$$

Wide variations of the empirical constants have been documented in the literature. From 20 investigators worldwide, the ranges of b, f, and l were found to be (Ming 1983)

$$0.39 < b < 0.60,\ 0.29 < f < 0.40,\ 0.09 < l < 0.28 \tag{17-21}$$

The coefficients a, c, and k depend on a number of variables, including the size of bed material and the type of channel bank. From an extensive study of rill development in seedbeds on 10 different soil types, Gilley et al. (1990) proposed $a = 1.13$ and $b = 0.303$ in the width-discharge relation (Eq. 17-16). From a limited number of data ($n = 7$), Lane and Foster (1980) obtained $a = 4.48$ and $b = 0.482$.

Sidorchuk (1996) analyzed extensive erosion data ($n = 617$) from the Yamal peninsula in the permafrost area of northwestern Siberia, which resulted in width-discharge constants of $a = 3.17$ and $b = 0.368$ (Nachtergaele et al. 2002), and which was recommended by Nachtergaele et al. (2002) for modeling ephemeral gully erosion. Based on rill and gully erosion data from laboratory and field experimental plots and field measurements in simulated cultivated topsoil and on cropland around the world, Nachtergaele et al. (2002) proposed the width-discharge constants of $a = 2.51$ and $b = 0.412$. Based on all these values, Nachtergaele et al. (2002) suggested different width-discharge exponent b values for the rill, gully, and river erosion domains of 0.3, 0.4, and 0.5, respectively.

An extensive equation for predicting ephemeral gully channel width has been used in the ephemeral gully erosion model (EGEM; Woodward 1999), and is expressed as (Watson et al. 1986)

$$W = 2.66\,Q_p^{0.396}\,n^{0.387}\,s^{-0.16}\,\tau_{cr}^{-0.024} \tag{17-22}$$

where

Q_p = peak flow discharge ($m^3\ s^{-1}$);
n = Manning's roughness coefficient;
s = soil surface slope ($m\ m^{-1}$); and
τ_{cr} = critical flow shear stress (Pa).

EGEM computes the critical flow shear stress as (Smerdon and Beasley 1961):

$$\tau_{cr} = 0.311 \cdot 10^{(0.0182\,P_c)} \tag{17-23}$$

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where

P_c = percentage of clay content.

From an analysis of 409 data points obtained from slopes ranging from 0.035 to 0.45 m m^{-1} and soil materials ranging from stony sands over silt loams to vertisols, Govers (1992) found the coefficient and exponent of $k = 3.52$, $l = 0.294$ in flow velocity-discharge relationships (Eq. 17-18) for developing rills on loose nonlayered materials (e.g., seedbed conditions). Once a, b, k, and l are determined, the mean depth-discharge relation constants c and f may be computed from solving Eqs. (17-19) and (17-20).

The next major difficult variable in predicting gully erosion is the gully advancement rate. Thompson (1964) studied gully head advancement at locations in Minnesota, Iowa, Alabama, Texas, Oklahoma, and Colorado and developed the empirical equation

$$R = (7.13 \times 10^{-5})\, A^{0.49}\, S^{0.14}\, P^{0.74}\, E \tag{17-24}$$

where

R = gully head advancement for the time period of interest (m);
A = drainage area above the gully head (m^2);
S = slope of the approach channel above the gully head (%);
P = summation of rainfall from 24-h rains equal to or greater than 12.7 mm for the time period of interest (mm); and
E = clay content of the eroding soil profile (%).

The United States Soil Conservation Service (1966) recommended a simplified form of this equation:

$$R = (5.25 \times 10^{-3})\, A^{0.46}\, P^{0.20} \tag{17-25}$$

17.4 STREAMBED AND BANK EROSION

Streambed erosion mechanics and quantification are extensively discussed in Chapters 2 to 4. Local bridge scour is another form of streambed erosion; its processes and quantification are discussed in Chapter 10. Quantification of streambed erosion and bed elevation changes using one-, two-, or three-dimensional numerical models is discussed in Chapters 14 and 15. Quantification of streambed erosion, along with upland soil erosion (sediment yield), using watershed simulation models is discussed later in this chapter.

Mechanics of streambank erosion and river width adjustment and their quantification are extensively discussed in Chapter 7 and by the ASCE Task Committee on Hydraulics, Bank Mechanics, and Modeling of River Width Adjustment (1998a; 1998b). Twelve quantitative time-dependent models that may be used to quantify streambed and bank erosion were also reviewed and described there.

17.5 GROSS EROSION, DELIVERY RATIO, AND SEDIMENT YIELD

Gross erosion is the total soil eroded in a drainage area or watershed through interrill, rill, gully, and stream erosion processes. All the sediment generated from these processes (gross erosion) may not be delivered at the watershed outlet because some of it may be deposited at various locations in the watershed. Soil material eroded from a field slope may be deposited along field boundaries, in terrace channels, in depressional areas, or on flat or vegetated areas traversed by overland flow before it reaches a watercourse (stream). Sediment may be also deposited within the stream channel system itself, either in specific locations such as sand bars, or generally across the bottom of a long stream reach.

Sediment yield is the total sediment delivered past a point of interest or the watershed outlet during any given time. Sediment yield at a point may be computed simply by multiplying gross erosion in the watershed above that point by a delivery ratio. The sediment delivery ratio is the fraction of the gross erosion that is expected to be delivered to the point of the watershed under consideration.

The sediment delivery ratio is dependent upon drainage area size, watershed characteristics as described by relief and stream length, sediment source and its proximity to the stream, transport system, and texture of the eroded material. The United States Soil Conservation Service (1971) developed a general sediment delivery ratio versus drainage area relationship from data of earlier studies. The relationship shows that the sediment delivery ratio varies approximately inversely as the 0.2 power of the drainage area in acres (1 acre = 0.405 ha). The wide scatter of data used in the development of this relationship indicates that additional variables affect the relationship. Table 17-2 shows some estimates of the delivery ratios.

The use of the sediment delivery ratio estimates from Table 17-2 should be tempered by consideration of other factors that may affect the values at a particular location. A higher delivery ratio should be used when the eroding soil is fine-textured (high in silt or clay content) and a lower one if the eroding soil is coarse-textured (high in sand content). The conditions of the streams and the delivery system should also be evaluated to assess and alter, if need be, the general relationship of Table 17-2. Delivery ratio values from Table 17-2 should be used only if local or regional relationships are not established and time is not available to develop a sediment-yield relationship for the area of interest.

Note that the sediment delivery ratios listed in Table 17-2 all have values of less than 1.0. This implies that the channel system is aggrading, or accumulating deposited sediment. This will be the case in most watershed studies examining

Table 17-2 General Sediment Delivery Ratios[a]

Drainage area, km^2	Sediment delivery ratio
0.05	0.580
0.10	0.520
0.50	0.390
1.00	0.350
5.00	0.250
10.00	0.220
50.00	0.153
100.00	0.127
500.00	0.079
1000.00	0.059

[a]Based on United States Soil Conservation Service (1971).

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the impacts of increased human activities, because such activities generally increase upland erosion and the delivery of sediment to the channel system. If things go the other way, and a watershed undergoing severe erosion is put under conservation management so that upland erosion is greatly reduced, the sediment delivery ratio may in fact become greater than 1.0, as little new sediment is delivered to the channel system but the sediment within the system is flushed out or new sediment is generated from streambed and/or bank erosion by continuing stream flows.

The most reliable sediment yield estimates come from direct measurements of suspended sediment and bed load at the point of interest. Sediment-yield calculations for the Illinois River Basin (Demissie et al. 2003) are an example. Reservoirs of known age and sedimentation history determined by surveys are also excellent data sources for determining sediment yields. The sediment accumulation over a known time span can be used to obtain the average annual sediment yield. However, reservoir deposition and sediment yield may not be the same, because the reservoir trap efficiency may not be 100%. The trap efficiency of a reservoir is the portion of the total sediment delivered to the reservoir that is retained in the reservoir. These methods and the associated data were presented and discussed extensively in Vanoni (1975). Recent advancements are discussed here in Chapters 5 and 12 and Appendix D.

More discussions and methods of computing delivery ratio and sediment yield may be found in Agricultural Research Service—U.S. Department of Agriculture (1975), Walling (1983), and Williams (1977). The first publication is a comprehensive compilation of research prior to 1972 and provides excellent background, data, analysis, and conceptual materials.

17.6 WATERSHED MODELS

Watershed models simulating hydrologic processes, upland soil and stream erosion, and transport and deposition of sediment are comprehensive tools in computing and predicting sediment yields from watersheds. In addition to simulating hydrologic, erosion, and sedimentation processes, some of the watershed models simulate chemical mixing with water and sediment and transport of these through watersheds. These models are also called non-point-source pollution models because they simulate surface-water pollutants, including sediment, nutrients, pesticides, and other chemicals, originated from nonpoint or diffused sources. Such models are useful analysis tools to understand some of environmental problems (flooding, upland soil and streambed-bank erosion, sedimentation, contamination of water, etc.) and to find solutions through land-use changes and best management practices (BMPs).

The models assist in the development of total maximum daily load (TMDL) estimates required by the United States Clean Water Act and in evaluating alternative land-use and BMP scenarios, implementation of which can help in meeting water-quality standards and reducing the damaging effects of storm-water runoff on water bodies and the landscape. The TMDL is the maximum amount of a pollutant from point (e.g., wastewater treatment plant) and nonpoint sources that a water body can receive and still meet water-quality standards. According to the U.S. Environmental Protection Agency report (USEPA 1998), agriculture is the leading contributor of non-point-source pollutants (sediment and nutrients) to streams and rivers in the United States. Other contributors include golf courses, urban development, streambank erosion, and mining operations.

Some of the commonly used watershed-scale hydrologic and non-point-source pollution models include the Areal Nonpoint Source Watershed Environment Response Simulation or ANSWERS (Beasley et al. 1980), the Precipitation-Runoff Modeling System or PRMS (Leavesley et al. 1983), the Agricultural NonPoint Source pollution model or AGNPS (Young et al. 1987), the KINematic runoff and EROSion model or KINEROS (Woolhiser et al. 1990), the Hydrological Simulation Program—Fortran or HSPF (Bicknell et al. 1993), the European Hydrological System model or MIKE SHE (Refsgaard and Storm 1995), the Soil and Water Assessment Tool or SWAT (Arnold et al. 1998), the Annualized Agricultural NonPoint Source model or AnnAGNPS (Bingner and Theurer 2001), the Dynamic Watershed Simulation Model or DWSM (Borah et al. 2002b), ANSWERS-Continuous (Bouraoui et al. 2002), and CASCade of planes in 2-Dimensions or CASC2D (Ogden and Julien 2002). Sources and descriptions of more models, including field-scale models, are available in the literature (e.g., Singh 1995; Singh and Frevert 2002a; 2002b).

Some of the models are based on simple empirical relations having robust algorithms, and others use physically

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based governing equations having computationally intensive numerical schemes. The simple models are sometimes incapable of giving desirable detailed results, and the detailed models are inefficient and could be computationally prohibitive for large watersheds. Therefore, finding an appropriate model for an application and for a certain watershed is quite a challenging task. Borah and Bera (2003) reviewed the 11 models mentioned and compiled a report on their mathematical bases, computational techniques, and important features or structures. This report is useful for selecting the most suitable model for a specific application depending upon the problem, watershed size, desired spatial and temporal scales, expected accuracy, user's skills, computer resources, etc. The review is also helpful in determining the strengths, weaknesses, and directions for enhancements of the models. The following nine subsections are based on that review.

In addition to these 11 watershed-scale models, two other field-scale models are worth mentioning: Chemicals, Runoff, and Erosion from Agricultural Management System or CREAMS (Knisel 1980) and Water Erosion Prediction Project or WEPP (Foster and Lane 1987; Lane and Nearing 1989). These two models have been widely used in estimating sediment yields from field-scale catchments and hill slopes. WEPP is a detailed soil-erosion and sediment-transport model and can be considered as state-of-the-art in hill-slope simulations. There are many other models available in the literature. The Department of Defense (Doe et al. 1999) evaluated 24 soil-erosion models for use on military installations. Among those, the Simulated Water Erosion (SIMWE) model (Mitas and Mitasova 1998) was found to be one of the "best" erosion models.

17.6.1 Review of Watershed Models

AnnAGNPS, ANSWERS-Continuous, HSPF, and SWAT are long-term continuous simulation models useful for analyzing long-term effects of hydrological changes and watershed management practices, especially agricultural practices. AGNPS, ANSWERS, DWSM, and KINEROS are single-storm-event models useful for analyzing severe actual or design single-event storms and evaluating watershed management practices, especially structural practices. CASC2D, MIKE SHE, and PRMS have both long-term and storm-event simulation capabilities. The mathematical bases of different components of these models, the most important elements of these mathematical models, were identified and compiled by Borah and Bera (2003). A summary compilation is presented in Table 17-3 for the long-term continuous models and Table 17-4 for the storm-event models. PRMS has both long-term and storm-event modes. The long-term mode of PRMS is only a hydrological model. The storm mode of PRMS has a sediment component as well. Therefore, only the PRMS storm mode is reviewed and presented in Table 17-4. MIKE SHE and CASC2D are listed separately; MIKE SHE is presented in Table 17-3 with the continuous models, and CASC2D is listed in Table 17-4 with the storm-event models. In each of these tables, the summary includes model components or capabilities, temporal scale, watershed representation, procedures to compute rainfall excess or water balance on overland planes, overland runoff, subsurface flow, channel runoff, reservoir flow, overland sediment, channel sediment, reservoir sediment, chemicals, and BMP evaluations. Sources and brief backgrounds of the 11 models are given below.

AGNPS, the Agricultural NonPoint Source pollution model (Young et al. 1987; 1989), was developed at the USDA-ARS North Central Soil Conservation Research Laboratory in Morris, Minnesota. It is an event-based model simulating runoff, sediment, and transport of nitrogen (N), transport of phosphorus (P), and chemical oxygen demand (COD) resulting from single rainfall events. Version 4.03 of the model (Young et al. 1994) was widely distributed. The model is currently undergoing extensive revisions and upgrading at the USDA-ARS National Sedimentation Laboratory (NSL) in Oxford, Mississippi, and one of its upgrades is AnnAGNPS, the Annualized Agricultural NonPoint Source model (Bingner and Theurer 2001), for continuous simulations of hydrology, soil erosion, and transport of sediment, nutrients, and pesticides. It is designed to analyze the impact on the environment of non-point-source pollutants from predominantly agricultural watersheds.

ANSWERS, Areal Nonpoint Source Watershed Environment Response Simulation (Beasley et al. 1980), was developed at Purdue University in West Lafayette, Indiana, and uses a distributed parameter concept to model the spatially varying processes of runoff, infiltration, subsurface drainage, and erosion for single-event storms. The model has two major components: hydrology and upland erosion responses. The conceptual basis for the hydrologic model was taken from Huggins and Monke (1966) and for the erosion simulation from Foster and Meyer (1972). Similar to AnnAGNPS, ANSWERS-Continuous (Bouraoui and Dillaha 1996; Bouraoui et al. 2002) emerged from ANSWERS as a continuous model at the Virginia Polytechnic Institute and State University in Blacksburg, Virginia. The model was expanded with upland nutrient transport and losses based on GLEAMS (Leonard et al. 1987), EPIC (Williams et al. 1984), and others.

CASC2D, CASCade of planes in 2-Dimensions, initially developed at Colorado State University in Fort Collins, Colorado (Julien and Saghafian 1991; Julien et al. 1995), and further modified at the University of Connecticut in Storrs, Connecticut (Ogden 1998; Ogden and Julien 2002), is a physically based model. It simulates water and sediment in two-dimensional overland grids and one-dimensional channels and has both single-event and long-term continuous simulation capabilities. Similarly, MIKE SHE (Refsgaard and Storm 1995), based on SHE, the European Hydrological System (Abbott et al. 1986a; 1986b), is a comprehensive, distributed, and physically based model simulating water,

Table 17-3 Summary of Watershed-Scale Long-Term Continuous Models[a]

Description/ criteria	AnnAGNPS	ANSWERS-Continuous	HSPF	MIKE SHE	SWAT
Model components/ capabilities	Hydrology, transport of sediment, nutrients, and pesticides resulting from snowmelt, precipitation and irrigation, source accounting capability, and user interactive programs including TOPAGNPS (Bingner and Theurer 2001) generating cells and stream network from Digital Elevation Model.	Daily water balance, infiltration, runoff and surface-water routing, drainage, river routing, evapotranspiration, sediment detachment, sediment transport, nitrogen and phosphorus transformations, nutrient losses through uptake, runoff, and sediment.	Runoff and water-quality constituents on pervious and impervious land areas, movement of water and constituents in stream channels and mixed reservoirs, and part of the USEPA BASINS modeling system with user interface and ArcView Geographic Information System (GIS) platform.	Interception-ET, overland and channel flow, unsaturated zone, saturated zone, snowmelt, exchange between aquifer and rivers, advection and dispersion of solutes, geochemical processes, crop growth and nitrogen processes in the root zone, soil erosion, dual porosity, irrigation, and user interface with pre- and postprocessing, GIS, and UNIRAS (Refsgaard and Storm 1995) for graphical presentation.	Hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, agricultural management, channel and reservoir routing, water transfer, and part of the USEPA BASINS modeling system with user interface and ArcViewGIS platform.
Temporal scale	Long-term; daily or subdaily steps.	Long-term; dual time steps: daily for dry days and 30 s for days with precipitation.	Long-term; variable constant steps (hourly).	Long-term and storm event; variable steps depending on numerical stability.	Long-term; daily steps.
Watershed representation	Homogeneous land areas (cells), reaches, and impoundments.	Square grids with uniform hydrologic characteristics, some having companion channel elements; one-dimensional simulations.	Pervious and impervious land areas, stream channels, and mixed reservoirs; one-dimensional simulations.	Two-dimensional rectangular/square overland grids, one-dimensional channels, one-dimensional unsaturated and three-dimensional saturated flow layers.	Subbasins grouped based on climate, hydrologic response units (lumped areas with same cover, soil, and management), ponds, groundwater, and main channel.
Rainfall excess on overland/ water balance	Water balance for constant subdaily time steps and two soil layers (8-in. tillage depth and user-supplied second layer).	Daily water balance, rainfall excess using interception, Green-Ampt infiltration equation, and surface storage coefficients.	Water budget considering interception, ET, and infiltration with empirically based areal distribution.	Interception and ET loss and vertical flow solving Richards equation using implicit numerical method.	Daily water budget; precipitation, runoff, ET, percolation, and return flow from subsurface and groundwater flow.
Runoff on overland	Runoff curve number generating daily runoff following SWRRB and EPIC procedures and USSCS (1986) TR-55 method for peak flow.	Manning and continuity equations (temporally variable and spatially uniform) solved by explicit numerical scheme.	Empirical outflow depth to detention storage relation and flow using Chezy-Manning equation.	Two-dimensional diffusive wave equations solved by an implicit finite-difference scheme.	Runoff volume using curve number and flow peak using modified Rational formula or SCS TR-55 method.

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Table 17-3 Summary of Watershed-Scale Long-Term Continuous Models[a] *(Continued)*

Description/ criteria	AnnAGNPS	ANSWERS-Continuous	HSPF	MIKE SHE	SWAT
Subsurface flow	Lateral subsurface flow using Darcy's (1856) equation or tile drain flow using Hooghoudt's (Smedema and Rycroft 1983) equation and parallel drain approximation.	Subsurface flow defined by tile drainage coefficient and groundwater or interflow release fraction; unsaturated zone drainage determined using Darcy's gravity flow.	Interflow outflow, percolation, and groundwater outflow using empirical relations.	Three-dimensional groundwater flow equations solved using a numerical finite-difference scheme and simulated river-groundwater exchange.	Lateral subsurface flow using kinematic storage model (Sloan et al. 1983), and groundwater flow using empirical relations.
Runoff in channel	Assuming trapezoidal and compound cross-sections, Manning's equation is numerically solved for hydraulic parameters and TR-55 for peak flow.	Manning and continuity equations (temporally variable and spatially uniform) solved by explicit numerical scheme.	All inflows assumed to enter one upstream point, and outflow is a function of reach volume or user-supplied demand.	One-dimensional diffusive wave equations solved by an implicit finite-difference scheme.	Routing based on variable storage coefficient method and flow using Manning's equation adjusted for transmission losses, evaporation, diversions, and return flow.
Flow in reservoir	Average outflow during runoff event is calculated based on permanent pool storage and stage, runoff volume, and coefficients derived from elevation-storage relation.	Not simulated.	Same as channel.	No information.	Water balance and user-provided outflow (measured or targeted).
Overland sediment	Uses RUSLE to generate sheet and rill erosion daily or user-defined runoff event, HUSLE (Theurer and Clarke 1991) for delivery ratio, and sediment deposition based on size distribution and particle fall velocity.	Raindrop detachment using rainfall intensity and USLE factors, flow erosion using unit-width flow and USLE factors, and transport and deposition of sediment sizes using modified Yalin equation.	Rainfall splash detachment and washing off of the detached sediment based on transport capacity as function of water storage and outflow plus scour from flow using power relation with water storage and flow.	No information.	Sediment yield based on Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt 1977) expressed in terms of runoff volume, peak flow, and USLE factors.
Channel sediment	Modified Einstein equation for sediment transport and Bagnold equation to determine transport capacity of flow (Theurer and Cronshey 1998).	Not simulated.	Noncohesive (sand) sediment transport using user-defined relation with flow velocity or Colby (1957) or Toffaleti (1969) method, and cohesive (silt, clay) sediment transport based on critical shear stress and settling velocity.	No information.	Bagnold's stream power concept for bed degradation and sediment transport, degradation adjusted with USLE soil erodibility and cover factors, and deposition based on particle fall velocity.

(Continued)

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Table 17-3 Summary of Watershed-Scale Long-Term Continuous Models[a] *(Continued)*

Description/ criteria	AnnAGNPS	ANSWERS-Continuous	HSPF	MIKE SHE	SWAT
Reservoir sediment	Sediment deposition based on constant detention discharge, zero transport capacity, and dilution with pool water.	Not simulated.	Same as channel.	No information.	Outflow using simple continuity based on volumes and concentrations of inflow, outflow, and storage.
Chemical simulation	Soil moisture, nutrients, and pesticides in each cell are tracked using U.S. Natural Resource Conservation Service soil databases and crop information; reach routing includes fate and transport of nitrogen, phosphorus, individual pesticides, and organic carbon.	Nitrogen and phosphorus transport and transformations through mineralization, ammonification, nitrification, and denitrification, and losses through uptake, runoff, and sediment.	Soil and water temperatures, dissolved oxygen, carbon dioxide, nitrate, ammonia, organic N, phosphate, organic P, pesticides in dissolved, adsorbed, and crystallized forms, and tracer chemicals chloride or bromide to calibrate solute movement through soil profiles.	Dissolved conservative solutes in surface, soil, and ground waters by solving the advection-dispersion equation numerically for the respective regimes.	Nitrate N based on water volume and average concentration, runoff P based on partitioning factor, daily organic N and sediment-adsorbed P losses using loading functions, crop N and P use from supply and demand, and pesticides based on plant leaf-area index, application efficiency, wash-off fraction, organic carbon adsorption coefficient, and exponential decay according to half-lives.
BMP evaluation	Agricultural management.	Impact of watershed management practices on runoff and sediment losses.	Nutrient and pesticide management.	No information.	Agricultural management: tillage, irrigation, fertilization, pesticide applications, and grazing.

[a]After Borah and Bera (2003).

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sediment, and water-quality parameters in two-dimensional overland grids, one-dimensional channels, and one-dimensional unsaturated and three-dimensional saturated flow layers. It also has both continuous long-term and single-event simulation capabilities. The model was developed by a consortium of the U.K. Institute of Hydrology, the French consulting firm SOGREAH, and the Danish Hydraulic Institute.

DWSM, the Dynamic Watershed Simulation Model (Borah et al. 2002b), was put together at the Illinois State Water Survey (ISWS) in Champaign, Illinois, based on research conducted over many years at several institutions (Borah 1989a; 1989b; Ashraf and Borah 1992; Borah et al. 1980; 1981; 2002b; 2002c; 2004). DWSM simulates distributed surface and subsurface storm-water runoff, propagation of flood waves, upland soil and streambed erosion, sediment transport, and agrochemical transport in agricultural and rural watersheds during rainfall events. Similarly, KINEROS, the KINematic runoff and EROSion model (Woolhiser et al. 1990; Smith et al. 1995), which evolved from the 1960s to the 1980s at the USDA-ARS in Fort Collins, Colorado, is a distributed rainfall-runoff and soil erosion-sediment transport model for single rainfall events.

Table 17-4 Summary of Watershed-Scale Storm-Event Models[a]

Description/ criteria	AGNPS	ANSWERS	CASC2D	DWSM	KINEROS	PRMS storm mode
Model components/ capabilities	Hydrology, soil erosion, and transport of sediment, nitrogen, phosphorus, and chemical oxygen demand from nonpoint and point sources, and user interface for data input and analysis of results.	Runoff, infiltration, subsurface drainage, soil erosion, and overland sediment transport.	Spatially varying rainfall inputs including radar estimates, rainfall excess and two-dimensional flow routing on cascading overland grids, continuous soil moisture accounting, diffusive wave or full-dynamic channel routing, upland erosion, sediment transport in channels, and part of U.S. Army Corps of Engineers' Watershed Modeling System (Ogden and Julien 2002) with graphical user interface and GIS data processing.	Spatially varying rainfall inputs; individual hyetograph for each overland, rainfall excess, surface and subsurface overland flow, surface erosion and sediment transport, agrochemical mixing and transport, channel erosion and deposition and routing of flow, sediment, and agrochemical and flow routing through reservoirs.	Distributed rainfall inputs; each catchment element assigned to a rain gauge from a maximum of 20, rainfall excess, overland flow, channel routing, surface erosion and sediment transport, channel erosion and sediment transport, flow and sediment routing through detention structures.	Hydrology and surface runoff, channel flow, channel reservoir flow, soil erosion, overland sediment transport, and linkage to USGS data-management program ANNIE for formatting input data and analyzing simulated results.
Temporal scale	Storm event; one step is the storm duration.	Storm event; variable constant steps depending on numerical stability.	Long-term and storm event; variable steps depending on numerical stability.	Storm event; variable constant steps.	Storm event; variable constant steps depending on numerical stability.	Storm event; variable constant steps depending on numerical stability.
Watershed representation	Uniform square areas (cells), some containing channels.	Square grids with uniform hydrologic characteristics, some having companion channel elements; one-dimensional simulations.	Two-dimensional square overland grids and one-dimensional channels.	Overland, channel, and reservoir segments defined by topographic-based natural boundaries; one-dimensional simulations.	Runoff surfaces or planes, channels or conduits, and ponds or detention storage; one-dimensional simulations.	Flow planes, channel segments, and channel reservoirs; one-dimensional simulations.
Rainfall excess on overland	Runoff curve number method.	Surface detention with empirical relations and infiltration with modified	Interception and ET loss, infiltration using Green-Ampt method, and overland	Two options: simple runoff curve number procedure for computing time varying rainfall	Interception loss and extensive infiltration procedure by Smith and Parlange (1978).	Interception and infiltration using an empirically based areal distribution of point infiltration

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Table 17-4 Summary of Watershed-Scale Storm-Event Models[a] *(Continued)*

Description/ criteria	AGNPS	ANSWERS	CASC2D	DWSM	KINEROS	PRMS storm mode
		Holton-Overton relation.	flow retention.	intensities, or extensive interception and Smith-Parlange (1978) infiltration procedure.		(Green-Ampt equation), similar to HSPF.
Runoff on overland	Runoff volume using runoff curve number, and flow peak using an empirical relation similar to rational formula or SCS TR-55 method.	Manning and continuity equations (temporally variable and spatially uni-form) solved using an explicit numeri-cal scheme.	Two-dimensional diffusive wave equations solved by explicit finite-difference scheme.	Kinematic wave equations solved using analytical and approximate shock-fitting solutions.	Kinematic wave equations solved by an implicit numerical scheme.	Kinematic wave equations solved using a numerical scheme.
Subsurface flow	Not simulated.	Water moving from a control zone to tile drainage and groundwater release or inter-flow depending on infiltration rate, total poros-ity, and field capacity.	Not simulated.	Combined interflow, tile drain flow, and base flow using Sloan et al. (1983) kinematic storage equation and spatially uniform and temporally varying continuity equation.	Not simulated.	No subsurface simulation in the storm mode.
Runoff in channel	Included in the overland cells.	Same as overland.	Two options: one-dimensional diffusive wave equations solved by explicit finite-difference method mostly for head water channels, or implicit finite-difference solution of the one-dimensional full dynamic equations for limited subcritical flows.	Same as overland.	Same as overland.	Same as overland.
Flow in reservoir	Flow routing through impound-ments associated with terrace systems having pipe outlets.	Not simulated.	Not simulated.	Modified Puls method solving analytically the temporally varying and spatially uniform continuity equation.	Finite difference solution of the temporally varying and spatially uniform continuity equation.	Modified Puls method solving the temporally varying and spatially uniform continuity equation.

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Table 17-4 Summary of Watershed-Scale Storm-Event Models[a] *(Continued)*

Description/ criteria	AGNPS	ANSWERS	CASC2D	DWSM	KINEROS	PRMS storm mode
Overland sediment	Soil erosion using USLE and routing of clay, silt, sand, and small and large aggregates through cells based on steady-state continuity; effective transport capacity from a modification of the Bagnold stream power equation, fall velocity, and Manning's equation.	Raindrop detachment using USLE factors and flow erosion and transport of four sizes (0.01 to 0.30 mm) using modified Yalin's equation and an explicit numerical solution of the steady-state continuity equation.	Soil erosion and sediment deposition are computed using modified Kilinc-Richardson (1973) equation with USLE factors and conservation of mass.	Raindrop detachment and sediment transport, scour, and deposition of user-specified particle size groups based on sediment-transport capacity and approximate analytical solution of temporally and spatially varying continuity equation.	Raindrop detachment and sediment transport, scour, and deposition of one particle size based on sediment-transport capacity and explicit numerical solution of temporally and spatially varying continuity equation.	Raindrop detachment based on rainfall intensity, overland flow detachment based on transport capacity, and routing based on sediment continuity.
Channel sediment	Included in overland cells.	Assumed negligible and not simulated.	Sand-size total sediment load is computed using Yang's unit stream power method.	Streambed scour/deposition and sediment transport of the same size groups based on sediment-transport capacity and approximate analytical solution of temporally and spatially varying continuity equation.	Streambed scour/deposition and sediment transport of the same sediment size based on sediment-transport capacity and explicit numerical solution of temporally and spatially varying continuity equation.	Sediment delivered from flow planes is transported as conservative substance without detachment or deposition.
Reservoir sediment	Sediment routing through impoundments associated with terrace systems having pipe outlets.	Not simulated.	Not simulated.	Assumes all sediments are trapped and no downstream discharge.	For shallow ponds, erosion and deposition are simulated with a mean particle diameter; for reservoirs, deposition is simulated with a particle-size distribution.	Not simulated.
Chemical simulation	Nitrogen and phosphorus in runoff using extraction coefficients, and sediment using enrichment ratios and chemical oxygen demand in runoff water assuming accumulation without loss.	Not simulated.	Not simulated.	Nutrients and pesticides are simulated in dissolved and adsorbed phases with water and sediment, respectively, through mixing and exchange between rainfall, runoff, soil, and pore water, and routing through overland and channel segments using approximate analytical solutions of spatially and temporally varying continuity equations.	Not simulated.	Not simulated.

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Table 17-4 Summary of Watershed-Scale Storm-Event Models[a] (Continued)

Description/ criteria	AGNPS	ANSWERS	CASC2D	DWSM	KINEROS	PRMS storm mode
BMP evaluation	Agricultural management.	Agricultural management.	No information.	Detention basins, alternative ground covers, and alterations to hydrologic and hydraulic conditions.	Detention basins and alterations to hydrologic and hydraulic conditions.	No information.

[a]After Borah and Bera (2003).

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HSPF, the Hydrological Simulation Program—Fortran (Donigian et al. 1995), first publicly released in 1980, was put together by a group of consultants (Johanson et al. 1980) under contract with the USEPA. It is a continuous watershed simulation model that produces a time history of water quantity and quality at any point in a watershed. HSPF is an extension of several previously developed models: the Stanford Watershed Model (SWM) (Crawford and Linsley 1966); the Hydrologic Simulation Program (HSP) including HSP Quality (Hydrocomp 1977); the Agricultural Runoff Management (ARM) model (Donigian and Davis 1978); and the Nonpoint Source Runoff (NPS) model (A. S. Donigian, Jr., and N. H. Crawford, unpublished report, U.S. EPA Environmental Research Lab, 1979). HSPF uses many of the software tools developed by the U.S. Geological Survey (USGS) to providing interactive capabilities for model input, data storage, input-output analyses, and calibration. Several versions of the model have been released: Version 8 was released in 1984 (Johanson et al. 1984), and Version 10 was released in 1993 (Bicknell et al. 1993). HSPF has been promoted and marketed by these consultants worldwide. Its major application in the United States is the Chesapeake Bay basin model (Donigian et al. 1986). HSPF has been incorporated as a non-point-source model (NPSM) into the USEPA's Better Assessment Science Integrating Point and Nonpoint Sources (BASINS), which was developed by Tetra Tech, Inc. (Lahlou et al. 1998), under contract with the USEPA. The main purpose of BASINS is to analyze for and develop TMDLs nationwide.

PRMS, the Precipitation-Runoff Modeling System (Leavesley et al. 1983; Leavesley and Stannard 1995), developed at the USGS in Lakewood, Colorado, is a modular-design, distributed-parameter, physical-process watershed model that was developed to evaluate the effects of various combinations of precipitation, climate, and land use on watershed response. Watershed response to normal and extreme rainfall and snowmelt can be simulated to evaluate changes in water-balance relations, flow regimes, flood peaks and volumes, soil-water relations, sediment yields, and groundwater recharge. PRMS has been coupled with USGS's data management program ANNIE (Lumb et al. 1990) and the U.S. Weather Service's Extended Streamflow Prediction (ESP) program (Day 1985) to produce a watershed-modeling and data-management system for hydrologic simulation and data analysis. PRMS has both long-term and single-storm modes. The long-term mode of PRMS is only a hydrological model. The storm mode of PRMS has a sediment component as well. Therefore, only the PRMS Storm Mode is considered and discussed here.

SWAT, the Soil and Water Assessment Tool (Arnold et al. 1998; Neitsch et al. 2002), was developed at the USDA-ARS Grassland, Soil, and Water Research Laboratory in Temple, Texas. It emerged mainly from SWRRB (Arnold et al. 1990) and has features from CREAMS (Knisel 1980); EPIC (Williams et al. 1984); GLEAMS (Leonard et al. 1987); and ROTO (Arnold et al. 1995). It was developed to assist water resources managers in predicting and assessing the impact of management on water, sediment, and agricultural chemical yields in large ungauged watersheds or river basins. The model is intended for long-term yield predictions and is not capable of detailed single-event flood routing. It is an operational or conceptual model that operates on a daily time step. The model has eight major components: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. Although most of the applications of SWAT have been on a daily time step, recent additions to the model are the Green and Ampt (1911) infiltration equation using rainfall input at any time increment and channel routing at an hourly time step (Neitsch et al. 2002). Similarly to HSPF, SWAT is also incorporated into the USEPA's BASINS for non-point-source simulations on agricultural watersheds.

17.6.2 Basic Flow-Governing Equations

Flow routing is governed by flow equations basic to all of the hydrologic, soil erosion-sediment transport (sediment yield) and non-point-source pollution models. Performance,

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efficiency, and applicability of a model depend greatly on these basic equations and how they are solved.

The basic flow-governing equations are the dynamic wave equations, often referred to as the St. Venant equations or shallow-water wave equations. These consist of the equations of continuity and momentum, respectively, for gradually varied unsteady flow, expressed as (Singh 1996)

$$\frac{\partial h}{\partial t}+\frac{\partial Q}{\partial x}=0 \qquad (17\text{-}26)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+g\frac{\partial h}{\partial x}=g\left(S_0-S_f\right) \qquad (17\text{-}27)$$

where

h = flow depth (m);
Q = flow per unit width ($m^3\ s^{-1}\ m^{-1}$);
u = water velocity ($m\ s^{-1}$);
g = acceleration due to gravity ($m\ s^{-2}$);
S_0 = bed slope ($m\ m^{-1}$);
S_f = energy gradient ($m\ m^{-1}$);
t = time (s);
x = longitudinal distance (m).

There is no analytical solution of Eqs. (17-26) and (17-27). Approximate numerical solutions of these two equations have been used in river flood routing models, such as the U.S. Army Corps of Engineers' Unsteady flow through a full NETwork of open channels (UNET) model (Barkau 1993); the National Weather Service's OPERational Dynamic Wave (DWOPER) model (Fread 1978); and models by Amein and Fang (1970), Strelkoff (1970), and Balloffet and Scheffler (1982), to name a few.

The dynamic wave equations have not been used in watershed models because of their computationally intensive numerical solutions. Only the CASC2D model uses these equations on a limited basis. Some of the models use approximations of these equations, ignoring certain terms in the momentum equation (Eq. (17-27)), as discussed below.

17.6.3 Diffusive Wave Equations Used by CASC2D and MIKE SHE

The diffusive wave equation consists of the continuity and simplified momentum equations, respectively expressed as (Singh 1996)

$$\frac{\partial h}{\partial t}+\frac{\partial Q}{\partial x}=q \qquad (17\text{-}28)$$

$$\frac{\partial h}{\partial x}=S_0-S_f \qquad (17\text{-}29)$$

where

q = lateral inflow per unit width and per unit length ($m^3\ s^{-1}\ m^{-1}\ m^{-1}$).

These equations are also known as "noninertia wave" equations (Yen and Tsai 2001).

The continuity equation (Eq. (17-28)) includes lateral inflow. The simplified momentum equation (Eq. (17-29)) expresses the pressure gradient as the difference between the bed slope and energy gradient, and is derived from Eq. (17-27) after ignoring the first two terms, representing, respectively, the local and convective accelerations.

As with the dynamic wave equations, there is no analytical solution of the diffusive wave equations (Eqs. (17-28) and (17-29)). Watershed models CASC2D and MIKE SHE use approximate numerical solutions of these equations for routing surface runoff over overland planes and through channel segments. CASC2D uses two numerical methods to solve Eqs. (17-28) and (17-29) for overland flow and channel flow (Ogden and Julien 2002). In solving these equations, Manning's formula is used to compute flow, and is expressed as

$$Q=\frac{1}{n}AR^{2/3}S_f^{1/2} \qquad (17\text{-}30)$$

where

n = Manning's roughness coefficient;
A = flow cross-sectional area per unit width ($m^2\ m^{-1}$);
R = hydraulic radius (m).

17.6.4 Kinematic Wave Equations Used by DWSM, KINEROS, and PRMS

The kinematic wave equations are the simplest form of the dynamic wave equations. Lighthill and Whitham (1955) developed the kinematic wave theory and used it to describe the movement of flood waves in long rivers. Kinematic wave theory is now a well-accepted tool for modeling a variety of hydrological processes (Singh 1996). The governing equations consist of the continuity equation and the simplest form of the momentum equation, ignoring all the acceleration and pressure gradient terms of Eq. (17-27), respectively expressed as

$$\frac{\partial h}{\partial t}+\frac{\partial Q}{\partial x}=q \qquad (17\text{-}31)$$

$$S_0=S_f \qquad (17\text{-}32)$$

The momentum equation (Eq. (17-32)) expresses simply that the energy gradient is equal to the bed slope. Any suitable law of flow resistance can be used to express this equation as a parametric function of the stream hydraulic parameters. A widely used expression is

$$Q = \alpha h^m \tag{17-33}$$

where

α = the kinematic wave parameter;
m = the kinematic wave exponent;

and α and m are related to channel (or plane) roughness and geometry. Manning's formula (Eq. (17-30)) may be used to define α and m in terms of Manning's roughness coefficient (n) and channel or plane geometry (Borah 1989a).

Equations (17-31) and (17-33) constitute the kinematic wave equations. The advantage of these equations is that they have an analytical solution by the method of characteristics (Borah et al. 1980). The equations generate only one system of characteristics, which means that they cannot represent waves traveling upstream, as in the case of backwater flow. Research suggests that for most cases of hydrological significance, the kinematic wave solution gives accurate results (V. P. Singh, unpublished paper, "Kinematic wave modeling in hydrology," ASCE-EWRI Task Committee on Evolution of Computer Methods in Hydrology, Reston, Va., 2002). In open-channel flow, dynamic waves always occur. The friction and slope terms modify the wave amplitudes to such a degree that the dynamic waves rapidly become negligible and the kinematic wave assumes the dominant role.

The analytical solution of Eqs. (17-31) and (17-33) does not apply when two characteristics intersect, forming a shock wave and physically representing a larger and faster wave superseding a smaller and slower wave. Approximate numerical solutions of Eqs. (17-31) and (17-33), such as the ones presented by Li et al. (1975) and Smith et al. (1995), do not recognize shocks. The numerical solutions can be used for any situation but the numerical solutions smooth out the waves and the hydrographs (Borah et al. 1980), thus undermining the fundamental reason that Lighthill and Whitham (1955) introduced this simple theory. With the analytical and an approximate shock-fitting (closed-form) solution, the kinematic wave theory represents salient features of a hydrograph, including the sharp rising part under shock-forming conditions (Borah et al. 1980).

The DWSM, KINEROS, and PRMS watershed models are based on the kinematic wave equations. KINEROS (Smith et al. 1995) and PRMS (Leavesley and Stannard 1995) use approximate numerical solutions of Eqs. (17-31) and (17-33), whereas DWSM uses the analytical and shock-fitting solution (Borah 1989a; Borah et al. 1980).

17.6.5 Storage-Based Equations Used by ANSWERS, ANSWERS-Continuous, and HSPF

Many of the models, such as ANSWERS, ANSWERS-Continuous, and HSPF, use the simple storage-based (nonlinear reservoir) equations for flow routing. The equations consist of the spatially uniform and temporally variable continuity equation and a flow equation expressed in terms of channel (or plane) roughness and geometry, such as the Manning equation (Eq. (17-30)). The continuity equation is expressed as

$$\frac{ds}{dt} = I - O \tag{17-34}$$

where

s = storage volume of water (m^3);
I = inflow rate (m^3 s^{-1});
O = outflow rate (m^3 s^{-1}).

Equation (17-34) assumes a level water surface throughout the overland plane or channel segment and does not represent any waveforms. This equation is more suitable for flood routing in lakes and reservoirs.

17.6.6 Curve Number and Empirical Equations Used by AGNPS, AnnAGNPS, and SWAT

Many of the models, such as SWAT, AGNPS, and AnnAGNPS, do not route water using mass-conservation-based continuity equations as described above. SWAT and AnnAGNPS maintain water balance through daily or sub-daily water budgets. All three of them use the USDA Soil Conservation Service runoff curve number method (United States Soil Conservation Service 1972) to compute runoff volumes and other empirical relations similar to the rational formula (Kuichling 1889; Rosemiller 1982) to compute peak flows, which may be expressed as

$$Q_r = \frac{(P - 0.2S_r)^2}{P + 0.8S_r} \tag{17-35}$$

$$S_r = \frac{25400}{CN} - 254 \tag{17-36}$$

$$Q_p = 0.0028CiA \tag{17-37}$$

where

Q_r = direct runoff (millimeters or mm);
P = accumulated rainfall (mm);
S_r = potential difference between rainfall and direct runoff (mm);
CN = curve number representing runoff potential for a soil cover complex (values 2 to 100);
Q_p = peak runoff rate (m^3 s^{-1});
C = runoff coefficient (values 0.02 to 0.95);
i = rainfall intensity (mm h^{-1});
A = watershed area (ha).

In addition, SWAT uses an empirical procedure to route water through channels. The SCS runoff curve number

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method (Eqs. (17-35) and (17-36)) is also used repeatedly by DWSM to compute rainfall excess rates at discrete time intervals in addition to an interception-infiltration alternative procedure (Table 17-4). Interception-infiltration routines are used by other models as well: ANSWERS, ANSWERS-Continuous, CASC2D, HSPF, KINEROS, MIKE SHE, and PRMS (Tables 17-3 and 17-4). The latest version of SWAT (Neitsch et al. 2002) has an option for using an infiltration equation for any time increment.

17.6.7 Model Algorithms and Efficiencies

CASC2D and MIKE SHE are both physically based models using multidimensional flow-governing equations with approximate numerical solution schemes, which make the models computationally intensive and subject to the numerical instabilities inherent in the numerical solutions. Both models use the diffusive (noninertia) wave equations (Eqs. (17-28) and (17-29)), and CASC2D uses the full dynamic wave equations (Eqs. (17-26) and (17-27)) on a limited basis, i.e., for stream channels less than 0.3% slope (Ogden and Julien 2002). Molnar and Julien (2000) examined the effects of grid size on the calculation of surface runoff using the CASC2D model. A sufficiently small time step is necessary to keep the model stable. The time step is on the order of 5 s for a 150-m grid size but decreases to about 1 s when standard 30-m GIS grid sizes are used. Calculation time can become prohibitive when the number of model grid cells exceeds 100,000 (Ogden and Julien 2002). MIKE SHE, using the same governing equations, has similar limitations. Although it uses a more stable numerical (implicit) scheme (Table 17-3), it is inefficient due to its iterative operation. Therefore, CASC2D and MIKE SHE would be suitable for small areas or watersheds for detailed studies of hydrology and non-point-source pollution under single rainfall events or for long-term periods in continuous mode.

Similar to CASC2D and MIKE SHE, the ANSWERS, KINEROS, and PRMS Storm Mode models (Table 17-4) are also physically based, using numerical solutions to solve the flow equations. ANSWERS uses the storage-based equations (Eqs. (17-34) and (17-30)), and KINEROS and PRMS use the kinematic wave equations (Eqs. (17-31) and (17-33)). These models were developed for single rainfall events using one-dimensional flow equations only, and therefore are less computationally intensive than CASC2D and MIKE SHE. However, potential problems inherent in the numerical solutions exist. Smith et al. (1995) suggested that KINEROS does a relatively good job of simulating runoff and sediment yield at watershed scales of up to approximately 1,000 ha. Therefore, applications of these models are limited to small watersheds and specific combinations of space and time increments for maintaining numerical solution stability. DWSM (Table 17-4), also a physically based model, uses analytical and approximate analytical solutions of the kinematic wave flow-governing equations (Eqs. (17-31) and (17-33)). Due to its robust closed-form solutions and algorithms, DWSM is not limited to any combinations of space and time increment sizes, and could potentially be used for large watersheds.

17.6.8 Long-Term Continuous Models

AnnAGNPS, ANSWERS-Continuous, CASC2D, HSPF, MIKE SHE, and SWAT are continuous simulation models and are useful for analyzing long-term effects of hydrological changes and watershed management practices. HSPF is capable of simulating urban and suburban land uses as well. Due to its use of daily time steps, SWAT does not simulate single-event storms adequately. HSPF can use time steps smaller than a day and, therefore, can simulate individual storm events. However, due to its conceptualization of the overland (subbasin) areas as leveled detention storage and use of the storage-based or nonlinear flow equations in routings, HSPF is not adequate for simulating intense single-event storms, especially for large subbasins and long channels. Reviews of applications of the HSPF and SWAT models (Borah and Bera 2004) revealed that these two models are not suitable for analyzing severe storm events. AnnAGNPS and ANSWERS-Continuous are also not adequately formulated to simulate intense single-event storms. Borah and Bera's (2004) reviews also confirmed that SWAT is applicable to predominantly agricultural watersheds and HSPF mixed agricultural and urban watersheds.

The long-term continuous models AnnAGNPS, ANSWERS-Continuous, HSPF, MIKE SHE, and SWAT have all three major components: hydrology, sediment, and chemicals (Table 17-3). Both HSPF and SWAT models are parts of the USEPA's BASINS for developing TMDL. With BASINS, both models have graphical user interfaces for data analysis, data processing, and graphical presentation of model outputs, which are useful for model calibration, validation, and analysis of BMPs and dissemination of model results. AnnAGNPS is a recent upgrade of the single-event AGNPS model. Similarly, ANSWERS-Continuous is a recent upgrade of the single-event ANSWERS model with extensive upland process simulations. However, ANSWERS-Continuous does not have channel erosion and sediment transport routines (Table 17-3), and, therefore, the sediment and chemical components are not applicable to watersheds. Due to its computationally intensive numerical schemes, MIKE SHE may become prohibitive for long-term continuous simulations in medium-to-large watersheds.

17.6.9 Storm-Event Models

Intense single-event storms cause flooding. These storms are especially critical when most of the yearly sediment and pollutant loads are carried through and out of a watershed (David et al. 1997; Borah et al. 2003). Certain BMPs, such as structural BMPs, must be designed to withstand certain single-event

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design storms. The storm-event models AGNPS, ANSWERS, CASC2D, DWSM, KINEROS, MIKE SHE, and PRMS-storm mode analyze severe actual or design single-event storms and evaluate watershed management practices, especially structural practices. The conceptual design and mathematical formulations of these models are different. AGNPS is a single-event, empirically based, lumped-parameter model using one time step (storm duration) and generating a single value for each of the output variables: runoff volume, peak flow, sediment yield, and average concentrations of nutrients. It is used to study the overall response from a single severe or design storm, but it is not suitable for analyzing a storm when the flow and constituent concentrations and loads vary with time. Time-varying water, sediment, and chemical discharges are critical in certain analyses. For example, peak flow, peak constituent concentrations, and their timings are crucial information in flood warning, floodwater management, watershed assessment, and BMP evaluations. Use of AGNPS in studying impacts of BMPs is qualitative (Borah et al. 2002a). ANSWERS, CASC2D, DWSM, KINEROS, MIKE SHE, and PRMS in storm mode can generate time-varying hydrograph and constituent graphs.

The storm-event models AGNPS, DWSM, and MIKE SHE all have the three major components hydrology, sediment, and chemical (Table 17-4). Among these three models, DWSM provides a balance between the simple AGNPS and complicated MIKE SHE models. It is suitable for simulations of agricultural and suburban watersheds (Borah and Bera 2004). CASC2D and KINEROS have complete hydrology and sediment components, but no chemical component (Table 17-4). ANSWERS and PRMS in storm mode have hydrology and overland sediment, but no chemical component, and no sediment simulation in stream channels (Table 17-4). AGNPS, CASC2D, KINEROS, and PRMS in storm mode have no subsurface flow simulations (Table 17-4).

17.6.10 Sediment Yield Predictions Using Watershed Models

Watershed models can be used to predict sediment yields from a watershed through simulations of hydrologic, soil erosion, sediment transport, and sediment deposition processes (Tables 17-3 and 17-4). The models dynamically account for sediment delivery through their routing procedures, and therefore, delivery ratios are not required. As summarized in Tables 17-3 and 17-4, different models use different procedures and algorithms to simulate these processes. It is impossible to present here all those procedures beyond the summaries presented in Tables 17-3 and 17-4. However, the major steps taken in one of the models (DWSM) to simulate hydrology (the basic component), soil erosion, sediment transport, and sediment deposition and ultimately to compute sediment yield are outlined below to provide an understanding of a modeling approach.

To apply DWSM, the watershed is divided into one-dimensional overland planes, channel segments, and reservoir units (Borah et al. 2002b). These divisions take into account nonuniformities in topographic, soil, and land-use characteristics, which are treated as being uniform with representative characteristics within each of the divisions. An overland plane is represented as a rectangle, with width equal to the adjacent (receiving) channel length, and length equal to the overland plane area divided by the width. Representative slope, soil, land cover, and roughness are based on physical measurements and observations. A channel segment is represented with a straight channel having the same length as in the field and having a representative cross-sectional shape, slope, and roughness based on physical measurements and observations. A reservoir unit is represented with a stage-storage-discharge relation (table) developed based on topographic data and discharge calculations using outlet measurements and established relations.

The overland planes are the primary sources of runoff and sediment. Two overland planes contribute surface runoff, subsurface flow, and sediment to one channel segment laterally from each side. The excess rainfall and eroded soil are routed across an overland plane, resulting in variable flow and sediment discharge along its slope length. However, cross-slope flow and sediment discharge are assumed to be uniform. Thus flow and sediment routing are only necessary within a unit width of the plane. Tile drain flows are combined with lateral subsurface flow using an effective lateral saturated hydraulic conductivity concept (Borah et al. 2002b; 2004). As a result, each channel receives time-varying, but spatially uniform, lateral inflows of water and sediment from the adjacent overland planes.

The network of channel segments carries the receiving water and sediment from the overland planes toward the watershed outlet. Depending upon the sediment load and transport capacity of the flow, further erosion of soil materials from the channel bed or sediment deposition may take place. The model simulates erosion and deposition of the channel bed only, not the banks. Therefore, the model is applicable to fairly stable streambank channels only. Also, the model assumes that all the incoming sediment is settled (deposited) within a lake, reservoir, or detention pond. Therefore, the sediment component is applicable to large detention ponds, and perhaps most reservoirs and lakes, where sediment is largely trapped and sediment bypass is negligible. For routing water and sediment through the watershed, a computational sequence is determined starting from the uppermost overland plane and ending in a channel segment or reservoir unit at the watershed outlet.

Rainfall is the primary model input. Rainfall records either from single or multiple rain gauges may be used. With multiple rain gauges, rain gauges are assigned to the overland planes using the Thiessen polygon method (Thiessen 1911). Rainfall excess and infiltration rates on each overland plane are computed from the rainfall records using two alternative

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procedures: the runoff curve number method (Eqs. (17-35) and (17-36)), as extended and described by Borah (1989a), and a detailed procedure involving computations of interception losses using a procedure of Simons et al. (1975) and infiltration rates using an algorithm developed by Smith and Parlange (1978), as described by Borah et al. (1981; 2002b). The first method computes rainfall excess rates, which are subtracted from rainfall rates (intensities) to compute infiltration rates assuming other losses, such as evapotranspiration are negligible during a storm event. The second method computes interception and infiltration rates, which are subtracted from rainfall intensities to compute rainfall excess rates. Losses in depression storage in the second method are indirectly accounted for in the interception as initial losses.

The excess rainfall over the overland planes and through the channel segments are routed using the kinematic wave equations (Eqs. (17-31) and (17-33)), as described in Borah (1989a). The routing scheme is based on analytical and approximate shock-fitting solutions (Borah et al. 1980) of Eqs. (17-31) and (17-33).

The sediment is divided into a number of particle size classes (groups). For agricultural watersheds, the sediment is divided into five size groups: sand, silt, clay, small aggregate, and large aggregate (Foster et al. 1985). Erosion, deposition, and transport of each size group are simulated individually, and total responses in the forms of sediment concentration and discharge and bed elevation change are obtained through integration of the responses from all the size groups.

The rate of soil detachment due to raindrop impact is computed using the relations (Meyer and Wischmeier 1969; Mutchler and Young 1975; Borah 1989b):

$$E_r = a_r I^2 (1-D_c)(1-D_g)\left(1-\frac{h+e}{3d_{50}}\right), \ \text{if } (h+e) < 3d_{50} \qquad \text{(17-38a)}$$

$$E_r = 0, \ \text{if } (h+e) \geq 3d_{50} \qquad \text{(17-38b)}$$

where

E_r = rate of soil detachment due to raindrop impact (m s^{-1});
a_r = raindrop detachment coefficient (RDC);
I = rainfall intensity (m s^{-1});
D_c = canopy cover density (m^{2}m^{-2});
D_g = ground cover density (m^{2}m^{-2});
h = water depth (m);
e = thickness of existing detached soil on the bed (m);
d_{50} = median raindrop diameter (m).

Equation (17-38a) can also be expressed similarly to the USLE or RUSLE (Eq. (17-1)), as shown by Van Liew and Saxton (1984) and Van Liew (1998) for interrill soil detachment rate. In that form, only the *K* and *C* factors are kept in the equation, the *R* factor is replaced with some power of rainfall intensity, and all multiplied by a coefficient (parameter). The *L* and *S* factors are dynamically accounted in the model algorithms, and the *P* factor is incorporated through changing all the model parameters affected by the support practice or appropriately subdividing the watershed to include the practice. These investigators use similar relationship for soil detachment rate by rill flow simply by replacing rainfall intensity with flow shear stress. In Eq. (17-38a), the *K* and *C* factors are lumped on the product $a_r(1-D_c)(1-D_g)$ in computing rate of soil detachment due to raindrop impact. In computing flow-induced erosion, the *K* and *C* factors are lumped into the FDC parameter discussed below.

Equations (17-38a) and (17-38b) give the detachment rate for the entire size distribution used in the simulation. The rate for each size group is calculated by multiplying this rate by the fraction of the corresponding size group in the distribution. The eroded (detached) soil is added to an existing detached (loose) soil depth, from which entrainment to runoff takes place during erosion if the sediment-transport capacity of the runoff water is sufficient. The model maintains a loose soil depth on the bed to keep track of loose soil accumulated from bed materials detached by raindrop impact and from deposited sediment.

Flow-induced erosion and sediment deposition depend on transport capacity of the flow and the sediment load (amount of sediment already carried by the flow). Sediment-transport capacity is computed using established formulas. Based on Alonso et al. (1981), the bed-load formula of Yalin (1963) is used to compute sediment-transport capacities in overland planes under any flow condition and for all size groups. In computing capacities in the channels, the total load formula of Yang (1973) is used for sediment sizes $\geq$0.1 mm (fine to coarse sands) and the total load formula of Laursen (1958) is used for sediment sizes $<$0.1 mm (very fine sands and silts). If the capacity is higher than the sediment load, erosion takes place and the flow picks up more materials from the bed. If the loose soil volume at the bed is sufficient, sediment entrainment takes place from the detached soil depth. Otherwise, the flow erodes additional soil from the parent bed material of the overland plane or channel segment. The potential erosion is the remaining transport capacity after partial fulfillment with the existing sediment load and the loose soil volume, if any. The actual erosion is computed simply by multiplying the potential erosion by a flow detachment coefficient (FDC). The FDC is a distributed calibration parameter, which may have different values for different overland planes and channel segments, depending on resistance to erosion.

If the sediment-transport capacity is lower than the sediment load, the flow is in a deposition mode and the potential rate of deposition is equal to the difference of the two. The actual rate of deposition is computed by taking into account particle fall velocities. Deposited sediment is added to the loose soil volume. If the sediment-transport capacity and the sediment load are equal, an equilibrium condition is

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assumed where there is neither erosion nor deposition. From the actual erosion and deposition, change in bed elevation during a computational time interval is computed.

All these processes are interrelated and must satisfy locally the conservation principle of sediment mass expressed by the sediment continuity equation (Borah 1989b),

$$\frac{\partial Q_s}{\partial x} + \frac{\partial CA}{\partial t} = q_s + g \qquad (17\text{-}39)$$

where

Q_s = volumetric sediment discharge (m^3s^{-1});
C = volumetric concentration of sediment (m^3m^{-3});
A = cross-sectional area of flow (m^2);
q_s = volumetric rate of lateral sediment inflow per unit length of a channel segment (q_s = 0 for overland plane) ($m^3s^{-1}m^{-1}$);
g = volumetric rate of material exchange with the bed per unit length ($m^3s^{-1}m^{-1}$);
x = downslope distance (m);
t = time (s).

Assuming sediment moves with the same velocity of water V, and water discharge Q remains constant within time and space intervals, Equation (17-39) may be written as

$$\frac{\partial A_s}{\partial t} + V\frac{\partial A_s}{\partial x} = q_s + g \qquad (17\text{-}40)$$

where

A_s = sediment load, volume of sediment present in the flow per unit length ($A_s = CA = Q_s/V$) (m^3m^{-1});
V = average water velocity (m s^{-1}).

Equation (17-40) is a quasi-linear hyperbolic equation governing the propagation of sediment load wave and is solved by the method of characteristics (Borah et al. 1981; Borah 1989b). Equation (17-40) and its solution are used to keep track of erosion, deposition, sediment discharge, and bed elevation change along the unit width of an overland plane or a channel segment as described in Borah (1989b) and Borah et al. (2002b).

Time integration of sediment discharges at outlet of any channel segment gives sediment yield from all the upstream areas (overland planes, channel segments, and reservoir units) contributing to the channel. Such a value at the watershed outlet gives the watershed sediment yield.

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