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Overland Erosion of Uranium Mill Tailings Impoundments: Physical Processes and Computational Methods

Prepared by ~~W.~~ H. Walters
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Overland Erosion of Uranium Mill Tailings Impoundments: Physical Processes and Computational Methods

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ABSTRACT

This report reviews the surface runoff and erosional processes of watersheds caused by rainfall-runoff. Soil properties, topography, and rainstorm distribution are discussed with respect to their effects on soil erosion. The effects of climate and vegetation are briefly presented. Regression models and physical process simulation models are reviewed.

ABSTRACT

This report reviews the surface runoff and erosional processes of water-sheds caused by rainfall-runoff. Soil properties, topography, and rainfall distribution are discussed with respect to their effects on soil erosion. The effects of climate and vegetation are briefly presented. Regression models and physical process simulation models are reviewed.

SUMMARY

Pacific Northwest Laboratory (PNL) is studying the mitigation of erosion of earthen suppression covers for uranium mill tailings impoundments. Such erosion may be caused by overland flow resulting from rainfall-runoff and by flood flows. This report reviews surface runoff and erosional processes and the computational methods used to estimate soil losses and sediment yields from watersheds. A report by Walters (1982) discusses the flood erosion problem and rock riprap design methods.

The surface runoff phenomena involve three basic processes: 1) infiltration capacity of soils, 2) overland flow, and 3) throughflow. The infiltration capacity (or rate) of a soil is the vertical movement of water through the soil surface and is largely determined by soil texture, thickness, degree of compaction, and soil moisture content. Overland flow moves over the ground surface, whereas throughflow moves nearly parallel to overland flow just below the soil surface. There are two processes of overland flow: 1) Horton overland flow, and 2) saturation overland flow. Horton overland flow occurs when rainfall intensity is so great that not all the water can infiltrate. This process is more common in the semi-arid western United States where erosion rates are severe. A key reason for these high erosion rates is the region's sparse vegetation; vegetation provides increased infiltration, rainfall interruption, canopy protection from raindrop splash, and thus, reduces overland flow. Saturation overland flow occurs when the upper soil layers become saturated to where the throughflow reaches the soil surface. This process is more common in humid and humid-temperate climates.

The detachment and movement of soil particles by raindrop impact is a critical initial phase of soil erosion. Intense rainfalls can generate extremely high levels of kinetic energy, which under certain conditions may account for high percentages of soil erosion. Important erosive properties of rainfall are drop mass, size, size distribution, direction, terminal velocity, and rainfall intensity.

The simplest computational methods for determining soil losses and watershed sediment yields are regression models. The most widely used of these is the Universal Soil Loss Equation (USLE). This model estimates soil losses on an annual basis and is generally applicable east of the Rocky Mountains. The Modified Universal Soil Loss Equation (MUSLE) estimates both soil losses and sediment yields for single rainfall events and on an annual basis.

Another model group, the physical process simulation models, can formulate the governing processes controlling sediment yield. These processes can be evaluated separately to identify model sensitivity to changing watershed conditions. The Agricultural Runoff Management model (ARM) is a well-documented, contaminant transport model for overland flow that could be used to evaluate the potential for erosion at tailings impoundment locations. Another applicable model is the Multiple Watershed Water and Sediment Routing Model (MULTSED) developed by Simons, Li and Fullerton (1980). The MULTSED model

allows watersheds to be subdivided into smaller components, providing a more accurate physical representation of erosional processes at tailings impoundments.

The Pacific Northwest Laboratory (PWL) is studying the mitigation of erosion of existing impoundments for uranium mill tailings impoundments. Such erosion may be caused by overland flow resulting from rainfall runoff and by flood flows. This report reviews surface runoff and erosion processes and the computational methods used to estimate soil losses and sediment yields from watersheds. A report by Waters (1982) discusses the flood erosion problem and rock trap design methods.

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1.0 INTRODUCTION

The long-term protection of uranium mill tailings piles is a serious concern for the uranium mining industry and for Government regulatory agencies. Of particular concern is the long-term protection from radon gas release. Radium-226 decays to radon gas and is supported by thorium-230, which has a half-life of 80,000 years.

The tailings are permanently stored in impoundments, either above-ground or below-ground, and are to be covered with an earthen cap several feet thick upon decommissioning. The earthen cap will serve as a suppression cover to prevent the release of airborne pollutants. Because all covers will be subjected to rainfall-runoff, the erosion of the cover by overland flow can be both a serious short-term and long-term problem. Some mill tailings impoundment areas will also experience flood erosion. Pacific Northwest Laboratory (PNL) is studying the mitigation of erosion through the use of rock riprap. The overall objectives of the study, sponsored by the U.S. Nuclear Regulatory Commission (NRC), are to develop and recommend generically applicable guidance for the effective use of riprap. This report is a baseline literature research document covering the physical computational methods used to determine soil loss from watershed areas. Although most of the information concerning overland erosion is derived from studies of agricultural soil losses, the same processes and computational methods generally apply to the uranium tailings erosion problem.

This report begins with a synopsis of basic designs of uranium mill tailings impoundments and the earthen suppression covers in Section 3.0. Sections 4.0 and 5.0 discuss the fluvial system of watersheds and the surface runoff processes that typically occur in watersheds. Section 6.0 relates runoff processes to the erosion of land surfaces. Section 7.0 provides details on the factors that influence soil erosion. Finally, Section 8.0 describes the more well-known and accepted mathematical models used to simulate overland erosional processes.

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2.0 CONCLUSIONS AND RECOMMENDATIONS

Surface runoff and erosion involves three basic processes: 1) infiltration, 2) overland flow, and 3) throughflow. Infiltration is the vertical movement of water through the soil surface and into the the upper soil zones. The major variables influencing the infiltration capacity of a soil are soil texture, thickness, degree of compaction, and soil-moisture content. The infiltration capacity controls the relationship between overland flow and throughflow. Overland flow travels over the ground surface, whereas throughflow travels just below the ground surface. There are two processes of overland flow: 1) Horton overland flow and 2) saturation overland flow. Horton overland flow occurs where rainfall intensity exceeds the infiltration capacity of a soil and saturation overland flow occurs when the upper soil layers become saturated to where throughflow reaches the soil surface. Horton overland flow is more common in the semi-arid western United States where vegetation is sparse and the soils are shallow and tend to crust-over between rainfall events. Saturation overland flow is more prevalent in the humid eastern United States.

A significant process in overland erosion is the loosening of soil by raindrop impact. Under certain conditions this process may account for as much as 90% of the erosion from agricultural lands. The properties of rainfall contributing to the kinetic energy of raindrop impact are drop mass, size, size distribution, direction, rainfall intensity, and raindrop terminal velocity. A rainfall with an intensity of 2 in./hr can generate, in 30 minutes, a kinetic energy of about 2 million ft-lbs; rainsplash has been observed to move 4-mm rock particles up to 20 cm. This would imply that small gravel sizes may not provide sufficient armoring against raindrop erosion.

The highest annual sediment yields in the United States occur typically in the semi-arid western regions where annual precipitation varies from 10 to 15 inches. Primarily, the semi-arid areas experience more erosion because they lack vegetal bulk, which depends on adequate precipitation, and because of high intensity, short-duration thunderstorms that are extremely erosive. One research study indicates that at least 70% ground cover is required to reduce overland flow and erosion to a point of stability. If annual precipitation decreases below 10 inches (arid regions) or increases beyond 15 inches (humid regions) the erosion rates decrease. Erosion rates are lower in arid regions simply due to the lack of water. The more humid regions have a higher and more even distribution of rainfall and, therefore, can support a thicker vegetative cover. The implications are that uranium tailings impoundments located in semi-arid areas will experience more severe erosion problems than those in other areas and that Horton overland flow will be the primary cause of soil loss from tailings impoundments.

The computational methods for overland flow and erosion include both regression models and physical process simulation models. Two examples of regression models are the Universal Soil Loss Equation (USLE) and the Modified Universal Soil Loss Equation (MUSLE). The USLE estimates soil losses on an

annual basis and is the most widely accepted, whereas the MUSLE estimates both soil losses and sediment yields for single rainfall events, and on an annual basis. The MUSLE is relatively new and lacks the application experience of the USLE. Soil loss represents the amount of sediment loosened from its original source but not necessarily removed from the field because deposition can occur at other field locations. Sediment yield is the net amount of soil actually removed from a field.

Although limitations exist regarding the applicability of the USLE in the western states, it still may be useful for determining erosion rates for tailings impoundments. The impoundments are small compared to most watersheds and only estimates of soil loss may be of interest. Also, detailed information will be available on the impoundment geometry and soil composition.

The physical process simulation models are based on mathematical simulations of the overland erosion processes and would provide the best estimates of sediment losses and yields from uranium tailings impoundments and surrounding watershed areas. This group of models simulates processes such as raindrop splash erosion, surface runoff, overland flow erosion and throughflow. Perhaps the most applicable physical process simulation model for uranium tailings locations and impoundments is the Multiple Watershed Water and Sediment Routing Model (MULTSED). This model is also referred to as a complex watershed model in that it relies on the subdivision of the watershed into smaller components that are linked together by representation of the actual watershed channel network. Simplified versions of this model (onsite erosion models) have also been developed.

Both types of models could be applied to the analysis of soil erosion at a uranium tailings site. The USLE and MUSLE could quickly determine the relative differences in erosion potential of the impoundment location in the watershed. Also, the erosion potential of various impoundment sideslopes could be evaluated. Because the USLE was developed from field plot data east of the Rocky Mountains, its accuracy is generally limited to that region, and may not apply to the high-intensity, short-duration rainfalls experienced in the semi-arid regions. The MUSLE is more applicable to semi-arid climates, but it requires calibration of two coefficients (except for certain areas in Texas and Nebraska). The physical process simulation models, such as MULTSED, would provide much more information on site-specific erosion problems, including the determination of possible deposition areas where erosion would not be a problem. MULTSED would also allow a more meaningful sensitivity analysis with respect to changing conditions at each site. The main drawbacks to the physical process models are the data requirements necessary to describe the study area.

3.0 URANIUM MILL TAILINGS

Uranium mill tailings are the solid residues and associated liquids that remain after uranium has been extracted from the ore. The solids consist primarily of the finely ground bulk of the original ore and a variety of chemicals precipitated from tailings liquids. The wastes are disposed of in waste retention systems, referred to as tailings impoundments. The basic designs and operating objectives for the impoundments are to provide physical and chemical stability of the tailings and to limit the escape of contaminants to acceptable low levels.

After the impoundment is decommissioned, the problems of control, surveillance, and maintenance of the tailings will last long into the future. The severity of some of these problems is dictated by the fluid properties of the slimes, adverse climatic and rainfall conditions leading to impoundment erosion, seepage, and acid production from ores containing pyrites (Thomas 1981). One isotope that is a cause for concern is radon-222. Although radon has a short half-life of 3.8 days, it is produced continuously by radium-226, which has a half-life of 1600 years. The emanation of radon-222 could continue for thousands of years as the activity of radium-226 is in equilibrium with thorium-230, which has a half-life of about 80,000 years. Realistically, the continued presence of the parent radionuclides over such long periods of time does not seem probable. For some assessments, a mean residence time of 1000 years has been assumed for radium and thorium (Thomas 1981).

3.1 IMPOUNDMENT DESIGNS

The decommissioning of tailings impoundments assumes that resources will no longer be available to monitor or maintain the impoundment site. In recent years efforts have been under way to improve the techniques for managing mill tailings; these efforts include the development of better impoundment designs and placement techniques.

Deep mines below the surface have been considered but have been rejected because of insurmountable problems caused by long transportation distances, ground-water contamination potential, and institutional barriers (U.S. Nuclear Regulatory Commission 1980). Only above-grade and below-grade (near the surface impoundments) have been used in the United States. Typical designs for both these types of impoundments are shown in Figure 3.1.

3.1.1 Below-Grade In-Pit Impoundment

The U.S. Nuclear Regulatory Commission (1980) has recommended the below-grade, near-surface, in-pit disposal for impoundment design. This design minimizes the potential for long-term detrimental effects. Tailings are placed by discharging the tailings slurry into the prepared pit.

FIGURE 3.1. Diked Surface Impoundment/In Pit or Natural Basin
(after Robertson, Bamberg and Lange 1978)

The use of the in-pit design offers several advantages. This design eliminates the need for a specially constructed retention structure and does not create a prominent surface feature. The low-surface profile of this design reduces the chances of long-term disturbance by natural erosional forces. The amount of earthen material required for the cover liner is reduced because pit depths and steep walls can be used to minimize the tailings surface area. Also, because the tailings are confined within excavated walls, the failure hazards of above-ground impoundments are significantly reduced.

Disadvantages are also associated with in-pit disposal. The most critical disadvantage is the proximity to the water table, compared to the above-grade design. The long-term performance of the below-grade design is questionable because of possible increases in water table elevations in response to climatic changes. In addition, pit excavations could penetrate soil and rock strata that intersect confined ground-water aquifers. Another disadvantage occurs when backfill is used to raise the tailings above the ground-water table: this could lead to differential settlement along the impoundment, which in turn, could cause the liners or radon suppression cap to rupture.

3.1.2 Above-Grade Impoundment

When geologic or topographic conditions preclude the use of below-grade impoundments, above-grade impoundment designs are acceptable if they protect the tailings from natural erosional forces. Two typical designs of above-grade tailings piles are the valley dam and ring dike impoundments.

Valley Dam Impoundments

A valley dam impoundment basin is created by constructing a dam wall across a small valley, as shown in Figure 3.2. Liquid wastes are confined

within the basin by strata with naturally low permeabilities or by an impermeable liner placed over the basin floor. The tailings slurry is discharged into the basin near the upstream face of the dam, forming a beach area sloping away from the dam.

The valley dam design uses natural topographic features where the valley provides three sides of the impoundment; thus, only a single dam structure is needed to confine the tailings. This procedure is economical and presents less risk of failure than do multiple dike designs. Another advantage is that the shape of the valley restricts seepage and surface flow to a known path, greatly simplifying monitoring and control measures.

On the other hand, the valley dam impoundments have important hydrological disadvantages. Because of the valley location, runoff from the upstream drainage network is naturally directed toward the impoundment and must be diverted around the dam. The larger the upstream catchment area the more extensive the diversion works need to be. Also, a maintenance and surveillance program may be required to ensure long-term stability. Other disadvantages concerning the site hydrology involve the ground water. Because the horizontal permeabilities along most valley floors can be expected to be high, cutoff walls and liners will have to be installed. Valley floors also tend to have the shortest travel distances to the ground-water table.

Ring Dike Impoundments

The cross-section of a ring dike impoundment is shown on the left-hand side of Figure 3.1. Construction methods for the dikes are similar to those for the valley dam design. Ring dike designs allow for any shape of impoundment and can be adapted to blend with the surrounding topographic features.

FIGURE 3.2. Typical Cross-Section of a Valley Dam Impoundment
(after Robertson, Bamberg and Lange 1978)

Ring dikes allow flexibility in site selection and can generally be located close to the mining operation, permitting the economical use of overburden material for dike construction or impoundment cover material. Ring dikes can be located away from flood plain areas to reduce their susceptibility to erosion by major floods.

The primary disadvantage of ring dike designs is that extensive use of embankments increases the long-term probability of failure and seepage losses. Also, the relatively high elevation of a ring dike above the surrounding land surface makes it more susceptible to erosion by lateral flows.

3.2 RADON SUPPRESSION COVER DESIGN

A review of environmental impact statements issued by many of the currently active mill sites indicates that the proposed cover designs are all very similar and adhere to a 3-meter-thick criterion (Young, Long and Reis 1982). Because most soils in arid and semi-arid regions are shallow, the amount of soil available for earthen covers is limited. For this reason, overburden material probably will be used for cover construction. Most of the overburden will contain no organic matter and will have poor structure and water-holding capacity. The cover material will probably be uncompacted and have only residual moisture content, except for the steeper slopes.

4.0 THE FLUVIAL SYSTEM

Although surface runoff processes occur throughout the fluvial system, they are more dominant in certain areas. The relationship of runoff processes as they pertain to erosion and stability of the fluvial system has been documented by Schumm (1977).

Uranium mill tailings impoundments will be located within one of three zones of the fluvial system, shown in Figure 4.1. Zone 1 is the upper drainage basin or watershed area from which most of the water and sediment are derived; therefore, it is primarily an area of sediment production. Zone 2 is the transfer zone where the input of sediment closely approximates the output as long as the transporting channels are stable. Zone 3 is an area of sediment deposition.

Although the processes of erosion, transport, and deposition occur in all three zones, one process is usually dominant in each zone. Zone 1 is dominated by high overland erosion rates and (generally) low flood levels. Whereas Zone 1 flood volumes are usually less than those in the downstream zones, they do contribute to the increased erosion rates because the flow velocities can be extremely high as a result of the much steeper slopes. Also, the upper basin areas of Zone 1 are smaller and more easily covered by single storm events, which when combined with the steep slopes, can produce flashy and erosive floods. The surface drainage network of Zone 1 undergoes continual geomorphic change and development because of the relatively higher erosion rates.

Zone 2 is dominated by major river channels, including the lower segments of tributaries, and by flood plains. Although scour and deposition of sediment

FIGURE 4.1. Idealized Fluvial System (after Schumm 1977)

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occurs in this zone, the dominant process is sediment transport through the river channel system to Zone 3. The flood levels are much higher in Zone 2, where the flow frequently exceeds the capacity of the channel and sweeps across the flood plain.

The incoming sediment to Zone 3 is deposited on alluvial fans, alluvial plains, river deltas, or in deeper waters. The channels in Zone 3 are mostly distributary channels for the inflowing sediment and water and are usually extremely unstable because of the rapid deposition of sediment.

Uranium mill tailings impoundments are located primarily where the dominant processes are overland erosion (Zones 1 and 2) and erosion and transport by channel flow (Zone 2). This report addresses the overland flow and erosion processes only. A report by Walters (1982) addresses the stream channel flood flow problem with respect to erosion and riprap protection.

Overland erosion has been primarily an agricultural problem; much of the research into the processes of surface runoff erosion was directed toward farmland erosion. Other areas receiving similar attention in the past are deforestation, erosion of highway embankments, and erosion of disturbed areas during construction or mining.

5.0 SURFACE RUNOFF PROCESSES

Surface runoff processes refer to the movement of water, primarily derived from rainfall, over and through the surficial soils of a watershed to the major drainage system. Three basic processes can be identified with surface runoff: 1) infiltration, 2) throughflow, and 3) overland flow. Infiltration is the vertical movement of water through the soil surface and into the deeper and less-permeable soil horizons. The infiltration capacity of a soil is largely determined by soil texture, thickness, degree of compaction, and soil-moisture content, and controls the relationship between overland flow and throughflow. Throughflow involves water immediately below and moving nearly parallel to the surface, whereas overland flow is runoff moving over the surface. The relationship between the three processes is shown in Figure 5.1.

5.1 INFILTRATION

Infiltration may be considered a three-step sequence: 1) surface entry, 2) transmission through the soil, and 3) depletion of storage capacity in the soil (Chow 1964). The infiltration of water through the soil surface is directly affected by the inwash of fines or other particle arrangements that

FIGURE 5.1. Flow Processes Over and Within the Soil

prevent or retard the surface entry. Soils may have good permeability characteristics for drainage but may be sealed at the surface and have a low infiltration rate.

Water cannot continue to enter the soil more rapidly than it is transmitted downward and the transmission rates will vary for successive horizons of the soil profile. When the soil becomes saturated, the rate of infiltration is limited to the lowest transmission rate encountered by the infiltrating water up to that time. However, if the surface entry rate is slower than the transmission capacity of any horizon, infiltration is limited to the surface-entry rate throughout an entire storm.

Storage capacity of the soil has a direct effect on infiltration rates. If the transmission rates through the soil strata are controlling infiltration, the infiltration rates will diminish as storage above a restricting layer is depleted. The infiltration rate will then be equal to the rate of the restricting layer until a more restrictive layer is reached.

When the infiltration capacity of a soil is exceeded, the excess rainfall becomes surface runoff. Overland erosion takes place under these conditions. Investigations into overland erosional processes by Horton (1939) led to the development of an equation for infiltration, based on work-energy principles, which describes this process. According to Horton, the infiltration capacity, f , of a soil is controlled primarily by soil texture, soil structure, vegetational cover, biological structures in the soil, moisture content of the soil, and conditions of the soil surface. Infiltration capacity is defined as the maximum sustained rate at which a particular soil can transmit water. The rate varies during a rainstorm where it is initially quite rapid, f_0 , but declines with time to a constant value, f_c . The minimum infiltration capacity predominates during most long rainstorms. If the rate of precipitation exceeds the infiltration capacity, water accumulates on the surface and runoff results. For a rainfall period, t , the infiltration capacity, f , is expressed as:

$$f = f_c + (f_0 - f_c) e^{-kt} \quad (5.1)$$

where

f_0 = initial infiltration rate (in./hr)

f_c = final infiltration rate (in./hr)

k = proportionality factor

e = the base of Napierian logarithms.

The value of f drops off rapidly at first, then more slowly as it approaches f_c . Between rainfall events, the value of f approaches its initial value as the soil dries out and the crumb structure is restored. The parameter k is a function of soil and vegetation and the infiltration rates are 'capacity' rates, indicating that the rainfall rate is assumed to be always greater than infiltration capacity rates. Therefore, some ponding will always result. Horton's equation primarily applies under these conditions. This can be a major disadvantage in the application of the equation to all infiltration conditions because rainfall rates are highly variable and will fall below the

values of capacity infiltration rates (Overton and Meadows 1976). Whereas Horton's equation suffices for overland flow conditions, other equations are available that are valid for a wider range of infiltration processes. A discussion of these equations can be found in Gray (1973) and Overton and Meadows (1976).

The actual infiltration capacity of a drainage basin is difficult to measure at any one point in time because of the variation in soils and the continual changes taking place in the quantity of precipitation stored by the soil. Infiltration is also controlled by moisture conditions that exist before the onset of rain. In addition, infiltration varies with the seasons because these control the state of vegetation. Areas with vegetation have a higher infiltration capacity than barren areas.

Infiltration capacity is usually determined by field measurements on experimental plots. The amount of runoff is measured that results from a known quantity of artificially applied rainfall. From the relationship:

$$\text{Precipitation} = \text{Infiltration} + \text{Runoff}$$

an approximation of infiltration can be obtained.

5.2 OVERLAND FLOW

Overland flow, as defined by Horton (1939, 1945), is flow over the land surface that occurs when rainfall intensity is so great that not all the water can infiltrate. This type of overland flow is quite common under semi-arid climatic conditions, but is relatively rare under humid and humid-temperate conditions. The role of vegetation is a critical factor in this distinction. Vegetation increases the infiltration rate by promoting a thicker soil cover and a better soil texture, and by breaking the impact of raindrops on the surface. When raindrops strike an unprotected soil, fine surface material is thrown into suspension by the impact and is redeposited as a nearly impermeable glaze, which can lower the infiltration rate by as much as ten times (Kirkby 1971a). Therefore, vegetation influences overland flow by increasing both the initial depression storage and the infiltration capacity; thus, where dense vegetation cover is established, overland flow is unusual.

When the infiltration capacity of the soil is exceeded and the rain continues, the excess water initially collects in depressions on the ground surface. These depressions provide what is known as depression storage, shown in Figure 5.1.

As the rain continues, an overflow of depression storage occurs; however, flow does not begin until a water layer of some finite depth is developed. Several observers have noted in desert and tropics alike that after several minutes of rain, the land surface will suddenly appear to shine or glisten like a slick as overland flow begins (Leopold, Wolman and Miller 1964). This layer

of water at any moment is known as surface detention and represents water in transit. The detention increases with increasing distance away from the crest of the slope.

Another type of overland flow is saturation overland flow. This can occur whenever permeability is decreasing downward within the soil, causing a lateral deflection of the downward percolating water within the upper layer. If rainfall continues for a long time, the soil layers become saturated and the lateral subsurface flow is deflected closer and closer to the surface so that the upper, more permeable soil layers are filling up. When the soil becomes saturated up to the surface, the process of saturation overland flow will occur. Under steady rainfall, this condition will occur for rainfall intensities much lower than are required for Horton overland flow. The subsurface flow that is deflected toward the surface is also described as throughflow. The process of throughflow and associated equations are discussed in Section 5.3. Saturation overland flow and throughflow predominate in humid and humid-temperate areas, and are of less importance under more arid or less-vegetated conditions with thin soils.

Sections 5.2.1 through 5.2.5 present the equations that can be used to evaluate Horton overland flow. These equations illustrate the basic variables involved in the overland flow processes. Other equations describing the same processes are discussed in Chow (1964), Gray (1973), and Overton and Meadows (1976).

5.2.1 Depth of Horton Overland Flow

If the flow is turbulent, the variation of the water-surface profile with distance can be approximated by the following relationship (Leopold, Wolman and Miller 1964):

$$d \sim \left(r \frac{x}{ln} \right)^{3/5} \quad (5.2)$$

where

d = depth of water on the surface (in.)

r = supply rate (roughly equal to rainfall minus infiltration rate in in./hr)

l = total length of slope over which overland flow occurs (ft)

n = roughness coefficient (hr/ft^{1/3})

x = distance down the slope from the watershed divide (ft).

5.2.2 Velocity of Horton Overland Flow

The velocity of flow is given by Mannings equation (Leopold, Wolman and Miller 1964):

$$V = \frac{1.49}{n} d^{2/3} s^{1/2} \quad (5.3)$$

where

- V = mean velocity (ft/sec)
- d = depth of water on the surface (ft)
- s = slope (ft/ft)
- n = roughness coefficient (sec/ft^{1/3}).

Overland flow provides the force necessary to remove and transport soil particles on the ground surface. Equations (5.1) through (5.3) indicate that the water surface and depth, and therefore the available force of flowing water, are functions of six variables: 1) rainfall intensity, 2) infiltration capacity, 3) length of overland flow, 4) slope, 5) surface roughness, and 6) degree of turbulence or the type of flow.

The Mannings equation for the velocity was developed for open channel flow conditions where the flow is fully turbulent and the velocity is proportional to the square root of the slope. For overland flow the depth is exceedingly small and if the flow is nearly laminar, the exponent of slope may be larger (Leopold, Wolman and Miller 1964).

5.2.3 Runoff Discharge

The depth of overland flow is likely to be extremely small and measured in fractions of an inch. Based on Horton's (1945) example: 1 in./hr equals 1 ft³/sec/acre (1 acre = 43,560 ft²). The intensity of runoff, q_1 , in cfs from a strip 1 foot wide and a slope length, l , will be:

$$q_1 = q_r \left(l \frac{1}{43,560} \right) = 0.000023 \, l \, q_r \quad (5.4)$$

where q_r = runoff in inches per hour. Because discharge in the unit strip is also depth, d , times velocity, V , then:

$$q_1 = \frac{dV}{12} \quad (5.5)$$

where depth is in inches and velocity in feet per second. Therefore,

$$d = \frac{0.000277 \, l \, q_r}{V} \quad (5.6)$$

On a slope 100 feet long a velocity of 0.25 ft/sec at a depth of 0.11 inch will produce 1 inch of runoff per hour. Although the velocity and depth are exceedingly small, the flow is large and its capacity to erode is significant.

5.2.4 Horton Overland Flow Depth Versus Distance

By substituting the Manning Equation (5.3) for velocity in Equation (5.6), an equation can be derived for the depth of overland flow in terms of distance, x , from the watershed divide, runoff intensity, q_r , slope angle, and surface roughness, n (Leopold, Wolman and Miller 1964):

$$d_x = \frac{q_r n \times 3/5}{1020} \frac{1}{\tan^{0.3} \alpha} \quad (5.7)$$

5.2.5 Surface Roughness

The magnitude of the roughness factor, n , is similar to the values for river channels. Values for overland flow in sprinkled-plot experiments vary from 0.10 to <0.05 (Leopold, Wolman and Miller 1964). Whereas boundary resistance resulting from surface roughness of experimental plots may be similar to that for streams, highly increased resistance may occur because of surface obstructions such as vegetation, plant debris, stones or gravel.

5.3 THROUGHFLOW

Some of the water that infiltrates into the soil passes downward to recharge the water table, but the greater part flows down the hillside within the soil layers as throughflow and ultimately contributes to streamflow. Within a soil, the permeability varies and is generally highest in the upper layers. When permeability decreases downward within the soil, a part of the percolating water cannot penetrate into the lower layers fast enough, and is deflected laterally within the upper layer as throughflow.

The velocity of throughflow traveling through soil pore spaces is much lower than for overland flow. Rates of 20 to 30 cm/hr for throughflow are about a thousand times lower than overland rates, so that periods of about 1000 hours of rainfall are needed for steady-state conditions throughout an average basin (Kirkby 1971a). Because a steady-state is never attained for throughflow the equation for overland flow must be replaced with the equation for throughflow (Kirkby 1971a):

$$q_t = (p - f_b) vt \quad (5.8)$$

where

q_t = throughflow discharge per unit topographic contour length

p = rate of surface percolation equal to rainfall intensity after interception, or the infiltration rate, whichever is smaller

f_b = rate of infiltration at the base of the more permeable soil

v = velocity of throughflow

t = time elapsed.

For this equation, time elapsed is the most important control over the flow in place of the distance from the divide for overland flow.

Little or no outflow occurs from various depths in the soil during the initial transmission period. This is followed by a period during which outflow increases rapidly until the rainfall ceases, after which the outflow will decrease more slowly than it increased, resembling a flood hydrograph for a stream.

The equation for throughflow contains an unknown quantity: the velocity of throughflow, v . To evaluate throughflow more exactly, we use Darcy's Law. Darcy's Law, which states that flow through a permeable medium is to the pressure gradient, is combined with the continuity equation, which states that differences between inflow and outflow must be accommodated by changes in moisture content. For a soil layer of uniform permeability and moisture content (in depth) Darcy's Law for soil on a slope is (Kirkby 1971a):

$$Q = Z \cos \alpha (Km \sin \alpha - D \frac{\partial m}{\partial x}) \quad (5.9)$$

and the continuity equation is

$$\frac{\partial m}{\partial t} + \frac{\partial Q}{\partial x} = i \quad (5.10)$$

where

- Q = the downslope discharge measured in a horizontal direction
- x = the distance downslope measured in a horizontal direction
- K = the soil permeability (a function of soil moisture)
- D = the soil diffusivity (a function of soil moisture)
- α = the surface slope angle
- m = the soil moisture content
- Z = the thickness of the soil layer
- i = the rainfall intensity after interception
- t = the time elapsed.

The permeability term, K , is the more important for intermediate values of moisture, whereas the diffusivity term, D , becomes dominant at extreme low and high values of moisture. Only the high moisture case is of interest when the moisture content is approaching saturation. In this case soil moisture is constant and the continuity equation becomes:

$$\frac{\partial Q}{\partial x} = i \quad (5.11)$$

In practice this means that the near-saturated soil zones respond very rapidly to changes in rainfall intensity, even before overland flow begins. Equations (5.9) and (5.10) also provide a basis for assessing the influence of changing gradient or (with slight modification) of contour curvature on the throughflow discharge within the soil. Four regions of a slope are the most likely to become saturated, and hence contribute to more frequent saturation overland flow: 1) areas adjacent to streams, 2) areas of concave upwards slope profile, 3) hollows, and 4) areas with thin or impermeable soils.

6.0 EROSION BY SURFACE RUNOFF

Water detaches and transports soil by raindrop impact, overland flow over the surface, throughflow within the upper soil mantle, and by forming and enlarging networks of rills and gullies. Rainsplash detaches soil particles and produces a net downhill transport of material. Throughflow transports material in solution and in suspension within the upper soil mass, along lines of greater permeability or through small tunnels that are formed by the process. Overland flow transports soil particles detached by rainsplash and may erode distinct channels.

In humid and sub-humid regions natural vegetation helps bind the soil particles and reduces the flow velocity of surface water. Under undisturbed conditions, natural processes will usually create about as much soil as they remove. Removal of the vegetation greatly accelerates the erosion process. In semi-arid and arid regions vegetation is scarce and most topsoils are shallow and of poor quality. Erosion rates naturally tend to be higher in these regions than in others because during summer thunderstorms high-intensity rainfalls do occur, even though the precipitation is not sufficient to sustain an effective vegetative cover.

When rainfall rates exceed the infiltration capacity of a soil, the Horton overland flow and erosion process begins. The effectiveness of raindrops in detaching soil particles depends on the intensity of the rainstorms and at what season they occur. Generally, summer thunderstorms are the most severe. High rainfall intensities produce large raindrops with high velocities which can be magnified by wind speed and direction. The more intense the rainfall, the larger the soil fragments that are detached.

The removal of thin layers of soil from slopes is known as sheet erosion. Rill erosion occurs coincident with sheet erosion as water is gradually concentrated into definite channels. If rills continue to develop they tend to form gullies. Once gullies are formed, they can grow very rapidly, sometimes as much as a hundred feet a year headward in farmlands. The American Society of Civil Engineers (1975) draws the following distinction between rill and gully erosion: Rill erosion is the removal of soil by small concentrations of flowing water, with the formation of channels that are small enough to be smoothed completely by normal cultivation methods. Gully erosion is the removal of soil by concentrations of flowing water sufficient to cause the formation of channels that could not be smoothed completely by normal cultivation methods. The processes of rill and gully erosion are discussed in more detail in Section 6.2

6.1 RAINDROP EROSION

As research into the problem of agricultural erosion progressed in the 1930s, researchers realized that the amount of soil in runoff increased rapidly with raindrop energy, and that erosion could be greatly reduced by preventing

raindrop impact. Based on this research, it was recognized that the detachment and movement of soil particles by raindrop impact is an important initial phase of soil erosion. Under certain conditions, as much as 90% of erosion of agricultural land may result from this process (Cooke and Doornkamp 1974).

The major erosive factors of rainfall are drop mass, size, size distribution, direction, rainfall intensity, and raindrop terminal velocity. From these variables, the kinetic energy [$1/2 \text{ mass} \times (\text{velocity})^2$] and momentum ($\text{mass} \times \text{velocity}$) can be determined.

The median size of raindrops increases with rainfall for low- and medium-intensity rainfalls, as described by the following equation (Cooke and Doornkamp 1974):

$$D_{50} = aI^b \quad (6.1)$$

where

D_{50} = median size of raindrops (mm)

I = intensity (mm/hr)

a, b = constants.

The drop size decreases slightly for high intensity rainfalls where the maximum drop sizes are on the order of from 5 to 6 mm in diameter.

When a raindrop has reached terminal velocity the gravitational force is equal to the frictional resistance of the air. Because the fall distances required to reach maximum fall velocity are so short, most drops will strike the surface at their terminal velocity. Air turbulence and winds will also affect the terminal velocity during rainstorms.

In experimental studies, Wischmeier and Smith (1958) investigated the kinetic energy produced by the intensity of the 30-minute rainfall. The magnitude of kinetic energy generated by different rainfall intensities is shown in Figure 6.1. The curve in Figure 6.1 indicates that an intensity of 2 in./hr generates, in 30 minutes, a kinetic energy of slightly more than 2 million ft-lb/acre. This would be sufficient to raise an acre furrow slice by 1 foot. A rain of 8 in./hr intensity would produce, in 30 minutes, enough energy to raise an acre-ft of soil almost 3 feet (Copeland 1963). Although this represents cumulative energy generated over the 30-minute time period, it does provide an indication of energy that can be generated by rainfall.

Rainsplash does not move soil alone. On a level surface, rainsplash can move 4-mm rock particles distances up to 20 cm; 2-mm particles up to 40 cm; and smaller particles up to 150 cm (Kirkby 1971b). The particles are not transported in any one direction but are part of a random exchange.

The process of soil splash is defined by the relationship between rainfall, soil detachment, and transportation. Empirical studies have shown that splash erosion of sand was proportional to $(\text{kinetic energy})^{0.9}$; for soil, it was proportional to $(\text{kinetic energy})^{1.46}$ (Cooke and Doornkamp 1974). Soil

FIGURE 6.1. Kinetic Energy per Acre Produced by 30-Minute Rainfalls of Different Intensities--Constructed from Data by Wischmeier and Smith (1958), (adapted from Copeland 1963)

splash also depends on the detachability and transportability of the soil and the degree of vegetation cover. Soil loss can be greatly reduced by vegetative cover; however, this varies with the type and degree of cover. The ease with which soil can be detached by raindrops depends on the factors affecting soil consolidation (e.g., clay, stone, base, and organic-matter content). The slope of the surface is also important. If the surface is horizontal, splash erosion will occur but would not result in an overall loss from the field.

Ellison (1952) investigated the rainfall-runoff erosion process through a series of field plot studies. His studies identified the processes of sheet-erosion where the splashing raindrops and flowing surface water act in concert to produce the erosion. One of the first processes to be initiated takes place when the runoff water, made turbulent by raindrop splashes, helps to transport the detached particles downslope. Ellison further states that runoff erosion caused by rainfall-generated turbulence is not the same as the popular concept of a sheet of flowing surface water stripping away a thin layer of soil from a slope. Thin films of water may assist in soil transport but do not develop

erosive velocities. According to Ellison, scour and erosion do not occur until flow along very narrow lines of action sufficient velocity to carve rills and gullies.

The effects of raindrop diameter and fall velocity are shown in Table 6.1. The drop diameter in experiments 4, 5, and 6 (see Column 1) was approximately one and a half times as large as for experiments 1, 2, and 3. For nearly identical drop velocities in Experiments 1 and 4, the grams of soil eroded by splashing approximately double with the increased drop diameter.

Sheet erosion is also produced by splashes of raindrops falling on slopes, acting alone without the assistance of runoff. Splashing action on slopes can beat soils downslope in much the same way that they beat down and level a pile of sand in an open yard. Ellison states that this is one reason why splashing will cause surface soils to creep toward the base of a slope. His experimental measurements indicated that about three times more soil is transported downslope than is transported upslope on a 10% slope.

6.2 RILL AND GULLY EROSION

Most small ground-surface depressions do not develop into linear channels; however, nearby eroded channels that do form must begin with the concentration of flow in some of these small depressions. An analysis by Horton (1945) shows that a critical distance from the divide may be calculated, at which the hydraulic power of the flow initiates channel heads a short distance below a slope divide. Below this line there should be a set of rills, or shoestring gullies, covering the hillside. The critical distance is controlled by the overland flow intensity, the gradient, the surface roughness, and vegetation density and strength. A rill system such as this does not generally last for very long, but is rapidly converted into a normal dendritic network as a few dominant rills are enlarged to form gullies.

TABLE 6.1. Effects of Raindrop Velocities and Sizes on Soil-Splash
(after Ellison 1952)

<u>Expt.</u>	<u>Drop Diameter, mm</u>	<u>Rainfall Intensity, in./hr</u>	<u>Drop-fall Velocity, ft/sec</u>	<u>Splash, grams of soil</u>
1	3.5	4.8	18.0	227
2	3.5	4.8	14.5	68.0
3	3.5	4.8	12.0	15.3
4	5.1	4.8	19.2	526
5	5.1	4.8	15.0	209
6	5.1	4.8	12.0	28.0

Horton described the process of cross-grading, where water overtops the small divides between adjacent rills and leads to the progressive diversion of water into the lower-level rills. By this process an overall gradient is developed at an angle to the direction of rill flow. Where rills exist, cross-grading may be an important process of drainage network integration; however, rill systems are only common on slopes with sparse vegetation, such as those located in semi-arid to arid climates. Some distinctions that govern the location and process of gully development depend basically on whether gullies are developed by: 1) saturation overland flow or 2) Horton overland flow.

Saturation overland flow produces localized gullying, for example, in areas adjacent to streams, areas of concave-upward slope profiles, areas of thin or impermeable soils, and hollows. These areas are strongly influenced by local soil conditions and valley shape because throughflow, which causes saturation overland flow to develop, travels so slowly that the water flows only a short distance while the rain is still falling. Distance from the divide is, therefore, not a control on the location of gullies which arise from saturation overland flow.

To define the Horton overland flow process, we may calculate a critical distance from a divide at which the hydraulic power of the flow is great enough to overcome the strength of the soil and vegetation mat and erode a channel. The critical distance from the divide is controlled by the overland flow intensity, the gradient, the hydrodynamic roughness of the surface, and the strength of the vegetation mat. Beginning at a basin divide, most natural slopes are convex-upward and gradually make the transition into concave-upward. Therefore, the area of steepest gradient is at the inflection point of the slope profile. The greatest erosive force resulting from overland flow is a short distance downslope from this area. Here the Horton overland flow may be expected to initiate gullies. Another distinction is that Horton overland flow can initiate gullies that may be entirely separate from the main channel network, whereas saturation overland flow generally extends existing channel systems.

The distribution of overland flow, and how it affects the exact positions of gully and stream heads, influences not only the form of the slope profile but also the texture of the drainage net. A small change in the position of stream heads has a major effect on drainage density. Gullying appears to be the beginning of accelerated erosion: gullying produces a small valley, which diverts more water into the gully, which in turn increases the rate of erosion.

Horton described the process of cross-grading, where water overtops the small divides between adjacent hills and leads to the progressive division of water into the lower-level hills. By this process an overall gradient is developed at an angle to the direction of hill flow. Where hills exist, cross-grading may be an important process of drainage network integration; however, hill systems are only common on slopes with sparse vegetation, such as those located in semi-arid to arid climates. Some distinctions that govern the location and process of gully development depend basically on whether gullies are developed by: 1) saturation-overland flow or 2) Horton overland flow.

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7.0 FACTORS INFLUENCING RATES OF EROSION

The factors that control the rate of soil erosion fall within four major groups: 1) the depth, permeability, and other properties of the soil, 2) the land gradients (topography), 3) spatial and temporal distribution of rainstorms that can produce overland flow, and 4) the amount of vegetative cover.

7.1 SOIL PROPERTIES

Natural susceptibilities of soils to erosion are difficult to quantify from field observations. A relatively erosion-resistant soil may show signs of serious erosion when it is found on long or steep slopes or in areas with numerous high-intensity rainstorms. An easily erodible soil, on the other hand, may show little evidence of actual erosion under gentle rainfall when it is on short and gentle slopes, or when optimum management is practiced.

A soil's inherent erodibility, which is a major factor in erosion prediction and land-use planning, is a complex property that is determined by its infiltration capacity and the capacity to resist detachment and transport by rainfall and runoff. Wischmeier and Mannering (1969) and Wischmeier, Johnson and Cross (1971) investigated the relationships of these capacities to physical and chemical properties of soil during a five-year field, laboratory, and statistical study. They identified five soil parameters as prime considerations in predicting soil erodibility: 1) percent silt plus very fine sand, 2) percent sand greater than 0.10 mm, 3) organic matter content, 4) structure, and 5) permeability. The first two parameters listed above can be grouped under the category of particle-size distribution as determined by sieve analysis.

7.1.1 Particle-Size Distribution

In general, soil erodibility increased with greater silt content and decreased with greater sand, clay, and organic matter contents. However, the ability of these parameters to predict erodibility either singly or in combination was disappointing. To overcome this problem, a more meaningful boundary line between sand and silt classifications was introduced. The analysis of soil erodibility data had shown conclusively that particles in the very fine sand classification (0.05 to 0.10 mm) behave more like silt than like larger sand particles. Therefore, when silt was redefined to include very fine sand, and sand particles were defined as from 0.10 to 2.0 mm, the prediction capability improved appreciably.

7.1.2 Organic Matter

Organic matter content ranked next to particle size distribution as an indicator of erodibility. As the content of organic matter increased, more rainfall energy was required to start the runoff process and the final

infiltration rates increased. The studies confirmed that, within an organic matter range of 0 to 4%, soil erodibility tends to decrease as organic matter increases.

7.1.3 Soil Structure

The structure of a soil depends on the size and shape of the grains as well as on the minerals of which grains are formed. Orientation and stratification of the soil also affect the structure. The structure of clays is affected by the minerals of the grains and by the conditions prevailing at the time of deposition.

Structure grade (strength) did not significantly affect erodibility, probably because of a dependence on moisture content (as well as on the observers' judgment). Wischmeier, Johnson and Cross (1971) suggested four categories of soil structure to be used in determining erodibility: 1) very fine granular, 2) fine granular, 3) medium or coarse granular, and 4) blocky, platy, or massive.

7.1.4 Permeability

Permeability can be described as the ease with which water flows through a soil. Soil erodibility increases as permeability decreases. Generally, the more permeable a soil, the less water that will be available for runoff and overland erosion. Wischmeier, Johnson and Cross (1971) specified six categories of permeability related to soil classifications. Fragipan or tight claypan soils were considered to be the least permeable; claypan soils have a relatively high clay content and are usually formed by clay carried downward through the soil by percolating water. Moderately permeable surface soils underlain by massive clay or silty clay were considered to be slightly more permeable, followed by moderately permeable surface soils underlain by a silty clay or silty clay loam with a weak subangular or angular blocky structure. The next most permeable soils were described as having either a moderate or strong subsoil structure grade or a texture that remained coarser than silty clay loam. The last two categories were specified as soils with moderate to rapid and rapid permeabilities, but the respective soil descriptions were not discussed by the authors.

7.1.5 Influence of Parent Material on Soil Erodibility

Different geologic parent materials are often responsible for a variation in the infiltration capacity of soils. Conditions that affect the infiltration of precipitation also affect the amount of overland flow and resulting erosion. Copeland (1963) presented data on both normal and eroded soils from the Boise River watershed (Table 7.1). Along with the differing infiltration rates caused by differing parent material, the rates also significantly reduced after the more receptive surface horizons eroded. The rates reduced most drastically after erosion occurred in the finer textured soils derived from basalt and sedimentary rocks.

TABLE 7.1. Infiltration Rates of Boise River Watershed Soils
(after Copeland 1963)

Infiltration Rate (inches per hour)	Parent Material		
	Granite	Basalt	Sedimentary Rock
Soil in normal condition	6.9	7.1	5.6
Soil in eroded condition	2.8	1.5	2.0

Copeland referenced other investigations of six major soil groups in the northern Rocky Mountains region to determine the levels of resistance to erosive cutting by overland flow on logging roads. The order of increasing erodibility of the soils was hard sediments, basalt, granite, glacial silt, andesite, and loess. The prevailing characteristic of the more erodible soils is their tendency toward single-grained structure and uniform texture.

7.1.6 Bulk Density

Another soil property that has an effect on erodibility is bulk density, which is defined as the weight of a soil (including solid particles and any contained water) per unit volume including voids (Road Research Laboratory 1968). As soil bulk density increases, there is a corresponding decrease in porosity, a reduction in infiltration, and an increase in overland flow.

7.2 TOPOGRAPHY

From the previous discussions of overland flow (Section 5.3) and raindrop erosion (Section 6.1), it is clear that topographic variables of importance in water erosion include surface slope, surface length, and surface roughness. Cooke and Doornkamp (1974) summarized earlier conclusions by other investigators saying that soil loss varies as the 1.4 power of percent slope and as the 1.6 power of slope length.

Slope length is defined as the distance from point of origin of overland flow to the point where either the slope gradient decreases enough that deposition begins, or the runoff water enters a well-defined channel (Wischmeier and Smith 1978). The effect of slope length on annual runoff per unit area of cropland may be assumed to be negligible. However, the soil loss per unit area increases substantially as slope length increases. The greater accumulation of runoff on the longer slopes increases the detachment and transport capacities of the overland flow.

As the slope gradient increases, the soil loss increases much more rapidly than does runoff. Runoff generally increases with a gradient increase, although it may be significantly affected by ground cover.

The shape of a slope also affects soil loss. Many field slopes either steepen toward the lower end (convex slope) or flatten toward the lower end (concave slope). Convex slopes would steepen the gradient and cause an increase in erosion, whereas concave slopes would promote deposition.

7.3 RAINSTORM DISTRIBUTION

The ability of a rainstorm to erode soil depends on all the rainfall intensities involved and on the amount of rain. A long rain at low intensities may provide several inches of water with little erosion hazard. A short rain at a high intensity may cause serious erosion.

The problem of how much soil is lost in a single storm has been studied by the Agricultural Research Service (Wischmeier 1962). Data were assembled and studied from more than a quarter of a million individual-storm runoff and soil-loss measurements from small field plots at 45 research stations in 23 states. Single-storm losses ranged from 0 to 222 tons per acre. The latter is equivalent to removal of about 1.3 inches of topsoil. The general study results are summarized in the following paragraphs.

At a number of research locations, about three-fourths of the total soil loss was caused by an average of four storms a year. However, extreme amounts of rainfall did not occur in all four of these storms. If storms causing 75% of the erosion averaged four per year, three of the four were probably of a size which, over a long time period, would be equaled in size more than once a year. In a sample of 315 plot-years of soil loss measurements, the greater number of smaller storms that would have a return period of one year or less, moved as much soil from the experimental areas as did the smaller number of larger storms for which the return period would be two years or more.

The return period of a storm can be computed on the basis of any one of several storm parameters, such as the amount of rain, 15-minute intensity, maximum 30-minute intensity, or erosion-index value. The numerical value of the erosion-index is the product of rainstorm energy (ft-tons/acre-inches) and the maximum 30-minute intensity (in./hr). The relationships of these parameters to each other are not constant: therefore, a particular storm may have a two-year return period with respect to one of the parameters and at the same time have a substantially longer or shorter return period with respect to one of the other parameters.

The data were collected from research plots east of the Rocky Mountain area. Although the climate is generally more arid in the western states, extreme, high-intensity storms are common (Copeland 1963). The storms are usually of short duration and limited extent but produce high energy rainfalls.

These storms seldom occur when the soil mantle is saturated, but rather, when the mantle has the capacity to store several inches of water. However, the critical characteristic is that the rainfall intensities of these cloudbursts frequently exceed the infiltration rate of the soil, especially when plant cover is depleted and, thus, overland flow is inevitable.

7.3.1 Climate, Precipitation, and Sediment Yield

Langbein and Schumm (1958) studied the effects of mean annual precipitation on sediment yield. Their study related the variations in sediment yield associated with climate to the mean annual precipitation for a mean annual temperature of 50°F. Mean annual precipitation was used as the dominant climatic variable in sediment yield because of its effect on vegetation and runoff. The sediment yield data were obtained from about 100 sediment gaging stations, with preference to the smaller watersheds and reservoir sedimentation records. The results are plotted in Figures 7.1 and 7.2. The plots indicate that, within the 0 to 10-inch mean annual precipitation range, an increase in annual rainfall increases erosion. A decrease in annual rainfall correspondingly decreases erosion. For a precipitation range of from 15 to 45 inches, erosion decreases with increased precipitation, largely because of an improved vegetative cover. Sediment yields are nearly constant for mean annual precipitation above 45 inches.

Besides predicting the probable effects of climatic changes on sediment yields, the curves also indicate the precipitation range where the greatest amounts of erosion and sediment yields can be expected. This range is from about 10 to 15 inches of precipitation and is typical of the semi-arid regions where many tailings impoundments are located. Another indication is that

FIGURE 7.1. Effect of Climatic Variation on Sediment Yield as Determined from Records at Sediment Stations (after Langbein and Schumm 1958)

FIGURE 7.2. Effect of Climatic Variation on Sediment Yield as Determined from Reservoir Surveys (after Langbein and Schumm 1958)

either an increase or decrease in precipitation in these regions would result in a decrease in erosion and sediment yield. A more arid climate would yield less sediment because of the decrease in rainfall and snowmelt; a wetter climate would reduce erosion because of increased vegetation.

A later study by Schumm (1965) developed a set of sediment yield curves for a range of mean annual temperatures from 40°F to 70°F. The new curves are displaced laterally with respect to the 50°F curve, as shown in Figure 7.3. The curves indicate that, as annual temperature increases, the peak sediment yield should occur at higher values of mean annual precipitation. The reasons postulated for the displacement are that higher rates of evaporation and transpiration reduce the amount of precipitation at higher temperatures available to support vegetation. Therefore, runoff is less and this causes the peak rate of sediment yield to shift to the right.

Another climatic stress affecting sediment yield is the freeze-thaw cycle. Lusby (1963) studied freeze-thaw effects on sediment yield in the Badger Wash area near Grand Junction, Colorado. The average annual rainfall for the area is 8.3 inches with a wide yearly variation. Temperatures range from 0°F to about 100°F; potential evaporation rates average about 90 inches.

A typical erosion cycle would begin with a summer storm that would leave the soil surface sealed and wet. As the soil dries out, fine dessication fractures (which close when wetted) are formed. In this condition the slopes

FIGURE 7.3. Curves Illustrating the Effect of Temperature on the Relation Between Mean Annual Sediment Yield and Mean Annual Precipitation (after Schumm 1963)

are relatively impermeable and rilling occurs. During the winter cycles of freeze and thaw, heaving destroys the rill patterns, loosens the soil and increases permeability, and causes downslope creep of the soil. Then, when spring and early summer rains occur, the soil is highly permeable and is able to absorb more rainfall than later in the year. As rain continues to fall during the summer, the soil again becomes compacted and infiltration rates are lowered.

This cycle applied equally to all drainage basins in the Badger Wash area; however, runoff and sediment yield was greater in certain basins, a result of differences in soil type. The soils in the basins are derived from either sandstone or shale. The shale-derived soils were more susceptible to loosening by freeze and thaw. Whereas the runoff was not any greater from the steeper shale material slopes, sediment yield was greater because more material was available for transport as a result of the frost action. The sandstone soils were less susceptible to loosening by freeze and thaw.

7.4 VEGETATION

Vegetative cover is perhaps the greatest natural deterrent to soil erosion because it protects the surface from raindrop impact, reduces the amount of water available for runoff by improving infiltration capacity, and increases the surface roughness, which in turn, decreases the runoff velocity. A decrease in runoff velocity produces a corresponding increase in detention time. Plant roots also help bind the soil and keep it in place. Langbein and Schumm (1958) compared vegetal bulk with mean annual precipitation (Figure 7.4). The data indicate a definite break between forested and non-forested areas. The desert shrub data represent areas in Nevada, Utah, Idaho, and Arizona; the grassland data are from Colorado, Kansas, and Nebraska. The data on forest cover are primarily from coastal, northeastern, and southeastern states. Their conclusion was that in arid and semi-arid regions, the increase in vegetal bulk with precipitation reflects an increased opportunity for each plant to reach maximum development for the species environment, and for the growth of larger species.

Copeland (1963) compared the percent of ground cover with cumulative overland flow and with eroded soil (Figures 7.5 and 7.6, respectively). Simulated rainfall of 3.7 inches per hour was applied to study plots for 30 minutes, with varying percentages of ground cover on coarse-textured, single-grain, structured soils. The results indicated that no less than 70% ground cover is required to reduce overland flow and erosion to a point of stability. The cumulative values of overland flow and eroded soil increase sharply as the percent ground cover decreases from 70 to 30%.

FIGURE 7.4. Relation Between Precipitation and Weight of Vegetation Per Unit Area (after Langbein and Schumm 1958)

FIGURE 7.5. Relation of Ground Cover to Overland Flow (after Copeland 1963)

FIGURE 7.6. Relation of Ground Cover to Eroded Soil (after Copeland 1963)

8.0 COMPUTATIONAL METHODS FOR OVERLAND EROSION

Several mathematical approaches can be used to determine erosion rates and sediment yield from natural and disturbed land surfaces. In the case of uranium mill tailings impoundments, it may be desirable to determine the erosion rates from both the radon suppression cover and the surrounding watershed area. Identifying erosion and deposition areas is also important to the selection and evaluation of a potential impoundment site.

The simplest approaches to determining erosion rates and sediment yield are mathematical models based on regression equations, typified by the Universal Soil Loss Equation (USLE). This type of approach interprets input-output relations using simplified forms that may or may not have physical significance. This type of model is often used, but the parameters may not accurately represent observable physical characteristics.

Physical process simulation models formulate the governing processes controlling sediment yield where they may be evaluated separately to determine the model's sensitivity to changing watershed conditions. By simulating the selected phenomena in terms of its separate components, each individual process is analyzed and refined or altered to meet the needs of the user. Consequently, as each process component is upgraded, the model becomes more representative of the physical system. Use of component process models also allows the input of variables that have physical significance to the user and the field situation. Physical process simulation models relate to the physical processes such as surface runoff, subsurface flow, raindrop splash erosion, overland flow erosion, and others.

A variation on the physical process simulation model is the complex watershed and onsite erosion models. These models subdivide large watersheds into smaller watershed components; the components are linked together by physical process representations of the actual channel network within the watershed. Onsite erosion models are simplified versions of the complex watershed models.

Another approach is the use of stochastic models. This type of model assumes that if rainfall events, watershed responses, and runoff events are stochastic (probabilistic) in nature, the processes of sediment yield are also stochastic. Stochastic models have proven to be difficult to apply and do not readily respond to a watershed undergoing changes as a result of land-use activities (Simons, Li and Associates 1982). Also, most hypotheses used in these models have not been verified with field data.

The following discussion includes only the regression and physical process simulation types: these are most applicable to uranium mill tailings sites. The models are briefly described and reviewed; a detailed analysis of the formulation of each model is beyond the scope of this report. The advantages and limitations of each model or model category are included where documentation was available.

8.1 REGRESSION MODELS

8.1.1 The Universal Soil Loss Equation (USLE)

The Universal Soil Loss Equation (USLE) is the most widely used regression model for predicting soil erosion. It is an empirical formula for predicting soil loss as a result of sheet and rill erosion. The USLE was developed at the National Runoff and Soil Loss Data Center established in 1954 by the Agricultural Research Service in cooperation with Purdue University (Wischmeier and Smith 1978). Research projects at 49 locations contributed more than 10,000 plot-years of basic runoff and soil loss data for the study. The data analysis provided several major improvements for estimating soil loss: 1) rainfall-erosion index evaluated from local rainfall characteristics, 2) a quantitative soil erodibility factor that is evaluated directly from soil property data and is independent of topography and rainfall differences, 3) a method of evaluating cropping and management effects in relation to local climatic conditions, and 4) a method of accounting for effects of interactions between crop system, productivity level, tillage practices, and residue management.

Since 1965 the USLE has been further developed to provide techniques for estimating additional land uses, climatic conditions, and management practices. These developments include: a soil erodibility nomograph for farmland and construction areas, topographic factors for irregular slopes, and cover factors for various vegetation conditions.

The primary purpose of the USLE is to guide decision-making for conservation planning on a site-specific basis. The equation, specifically designed and field-tested, can be applied to (Wischmeier 1976):

- predicting average annual soil movement from a given field slope under specified land use and management conditions (This could be the average annual soil movement from a given crop system on the long-term average for a particular crop year in rotation.)
- guiding the selection of conservation practices for specific sites--the application for which the equation was initially intended
- estimating the reduction in soil loss attainable from various changes in cropping systems or cultural practices
- determining how much more intensively a given field could be safely cropped if contoured, terraced, or strip cropped
- determining the maximum slope length on which given cropping and management systems can be tolerated in a field
- providing local soil loss data for decision making regarding needs for erosion control and conservation planning

- estimating soil losses from construction, rangeland, woodland, and recreational areas. These estimates are sometimes less accurate than cropland estimates because effects of erosion management practices for the conditions have not been determined as accurately as for cropland conditions.

Detailed discussions on the application of the USLE can be found in Wischmeier and Smith (1978) and ASCE (1975).

Six major factors were used to develop the USLE:

$$A = R K L S C P \quad (8.1)$$

where

- A = average annual soil loss (tons/acre)
- R = rainfall erosivity factor
- K = soil erodibility factor (tons/acre per unit of rainfall factor, R)
- LS = topographic factor
- C = cropping-management factor
- P = erosion control practice factor (e.g., contouring or terracing).

The terms LS, C, and P are all dimensionless. The computed soil loss, A, has the time period of R and soil loss dimensions of K.

Rainfall Erosivity Factor (R)

This factor, which is also called the erosion index, expresses the erosion potential of average annual rainfall in the locality. It is a summation of the individual storm products of the kinetic energy of rainfall, in hundreds of foot-tons per acre, and the maximum 30-minute rainfall intensity, in inches per hour, for all significant storms on an average annual basis. A study by Wischmeier and Smith (1960) correlated seven expressions representing rainfall amount, intensity, and energy with soil loss. The R factor explained a larger percentage of soil loss variation than any other rainfall-derived parameters, with coefficients of determination from 0.71 to 0.89 for the five soils studied.

Soil Erodibility Factor (K)

The soil erodibility factor, K, is a function of percentage of silt, percentage of coarse sand, soil structure, permeability of soil, and percentage of organic matter.

The factor, K, represents the average soil loss, in tons per acre per unit of rainfall factor, R, from a particular soil in cultivated continuous fallow, with a standard plot length and percentage slope arbitrarily selected as 72.6 feet and 9, respectively. Values of K for the soils studied vary from 0.02 tons/acre/unit to 0.70 tons/acre/unit of rainfall factor, R. The soil erodibility nomograph is shown in Figure 8.1.

FIGURE 8.1. Soil Erodibility Nomograph Used to Determine Factor K for Specific Topsoils or Subsoil Horizons. Solutions are in tons/acre (from Wischmeier, Johnson and Cross 1971).

Topographic Factor (LS)

The topographic factor, LS, is defined as the ratio of soil loss from any slope and length to soil loss from a 72.6-foot plot length at a 9% slope, with all other conditions the same. Slope length is defined as the distance from the point of origin of overland flow to the point where either the slope gradient decreases to the extent that deposition begins or runoff water enters a well-defined channel (Wischmeier and Smith 1978). Increased slope length primarily increases the potential for soil loss because of greater accumulation of runoff on the longer slopes (Section 7.2). Based on data for slopes between 3 and 20% with lengths up to 400 ft, Wischmeier and Smith (1978) proposed the topographic factor to be computed as

$$LS = \left(\frac{\lambda}{72.6}\right)^m (65.41 \sin^2 \theta + 4.56 \sin \theta + 0.065) \quad (8.2)$$

where λ is slope length in feet, θ is the slope angle, and m is an exponent depending upon slope. The exponent m is given by

- $m = 0.2$ for slopes < 1 percent
- $m = 0.3$ for slopes of 1 to 3 percent
- $m = 0.4$ for slopes of 3.5 to 4.5 percent
- $m = 0.5$ for slopes > 5 percent.

Cropping-Management Factor (C)

The factor, C, is the ratio of soil loss from land cropped under specified conditions to the corresponding loss from clean-tilled, continuous fallow ground. The soil loss that would occur on a particular field in a fallow condition is computed by the product of RKLS in the soil loss equation. Actual soil loss from the cropped field is usually much less.

The cropping-management factor can be divided into three distinct types of effects: Type I--effects of canopy cover (C_I), Type II--effects of mulch or close-growing vegetation in direct contact with the soil surface (C_{II}), and Type III--tillage and residual effects of the land use (C_{III}). The cover and management factor is defined as the product of these factors:

$$C = C_I C_{II} C_{III} \quad (8.3)$$

Support Practice Factor (P)

Support practice factor, P, accounts for the effect on erosion of conservation practices such as contouring, stripcropping, and terracing. It is defined as the ratio of soil loss using one of these practices to the loss using straight row farming up and down the slope. Terracing is generally the most effective conservation practice for decreasing soil erosion. This factor can be set at 1.0 for straight-row farming.

Limitations of the USLE

Wischmeier (1976) discussed several limitations of the USLE regarding the use and misuse of the equation. These limitations can lead to significant sources of error in soil loss estimates, particularly if the user is only superficially acquainted with the equation as a handbook formula.

The USLE does not predict sediment yield from a field, only soil losses from the source. A field's sediment yield is the sum of the soil losses on the slope segments minus deposition in depressions within the field, at the toe of the slope, along field boundaries, and in terrace channels. The USLE does not account for this deposition. Also, erosion does not necessarily equate to soil loss. The soil loss from a contoured and stripcropped slope is much less than the amount eroded between the sod strips.

R-values obtained from the isoerodent map (Wischmeier and Smith 1978) are locational average annual values for 22-year weather cycles. Values for a specific year within that period usually range from less than half to more than double the 22-year average and are influenced by large random variations and cyclical effects. Thus, the USLE applies only for long-term averages.

The soil-erodibility factor, K, is an average for a given soil, but the soil loss per unit of R on a given field varies from storm to storm as a result of fluctuations in antecedent surface conditions and storm characteristics. Rain falling on relatively dry tilled soil may significantly infiltrate before runoff begins, resulting in a low average soil loss per unit R-value for that storm. Most of the rain falling on presaturated soil will quickly become runoff.

Simons, Li and Associates (1982) evaluated the USLE and pointed out important limitations to its use in the arid regions of the west. The data base used in developing the USLE was collected east of the Rocky Mountains. Significant errors can be introduced when applying it to the western areas, primarily because of the R-factor. Many arid regions receive a large percentage of rainfall in the form of high-intensity, short-duration thunderstorms. This is not the case in the central and eastern United States, where the effect of this type of rainfall cannot be totally incorporated. To collect a similar data base for semi-arid and forested watersheds will take an extremely long time because of the number of small rainfall events that occur over an area in a year and because of the limited number of data collection sites.

The weathering process caused by the wind and sun on the soil between rainstorms is much more severe in arid areas. Weathering creates an additional supply of easily eroded material that can significantly increase the erodibility factor, K.

In addition, the USLE was developed from data taken from small plots. Because it is a regression equation, the results are not as reliable when applied to much larger areas. The USLE was developed for material in the range

of 1 mm and finer, but does not predict the yield of larger sediment sizes. Despite the USLE's limitations for the western states, it still may be useful in evaluating the erosional characteristics of uranium tailings impoundments. Because only soil loss estimates from impoundments are of interest, sediment yields would not be a concern. Also, the impoundment surface area is small compared to most watersheds and much detailed information will be available regarding the soils and geometry of the decommissioning cap. This will allow for more accurate evaluations of the individual factors.

8.1.2 The Modified Universal Soil Loss Equation (MUSLE)

The modification of the USLE was developed primarily because the USLE is limited to soil loss and a procedure was needed to compute sediment yields from watersheds (Simons, Li and Associates 1982). The MUSLE model determines sediment yields based on single storm events. A runoff factor was substituted for the rainfall factor, R, into the USLE to estimate soil loss (Williams and Berndt 1976). This modification makes the MUSLE more applicable to the arid regions of the west because the effect of short-duration, high-intensity events can be more adequately represented. The MUSLE is:

$$Y_s = a (Q_v q_p)^\beta K LS CP \quad (8.4)$$

where Y_s is the sediment yield in tons for the storm event, Q_v is runoff volume in acre-feet, q_p is the peak flow rate in cubic feet per second, a and β are coefficients, and other terms are as previously defined for the USLE.

The coefficients were calibrated as 95 for a and 0.56 for β in watersheds in Texas and Nebraska. These coefficients vary and must be determined in other locations by calibration with reservoir data or other appropriate data.

Also, if the sediment yield from the land surface is desired on an annual basis rather than from a single-storm event, the MUSLE can be used: the soil loss is determined for events of varying return periods. Recommended return periods are 2, 10, 25, 50 and 100 years. The sediment yields are then weighted according to their incremental probability, resulting in a weighted storm average.

To compute the annual yield, the weighted storm yield is multiplied by the ratio of annual water yield to an incremental probability-weighted water yield. For the return periods recommended, the computation is (Simons, Li and Associates 1982):

$$A_s = \frac{Q_A (0.01Y_{s100} + 0.01Y_{s50} + 0.02Y_{s25} + 0.06Y_{s10} + 0.4Y_{s2})}{0.01Q_{v100} + 0.01Q_{v50} + 0.02Q_{v25} + 0.06Q_{v40} + 0.4Q_{v2}} \quad (8.5)$$

where A_s is the annual sediment yield, Q_A is the average annual water yield, and the numerical subscripts in the single storm event (Y_s) and water yield (Q_v) refer to the return period of the storm.

8.2 PHYSICAL PROCESS SIMULATION MODELS

8.2.1 Agricultural Runoff Management Model (ARM)

The model ARM was developed as an overland contaminant-transport model (Donigian et al. 1977; Donigian and Davis 1978). Basically, the model simulates changes in soil moisture content, the events that influence soil and contaminant conditions between storms, and the overland transport of water, sediment, and contaminants. ARM has been extensively tested and used throughout the United States (Donigian et al. 1977; Donigian and Davis 1978; Donigian and Crawford 1976). Although ARM was developed to simulate overland contaminant transport, it does have hydrologic response and sediment production subprograms that could be used alone to compute sediment yield from erosion of a uranium tailings cover surface and the surrounding watershed. A review of the model can be found in Onishi et al. (1982).

Model Formulation

ARM simulates runoff (including snow accumulation and melt), sediment, pesticides, and nutrient contributions to stream channels from both surface and subsurface sources. No channel routing procedures are included and uniform land use is assumed. Thus, the model applies to watersheds with uniform cropping and management practices that are small enough for channel processes and transformation to be assumed negligible. Although the limiting area will vary with climatic and topographic characteristics, watersheds greater than 2 to 5 km² are approaching the upper limit of ARM's applicability.

The major components of the model include the following subprograms:

- MAIN - controls the overall execution of the program; calls subroutines at proper intervals, transfers information between routines, and performs the necessary input and output
- LANDS - simulates the hydrologic response of the watershed
- SEDT - simulates the sediment production within the watershed
- ADSRB - simulates the pesticide adsorption/desorption mechanism
- DEGRAD - simulates the pesticide degradation mechanism
- NUTRNT - simulates nutrient transformations.

Only the subprograms that simulate the hydrologic response and sediment production concern the erosion of uranium tailings impoundments.

Hydrologic Response Subprogram (LANDS). The subprogram LANDS simulates the hydrologic response of the watershed to inputs of precipitation and evaporation. If snowmelt is to be simulated, additional meteorologic data are required. LANDS is a moisture-accounting procedure for water in each major

component of the hydrologic cycle. Parameters that characterize the land surface and soil profile characteristics can be determined from soil data, topographic characteristics, meteorologic data, and comparison of simulated and recorded streamflow.

The hydrologic subprogram operates continuously on a 15-minute interval throughout the simulation period. It simulates all flow components (surface runoff, interflow, ground-water flow) and soil moisture storages by representing the processes of interception, infiltration, overland flow, percolation, evapotranspiration, and snow accumulation and melt. The subprogram accounts for moisture above, at, and beneath the soil surface. If snowmelt is not simulated, precipitation first encounters the interception function. Interception is a storage function that depends on vegetation and land cover. Because of its dependency on vegetation, the interception capacity may vary with the seasons. When interception storage is filled, any remaining precipitation is added to the moisture supply of the infiltration function, which separates the available moisture into surface detention, interflow detention, and infiltration. Surface detention includes overland flow and an increment to upper zone soil moisture storage. Interflow detention is a delay mechanism controlling the release of interflow to the stream. Infiltration and percolation from the upper zone provide the means for moisture to reach lower zone storage. From lower zone storage, moisture moves to active ground-water storage from which the ground-water component of streamflow is derived.

Sediment Production Subprogram (SEDT). The subprogram SEDT simulates the erosion processes of soil particle detachment by rainfall and transport by overland flow. Only sheet erosion and rill erosion were included because gully erosion was not significant on small test watersheds. The processes of sheet and rill erosion include the detachment of soil fines (silt and clay fractions) by raindrop impact and the transport of soil fines by overland flow. The degree of soil fines detachment depends on the vegetal cover within a growing season and precipitation. The soil fines transport is determined by the amount of soil fines available for transport and the overland flow conditions. The model also includes a maximum capacity to transport soil fines which is a function of overland flow, soil, and subsurface characteristics. A user-input soil compaction factor reduces the amount of detached soil particles available for transport. It is basically a first-order decrease of the surface storage of soil fines performed on a daily basis during nonstorm periods. The factor attempts to represent the natural aggregation and mutual attraction of soil particles and the compaction of the surface soil zone from which erosion occurs. These processes are a complex function of soil characteristics, meteorological conditions, and tillage practices.

Limitations

The limitations of the hydrologic and sediment production components as they affect overland erosion are listed below (Unishi et al. 1982):

Hydrology

- One of the major limitations of the model is the quantity of historical data required to calibrate model coefficients and parameters. This limitation has been reduced somewhat as many hydrologic parameters have been regionalized.
- ARM is not formulated to handle channel flow simulation. As a result, the model applies only to watersheds that are small enough for channel processes to be assumed negligible. Modeling various catchment sizes is limited to climatic and topographic characteristics. Generally, ARM applied on areas from 2 to 5 km². Because of this limitation, the application of ARM to large watersheds requires that the watershed be subdivided into smaller subcatchments, and that a number of individual models be applied to the smaller subcatchments.
- Snow-melt hydrographs are not accurately simulated and the effect of frozen ground conditions is not represented. This is probably due to both inaccurate or insufficient meteorologic data and inadequacies in the snow-melt algorithms.

Sediment

- The effects of winter freeze/thaw conditions on sediment production and soil detachment and scour by overland flow are not considered in the model. Also, erosion simulation as a function of particle size is not considered.

8.2.2 Chemical, Runoff, and Erosion from Agricultural Management Systems (CREAMS) Model

The CREAMS model is a more recently developed code to simulate overland water, sediment, and contaminant transport (Knisel 1980). CREAMS is a daily simulation model that estimates runoff, erosion, and sediment transport, and plant nutrient, and pesticide yield from field-sized areas.

The hydrologic component has two options. When only daily rainfall data are available to the user, the model estimates surface runoff. If hourly or breakpoint rainfall data are available, an infiltration-based model simulates runoff. Both methods estimate percolation through the root zone of the soil. The erosion component maintains elements of the USLE, but includes a sediment transport capacity for overland flow. A channel erosion/deposition feature of the model permits consideration of concentrated flow within a field.

Because the model is new, errors in the computer formulation under certain conditions may exist. Extensive simulations of the model by various groups have not been documented as of yet; therefore, the supporting documentation is deficient (Onishi et al. 1982).

8.3 COMPLEX WATERSHED AND ONSITE EROSION MODELS

Complex watershed models are physical process simulation models that allow large watersheds to be subdivided into smaller components. The term 'complex' refers to this breakdown of a physically variable watershed into a series of smaller, less complicated components. The components are linked together by physical process representations of the channel network that constitute the linkage within the actual watershed. The essential physical processes evaluated in the watershed representation include (Simons, Li and Associates 1982):

- the rainfall event given by a rainfall histogram
- detachment of sediment due to raindrop impact
- the protection of soil from raindrop detachment by canopy and ground cover
- the determination of the portion of the rainfall event producing runoff based on interception and infiltration processes
- the routing of water as overland flow by either numerical finite difference techniques or analytical means (such as the method of characteristics)
- the determination of the sediment transport capacity for overland flow based on hydraulic conditions
- the routing of sediment on the overland flow regions by using the sediment continuity equation, computed transport capacity, and availability of sediment from raindrop and flow detachment.

Similar to the complex watershed models are the simplified onsite erosion models. The major difference between the models is that onsite models only consider water and sediment runoff from the land surface. Actually, an onsite model is the component of a complex watershed that evaluates water and sediment runoff from the overland flow segments of the complex watershed. The onsite models should be applied when the regression-type models are not valid for a particular situation, but when, configuration, a complex watershed model is not needed.

8.3.1 Multiple Watershed Water and Sediment Routing Model (MULTSED)

MULTSED (Simons, Li and Fullerton 1980) is complex watershed model designed to route storm water, determine soil erosion, and route sediment runoff from watersheds of complex geometry. The geometric approximation used in MULTSED consists of an arbitrary number of two-plane and one-channel ('open book') watersheds linked together by channels and reservoirs. All subwatershed units, planes, and open books have no upstream inflows and are routed using the

method-of-characteristics solution to the kinematic wave problem for overland and channel flow. The channel in this case is the intersection of the two planes of the open book. These primary channels also have no upstream inflow and are routed using the method of characteristics solution. The channels that join the subwatersheds have upstream inputs and require a numerical solution to the kinematic wave approximation.

The transformation of a watershed into a geometrical representation for simulation is shown in Figure 8.2. Figures 8.2(a) and 8.2(b) illustrate the representation of a topographic map of a small watershed by the open-book procedure. The primary channel, L_c , divides the watershed element into two areas, A_1 and A_2 , and defines the length of the intersection of the planes. The channel, L_c , is determined by extending the line normal to the topographic contours from the watershed outlet up to the divide. The areas A_1 and A_2 define the length of the overland flow units. The slopes of the planes S_1 and S_2 are determined by length-weight averages of flow paths on each plane. The primary channel slope is computed as rise divided by length.

Figure 8.2(c) depicts a more complex watershed map. In this case the watershed is subdivided into subwatersheds that are best represented by either a single plane or an open-book representation. Once this subdivision has been accomplished, the geometries of the subwatershed representations are determined in the same manner as before. The resulting approximation has a form illustrated by Figure 8.2(d).

The order of the computational sequence in calculating storm water runoff and the attendant sediment runoff is governed by gravity. The overland flow and primary channel routines are contained in program MSED1. This program performs the water and sediment routing for all of the subwatersheds in the system. The order of calculation of the subwatersheds is in the downstream direction of the main channel. The hydrographs calculated by MSED1 are reordered and assigned a common time grid by MSED2. The sorted data are then routed by MSED3 for the whole system on a time-increment by time-increment basis. This procedure allows overland and primary channel flow hydrographs to be stored on permanent files rather than in the central memory; thus, the size of the complex watershed modeled is not unduly restricted by the need to store all of the inflow hydrographs to the main channel.

MULTSED has been applied to a large number of engineering design and planning problems (Simons, Li and Associates 1982). A major application has been to determine water and sediment runoff from a surface coal mine in New Mexico. Both the water and sediment results were used to design new, and modify existing, hydraulic structures such as temporary diversion channels, restoration channels, culverts, and impoundments. The sediment results were also used to determine sediment control measures necessary to prevent larger sediment concentrations from leaving the disturbed mine area than had entered.

(a) ORIGINAL WATERSHED TOPOGRAPHIC MAP

(b) OPEN BOOK REPRESENTATION

FIGURE 8.2. Transformation of Topographic Map Into Watershed Geometric Representation

(c) ORIGINAL COMPLEX WATERSHED TOPOGRAPHIC MAP

(d) REPRESENTATION USING UPSTREAM SUBWATERSHED UNITS, PLANES AND A MAIN CHANNEL

FIGURE 8.2. (contd)

8.4 LIMITATIONS OF PHYSICAL PROCESS SIMULATION MODELS

The limitations or disadvantages of the physical process simulation models are related mainly to the increased complexity of the physical process models. These limitations, as compared to the regression-type models, are as follows (Simons, Li and Associates 1982):

- Most physical process models require a large number of complicated calculations requiring repetition over time and space. Therefore, access to a large computer is necessary for the models to be practical. Only small components of the models can be programmed on hand-held calculators, which severely limit data storage.
- Data requirements are more extensive because of the increased complexities. However, in some ways data requirements are simplified for physical process models because the necessary data are more easily measured and identified because of the physical process basis. Data requirements for regression models are often much more subjective and the parameters more difficult to relate to observed or measured quantities.
- The complexity of physical process models requires a background knowledge of erosion and sedimentation, and watershed response. Without adequate background, users probably cannot apply process models to achieve accurate results. Regression models require less knowledge because their rigid procedures are easy to apply. Although, without proper training, users applying a regression model can also produce invalid results.

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