Methodologies for Assessment of Soil Degradation Due to Water Erosion

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I. Introduction

Soil degradation due to water erosion is a serious threat to the quality of the soil, land, and water resources upon which man depends for his sustenance. Pimentel et al. (1995) estimated world wide costs of soil erosion to be about four hundred billion dollars per year, more than $70 per person per year. El-Swaify (1994), summarizing a recent study, indicated that water erosion had accounted for about 55% of the almost 2 billion ha of degraded soils in the world. There is no region of the globe where soil degradation due to water erosion is not a threat to the long-term sustainability of mankind.

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Erosion is the removal of a mass of soil from one part of the earth and its relocation to other parts of the earth. Water erosion is that portion of erosion caused by water. Our objective in this chapter is to review technology for assessing the potential for soil degradation and to assess the degradation that has occurred because of water erosion. In this chapter, we will limit ourselves to erosion processes that occur on relatively small tracts of land, avoiding the issues related to streams. Additionally, we will not discuss mass movement, whether due to man moving it (tillage erosion) or due to land slides.

Any method of assessment of soil degradation due to water erosion must be able to account for the broad differences in what constitutes a degraded soil around the world. In China, immense gullies have dissected the loess plateau into such small pieces and such steep slopes that farming would not be feasible using the same agricultural technology as European, Australian and North American farmers. Has that soil resource been degraded? The Chinese feed 20% of the world's population a sustaining diet that is produced in part on such dissected and eroded lands, and a trip through the loess plateau reveals a thriving agriculture and society using most of the land. In almost every country, highly degraded soils are cultivated. Dudal (1981) perhaps said it best: “Suitability must be expressed in terms of the level of technology and the inputs which are being applied.”

There are many soils and regions that depend on sediment deposition to maintain agricultural production, and when that source of sediment is eliminated, higher technological inputs may be required to sustain production. Examples of this abound–depositional areas in the loess plateau of China are the areas that produce the best in that region, the flood plain of the Nile in Egypt, and in times past, the flood plains along the Mississippi in the United States. The input of higher technology to replace deposition effects can also degrade the soil resource.

In this chapter, we will focus on the processes of soil erosion by water that cause soil degradation, where soil erosion becomes a problem in soil degradation, and measures for controlling soil erosion to limit soil degradation. While others have connected erosion with loss of production, we will consider mostly the mass of soil removed.

II. Erosion Processes and Soil Degradation

The water erosion process is frequently lumped into sheet and rill erosion and gully erosion. Recently, the erosion process was divided into interrill erosion (Sharma, 1996; Ellison, 1947) and rill and gully erosion (Grissinger, 1996a). In this chapter, we will follow their convention, except rill and gully erosion will be called channel erosion. This chapter will be divided into two sections, one dealing with interrill processes and the other with channel processes.

Interrill erosion is best described as the process of detachment and transport of soil by raindrops and very shallow flow (Sharma, 1996). Interrill erosion is constant over a slope–as long as soil and surface properties remain constant (Young and Wiersma, 1973). Interrill processes generally occur within a meter or so of the point of impact of a water drop, and deliver much material to nearby channels.

Runoff in these nearby channels then delivers the interrill material to points farther down stream. If there is no flow in a channel, the interrill material stays close to the point of detachment. Interrill erosion is usually most apparent on row sideslopes, or in the case of soils with some surface protection, as pedestalled soil under protective cover due to the washing away of adjacent unprotected soils. Soils seem to vary in their susceptibility to interrill erosion over a narrow range (about a factor of 5) while their susceptibility to channel erosion varies over a much wider range (about a factor of 15 or so) as shown in Table 1.

Channel erosion is the process of detachment and transport of soil due to flowing water. Channel erosion is distinctly and visibly different than interrill erosion, but the distinction is sometimes blurred at the boundary between the area where interrill processes occur and where channel processes occur. Because they are distinctly different processes, methods of assessment and control are much different, as are their effects on soil degradation. Generally, almost all erosion that is visible is due to channel erosion.

For short slopes, most erosion may be interrill erosion. As slopes increase and as slope length increases, erosion due to channel processes begins to dominate. In studies of ephemeral gullies in the United States, the ratio of erosion from these small channels to sheet and rill (also small channels) erosion ranged from .24 to 1.47 (Laflen et al., 1986). Bennett (1939) indicated that 20 million ha of former U.S. cropland were useless for further production because they had been stripped of topsoil or riddled with gullies and that most of this land had been abandoned. Trimble (1974) reported that the southern Piedmont had been stripped of its topsoil, and dissected and gullied so badly that the land was unsuitable for agriculture, with the entire region (about 150000 km^2) having lost an average of 0.17 m of topsoil. Trimble attributed nearly all of the erosion to the advent of clean-cultivated cash crops, and the exploitative nature of land clearing and farming methods. In fact, the exploitative farming methods Trimble described for the southern Piedmont for the 1700-1970 period are quite similar, both in description and effect, to those described by Lal (1990) for modern day tropical Africa.

III. Assessment of the Potential for Soil Degradation Due to Interrill Processes

The forces and energies in interrill processes are derived from waterdrops (rainfall and irrigation) and the shallow flows near where these drops impact the soil surface. Delivery to rills occurs very near where drops impact the soil surface, and is very closely related to the energy of these drops (Young and Wiersma, 1973). Interrill erosion is not positionally sensitive, being relatively constant over an entire surface where cover, microtopography, soil and waterdrops remain constant.

Soil degradation usually begins by interrill erosion, but rills and gullies drastically increase sediment detachment and transport down the hillslope. Without these channels, interrill erosion would do little toward soil degradation. Of course, since most of the total land area is made up of interrill areas, surface runoff comes

Table 1. Ki, Kr, and Tc values for WEPP cropland soils in the United States

Soil	Site	Texture	Ki[a]	Kr[b]	Critical shear	Clay	Silt	Very fine sand	Organic carbon
			(kg s m^{-1})	(S m^{-1})	(Pa)	(%)	(%)	(%)	(%)
Bonifay	Tifton, GA	Sa	5470062	0.0179	1.02	3.3	5.5	16.2	0.32
Tifton	Tifton, GA	Sa	2192459	0.0113	3.47	2.8	10.8	13.3	0.46
Amarillo	Big Spring, TX	Sa	9261962	0.0453	1.66	7.3	7.7	21.1	0.16
Hersh	Ord, NE	SaL	8412926	0.0112	1.70	9.6	13.4	32.9	0.49
Sverdrup	Wall Lake, MN	SaL	6611372	0.0100	1.37	7.9	16.8	3.7	1.28
Whitney	Fresno, CA	SaL	6648951	0.0233	4.66	7.2	21.7	8.1	0.19
Cecil (eroded)	Watkinsville, GA	SaL	3317005	0.0038	4.48	19.8	15.6	5.9	0.70
Hiwassee	Watkinsville, GA	SaL	3145089	0.0103	2.33	14.7	21.6	4.3	0.83
Academy	Fresno, CA	SaL	6108021	0.0057	1.60	8.2	29.1	20.2	0.41
Barnes	Morris, MN	L	4696644	0.0063	3.96	17.0	34.4	11.4	1.98
Woodward	Woodward, OK	L	11156412	0.0250	1.31	12.3	39.9	39.0	0.82
Caribou	Presque Isle, ME	L	2634362	0.0045	4.25	12.2	40.8	11.5	2.28
Zahl	Bainville, MT	L	5993645	0.0123	3.52	24.0	29.7	12.5	1.69
Manor	Ellicot City, MD	L	4878526	0.0054	3.58	25.7	30.7	7.1	0.96
Williams	MacClusky, ND	L	5425974	0.0045	3.42	26.0	32.4	11.5	1.79
Barnes	Goodrich, ND	L	4776000	0.0033	2.52	24.6	36.0	12.7	3.26
Lewisburg	Columbia, MD	CL	3978307	0.0059	3.41	29.3	32.2	10.9	0.87
Opequon	Flintstone, MD	CL	5657027	0.0035	6.28	31.1	31.2	5.9	1.42
Gaston	Salisbury, ND	CL	3310538	0.0049	4.37	39.1	25.4	7.5	1.12
Mianiam	Dayton, OH	L	3242856	0.0096	5.45	25.3	44.1	6.4	1.75
Frederick	Hancock, MD	SiL	4450583	0.0084	6.64	16.6	58.3	5.2	1.32
Portneuf	Twin Falls, ID	SiL	3596739	0.0106	3.11	11.1	67.4	19.3	0.72

Table 1. continued--

Soil	Site	Texture	Ki	Kr	Critical shear	Clay	Silt	Very fine sand	Organic carbon
			(kg s m^{-1})	(S m^{-1})	(Pa)	(%)	(%)	(%)	(%)
Pierre	Wall, SD	SiL	4475042	0.0117	4.80	49.5	40.9	7.3	1.46
Heiden	Waco, TX	SiC	2154983	0.0089	2.90	53.1	38.3	4.5	1.36
Collamer	Ithaca, NY	C	5583856	0.0241	6.38	15.0	78.0	4.6	1.01
Mexico	Columbia, MO	SiL	5855134	0.0036	0.69	26.0	68.7	1.1	1.56
Sharpsburg	Lincoln, NE	SiL	3409795	0.0053	3.18	39.8	55.4	4.6	1.85
Miami	Waveland, IN	SiCL	3607881	0.0095	3.32	23.1	72.7	2.0	0.82
Grenada	Como, MS	SiL	4595726	0.0073	4.47	20.2	77.8	1.5	1.27
Nansene	Colfax, WA	SiL	6978966	0.0307	3.05	11.1	68.8	18.1	1.49
Palouse	Pullman, WA	SiL	7641964	0.0066	0.74	20.1	70.1	8.8	1.76

[a]Interrill erodibility; [b]rill erodibility.

mostly from interrill areas, and is the major source of water that occurs in channels and that drives the erosion process in channels. It is within the interrill areas that drops do their largest damage, forming crusts on the soil surface that greatly increase surface runoff on interrill areas (Duley, 1939). This runoff then drives the erosion process in channels. Hence, the point to control soil erosion must begin in interrill areas in the control of rates and volumes of surface runoff.

An additional consideration is that interrill erosion occurs at the soil surface–the region of the soil that is most biologically and chemically active. Soil removed in the interrill erosion process removes a disproportionate amount of the soil's fertility, chemicals for the control of weeds, insects and diseases, and organic matter. These losses can eventually have serious consequences for the soil, and possibly for receiving waters as well. The loss of fertility was the basis for establishing soil tolerance values in the United States (Smith, 1941), and interrill erosion rates under clean tillage are often near the allowable soil loss.

A. Techniques for Measuring Interrill Erosion

Interrill erosion can be assessed a number of ways experimentally. The most common has been the use of a rainfall simulator on a small plot area where channel processes are not occurring (Meyer and Harmon, 1979). Such simulators have been used in the laboratory and in the field. One major consideration in such measurements is that the simulated rainfall has characteristics very similar to natural rainfall with regard to uniformity over the study area, drop size distributions, fall velocities and intensities. Another major consideration is that care must be taken to see that movement of interrill material outside the plot area due to raindrop splash does not occur, or that it is balanced with material being splashed into the plot. Bradford and Huang (1993) reported that an erosion plot in the laboratory having .32 m^2 had an interrill erosion rate comparable to field measurements but not to interrill erosion rates from a much smaller pan of .14 m^2, the inference being that the smaller pan was too small. An additional consideration is that care must be taken to observe whether or not rill erosion is occurring on the plot area, which is highly dependent on soil and topographic properties (Bradford and Huang, 1996).

Morgan (1981) studied splash detachment under plant covers using a field splash cup of 30 cm diameter and 10 cm high. A cylinder of soil 2.5 cm tall and 10 cm in diameter was exposed in the middle of the cup. His appraisal was that the equipment worked reasonably well, and he suggested only a few minor improvements for its use in field studies.

Laflen et al. (1991b) described cropland and rangeland soil erodibility experiments related to the Water Erosion Prediction Project (WEPP). Detailed cropland data were presented by Elliot et al. (1989) with descriptions of all procedures and computations. In these studies, a rotating boom rainfall simulator (Swanson, 1965) was used. Interrill plots were about 0.5 m wide by 0.75 m long. Interrill plots were replicated 6 times, and the average coefficient of variation was 21% (standard deviation/mean). Rainfall intensity was measured at each plot to use in computations of erodibility. Data were adjusted for plot slopes using a slope adjustment (Liebenow et al., 1990).

The interrill erodibility of a soil can be measured in field or laboratory settings, using either natural or simulated rainfall under field conditions. Particular care must be taken to design the interrill plots to account for splash out or into the plot area. In interrill studies using rainfall simulation, it is particularly important to use a simulator that replicates natural rainfall as regards drop size, fall velocity and drop size distributions.

B. Techniques for Estimating Interrill Erosion

Interrill erosion rates are generally expressed as a function of rainfall intensity and interrill flow rates, adjusted for interrill slope, canopy, surface cover, sealing and crusting and freezing and thawing. The relationship used in the WEPP (Water Erosion Prediction Project) model (Laflen et al., 1991a) for predicting single storm interrill sediment delivery to a rill is:

$$Di = Ki\ qI\ Sf\ ADJ \tag{1}$$

which is quite similar to the form proposed by Kinnell and Cummings (1993). In Equation 1, Di is interrill detachment rate (kg m^{-2} s^{-1}), Ki is interrill erodibility (kg s m^{-4}), q is runoff rate (m s^{-1}), I is rainfall intensity (m s^{-1}), and Sf is an interrill slope adjustment factor given by (Liebenow et al., 1990) as

$$Sf = 1.05-0.85\ e^{(-4 \sin q)} \tag{2}$$

where q is the interrill slope angle. ADJ is an adjustment factor for the other factors listed above. Adjustment factors for canopy cover can be written as:

$$CC = 1-2.94\ (cc/h)(1-e^{-.34h}) \tag{3}$$

where CC is the canopy adjustment, cc is canopy cover (fraction), and h is canopy height (m). The adjustment for ground cover is

$$GC = e^{-2.5gc} \tag{4}$$

where GC is the ground cover adjustment and gc is the ground cover (fraction). Values of Ki for the soils studied in the WEPP erodibility study are given in Table 1. More details on the WEPP soils can be found in Elliot et al. (1989).

Equation 1 can be rewritten as

$$Di = Ki\ I^2\ Sf\ ADJ \tag{5}$$

if runoff rates are unknown. If Equation 5 is used, the values of Ki (Table 1) should be reduced by about 25% to reflect differences between rate of runoff and rainfall intensity.

Interrill erosion rates can also be estimated with the Universal Soil Loss Equation (Wischmeier and Smith, 1978) or with the Revised Universal Soil Loss Equation (Renard et al., 1991) for very short slope lengths. For such lengths, interrill erosion rates would be estimated by:

$$A = R\,K\,LS\,C\,P \tag{6}$$

where R is the rainfall factor, K is the soil erodibility factor, C is a cropping management factor, P is a support practice factor and LS is a length-slope factor given by either

$$LS = (l/22.1)(65.41 \sin^2 q + 4.56 \sin q + .065) \tag{7}$$

$$LS = (l/22.1)\,(10.8 \sin q + .03) \qquad s<9\% \tag{8}$$

$$LS = (l/22.1)\,(16.8 \sin q - .50) \qquad s>9\% \tag{9}$$

where l is slope length and q is the slope angle. Equation 7 is from the Universal Soil Loss Equation (Wischmeier and Smith, 1978), and Equations 8 and 9 are from the Revised Universal Soil Loss Equation (Renard et al., 1991). Most interrill slopes are of very short length, in the order of only a meter or so.

Storm interrill soil erosion could be estimated using Equation 1. If the average intensity were about 25 mm/hr (.000007 m/s) for an hour, and runoff rate was about 15 mm/hr (.000004 m/s) for an hour, for an up-and-down hill freshly planted corn row with a row spacing of .75 m and an interrill slope of 50 mm between the corn row and the middle of the corn row (S=13%), for a Mexico silt loam (Table 1) the expected interrill erosion rate would be about .00009 kg m^{-2} s (3.2 t/ha for the storm). The range of expected interrill erosion rates for the soils given in Table 1 would range from about 1.2 to 6 t/ha.

Using the Universal Soil Loss Equation, typical annual interrill erosion rates for a clean tilled row crop in the corn belt in the United States would be in the order of 10 t/ha (using an interrill slope of 13%, slope length of .375 m, a C value of .3, a K value of .05, and an R value of 3000, with a P value of 1). Ranges in interrill erosion rates for soils for such conditions would be expected to be from a low of about 2 t/ha to a high of about 15 t/ha.

C. Limits on Interrill Erosion

Limits on soil erosion are extremely difficult to establish and are subject to considerable debate. The debate has in the past centered on the removal of nutrients (Smith, 1941), the replacement of soil materials by the conversion of bedrock to soil (Owens and Watson, 1979), and on long-term crop productivity estimates and measurements (Williams et al., 1983; Gilliam and Bubenzer, 1992).

Interrill erosion plays a very limited part in directly affecting topography or in affecting field operations.

For discussions on the effect of soil erosion on productivity, the reader is referred to Gilliam and Bubenzer (1992), Boli et al. (1994) and to a series of publications on soil erosion effects on crop productivity published in a symposium proceedings (Hall et al.,1985; Larson et al., 1985; Meyer et al., 1985; Reid, 1985; Langdale et al., 1985; Mannering et al., (1985); Burnett et al., 1985; Papendick et al., 1985; and Renard et al., 1985).

On severely eroded lands, interrill erosion is usually not the dominant process. On bare areas of 12 soils where interrill erosion was measured in situ, using a rainfall simulator, Meyer and Harmon (1979) found erosion rates from 0.7 to 7 t $ha^{-1}hr^{-1}$ in the first hour of simulation on steeply sloping row sideslopes. Even on the most susceptible of cropland soils, and with extremely high rainfall rates and amounts, most soils are little threatened by interrill erosion. However, there are exceptions.

One of these exceptions was noted by Bennema and DeMeester (1981) in an example concerning a thin forested soil over a hard limestone. When an area was deforested, the thin A horizon was quickly lost and there was no soil to sustain production. For very shallow soils such as these, interrill erosion can degrade the soil to such limits that it can no longer sustain production.

Morgan (1981), also reported extremely high interrill erosion rates on an annual basis, but his measurements were based entirely on the mass of soil splashed from a small area in a splash cup (Table 2). As shown by Bradford and Foster (1996), interrill erosion rates are frequently (but not always) much higher when measured as mass splashed rather than as sediment yield in runoff from a small interrill plot. The lone exception in their study where sediment yield exceeded mass splashed was for a soil and slope that had apparent rill erosion on what was generally an interrill area.

D. Indicators of Susceptibility to Interrill Erosion

Soil, climate, cover and topography are the determinants of the susceptibility of a particular site to both interrill and channel erosion. While the determinants of the susceptibility of a particular site may be the same, their effect is different. However, if a specific site is very susceptibile to one form of erosion, it is an indicator that the specific site is likely at risk to the other form.

Generally, soils that are high in sand, particularly very fine sand, low in organic matter and low in clay are the most susceptible to interrill erosion. The interrill erodibility in the Water Erosion Prediction Project model is predicted to increase with very fine sand for high sand soils, and to increase as clay content decreases for low sand soils (Alberts et al., 1995). For the USLE, erodibility increased with silt and very fine sand content and decreased as clay and organic matter increased (Wischmeier and Smith, 1978). Soils low in cohesion are those most susceptible to interrill erosion.

Table 2. Erosion processes–measurement and estimation methods and range of reported values

Erosion processes	Methods for estimation or measurement	Reported erosion rates (t/ha/yr)	References
Interrill measurement	Rainfall simulation	0.7 - 7 t/ha/hr	Meyer and Harmon, 1984
	Rainfall simulation	13 - 45 t/ha/hr	Liebenow et al., 1990
	Splash cups	42 - 365 t/ha/yr	Morgan, 1981
Interrill estimation	A = RKLSCP (USLE)		Wischmeier and Smith, 1978
	A = RKLSCP (RUSLE)		Renard et al., 1996
	Di = Ki ql Sf ADJ		Alberts et al., 1995
Channel-rill measurement	Rill meter	-----------	McCool et al., 1976
	Airborne lasers	-----------	Ritchey and Jackson, 1989
Channel-rill estimation	Di = Kr (t-t_c) (1 - G/Tc)		Foster, 1982
Channel-gully measurement	Stereo photography	1.2 t/ha/yr	Piest and Spomer, 1968
	Stereo photography	10 - 18 t/ha/yr	Thomas et al., 1995
	Airborne lasers	-----------	Ritchey and Jackson, 1989
Channel-gully estimation	Ephemeral Gully Model		Laflen et al., 1986

Climate to a large measure determines a site's susceptibility to interrill erosion. It does this through determining to a great extent the susceptibility of the soil to interrill erosion and it provides the driving force in the interrill erosion process-except when sprinkler irrigation is involved. Climate determines to a great extent the production of biological materials that may become organic materials in the soil, and it determines the rate at which they decompose. A hot moist climate may produce much organic matter, and while it decomposes rapidly, the cover produced and the organic material in the soil may be such that interrill erosion is of little consequence. On the other hand, a cool dry climate may produce little biomass, but there may be little rainfall, hence interrill erosion may not be a threat.

Cover provides considerable protection from raindrop impact. Surface cover effects are generally those due to the plant canopy and to residue in contact with the surface. Canopy cover intercepts raindrops, and then, drops may drip to the ground, detaching and transporting soil as interrill erosion. Residue in contact with the surface protects the surface from direct raindrop impact, and reduces interrill runoff velocities. An additional feature that is frequently overlooked is that canopy cover is indicative of plant water use, and compared to a bare surface, antecedent moisture contents may be lower and runoff volumes and rates reduced, further reducing interrill erosion.

Topography is an indicator of a soil's susceptibility to interrill erosion, although interrill erosion can occur on a flat surface. Interrill erosion is particularly noticeable on ridged rows where interrill slopes are high, and, in some cases, what is assumed to be interrill erosion may be detachment by flowing water-rill erosion. Frequently, material detached on row sideslopes is deposited at the bottom of the row sideslope and may only be transported from the site if row slopes are high.

IV. Assessment of the Potential for Soil Degradation Due to Channel Processes

The forces and energies in channels are derived from flowing water. The source of this water is from rainfall excess (mostly from interrill areas), snowmelt, irrigation, and from subsurface flow emerging at the ground surface. The force available for detachment of soil from the channel periphery is generally expressed as the hydraulic shear, and is approximately proportional to the product of the depth of the flowing water and the slope of the water surface.

In contrast to interrill processes, channel processes are positionally sensitive. Until the hydraulic forces that detach channel material exceed a limiting value, channel erosion does not occur. In fact, stable channel design can be based on the existence of a critical shear value. Depending on the nature of the forces and the resisting forces for rainfall conditions, this is at some point below where channel flow occurs. In cases where the flow is due to surface irrigation or snow melt, or the emergence of subsurface flow, forces exerted by the flow may decrease downstream. For rainfall conditions, channel erosion usually increases downstream as long as slope remains constant.

Channels also carry detached materials from interrill and channel areas to points of deposition. Channels are an important part of the soil formation process, particularly when upstream interrill and channel erosion rates are excessive. Channels also deposit materials in unwanted locations–such as culverts, reservoirs, road ditches and irrigation canals.

Channels are the visible erosion process that alerts the observer to the existence of a threat to the sustainability of a land resource due to water erosion. Nearly all land degradation caused by water erosion is due to channels. Interrill erosion scarcely leaves a visible mark on the land, channel erosion causes ditches and gullies, both impediments to farming, as well as a serious degradation of the soil resource.

A. Techniques for Measuring Channel Erosion

Channel erosion is best measured volumetrically, if rates are such that sufficient precision can be gained. Techniques to make such measurements have ranged from the use of rill meters (McCool et al., 1976) to stereo photography (Piest and Spomer, 1968) to airborne lasers (Ritchey and Jackson, 1989). Recently, a laser scanner has been developed for use in erosion studies that can precisely determine the location and volume of sediment detachment and deposition in rills and small channels (Flanagan et al., 1995). Of course, volume can be measured directly using standard surveying methods when precision is appropriate.

McCool et al. (1976) described a portable rill meter for measuring small channel cross sectional areas to estimate channel erosion. The rill meter was 1.83 m wide with pins spaced at 0.0127 m. The rill meter was designed to measure a rill up to 0.4 m deep. The desired accuracy was to be able to measure channel erosion to the nearest 10 % when channel erosion was about 7 t/ha. The rill meter was reported to have worked well, making rapid accurate measurements under adverse climatic and topographic conditions. A major consideration was that the device make measurements quickly (less than 5 minutes per measurement), and that it be transportable to places in a field that were inaccessible by vehicle. A camera was used to record pin position. McCool et al. (1993) described the measurement of erosion in fields in the Palouse area of the U.S. to establish better slope length and steepness factors for the Universal Soil Loss Equation using this equipment. The study involved over 2100 slope segments over a 80 km transect in Washington and Idaho. Using cross sectional area and soil bulk density samples, soil loss by segments was computed. These data were used in developing new slope length and steepness factors for use in the RUSLE (Renard et al., 1991).

Spomer and Mahurin (1984) described the use of time lapse aerial photography to measure gully erosion, as well as sheet and rill erosion, on a small watershed in Iowa. In this case, the stereo camera was mounted on a boom truck to measure the volume of removed sediment from gullies and from the land surface over time. They measured net erosion of 291 t/ha over a 9 year period by comparing stereo-photos taken in1978 with those taken in 1969. They compared several ways of determining gully cross sections and determined that the gullies were accurately mapped using the aerial photography. The time required to make measurements, using technology available at that time, seemed to be prohibitive.

Ritchie and Jackson (1989) used laser technology to measure dimensions of small channels–ephemeral gullies from a small airplane. They found that they could detect simulated gullies with depths of 20-30 cm. They concluded that they could compare laser profile data collected at different times during the year to calculate changes in the area of gullies. Aircraft altitudes ranged from 50-200 m. Sophisticated computer software was required to analyze the laser profile measurements. Channel erosion can also be measured indirectly in small flumes (King et al., 1995) or in channels. Care must be taken in such measurements to ensure that channel erosion rates in flumes are indicative of those in natural channels. Erosion values in small flumes can be greatly distorted if flumes are small, or if soil conditions are much different than those in natural channels.

B. Techniques for Estimating Channel Erosion

Methods to estimate channel erosion are less commonly used than are methods to estimate sheet and rill erosion. In recent years, modeling technology has moved to improve estimation of channel erosion (which includes rill erosion), and some methods to estimate gully growth and gully erosion have been developed, even though they are not in common use.

Rill erosion rate is commonly estimated (Foster, 1982) as

$$Dr = Kr\,(t-t_c)(1-G/Tc) \qquad (10)$$

Where Dr is rill detachment rate (kg m^{-2} s), Kr is rill erodibility (s m^{-1}), t is hydraulic shear (Pa), t_c is critical hydraulic shear (Pa), G is sediment load (kg s^{-1}) and Tc is sediment transport capacity (kg s^{-1}). Rill erodibility and critical hydraulic shear values as measured for a number of freshly tilled soils in the United States are given in Table 1. The rill detachment computed using Equation 10 is the detachment rate from the channel perimeter, not from the surface area of the watershed being studied. The portion of Equation 10 given by (1-G/Tc) reduces the capacity of water to detach sediment. As sediment load approaches the sediment transport capacity, the ability of flowing water to detach soil decreases. When sediment load exceeds transport capacity, such as when a slope flattens, deposition occurs.

Hydraulic shear is commonly computed as

$$t = \gamma\, R\, S \qquad (11)$$

where γ is the specific weight of water (about 9800 kg m^{-2} s^{-2}), R is the hydraulic radius (m) and S is the channel slope (m/m). R can be approximated by the flow depth. The variation of hydraulic shear down a 9% slope is shown in Figure 1 for 4 different runoff rates. The channel width is assumed to be 10 cm. For this

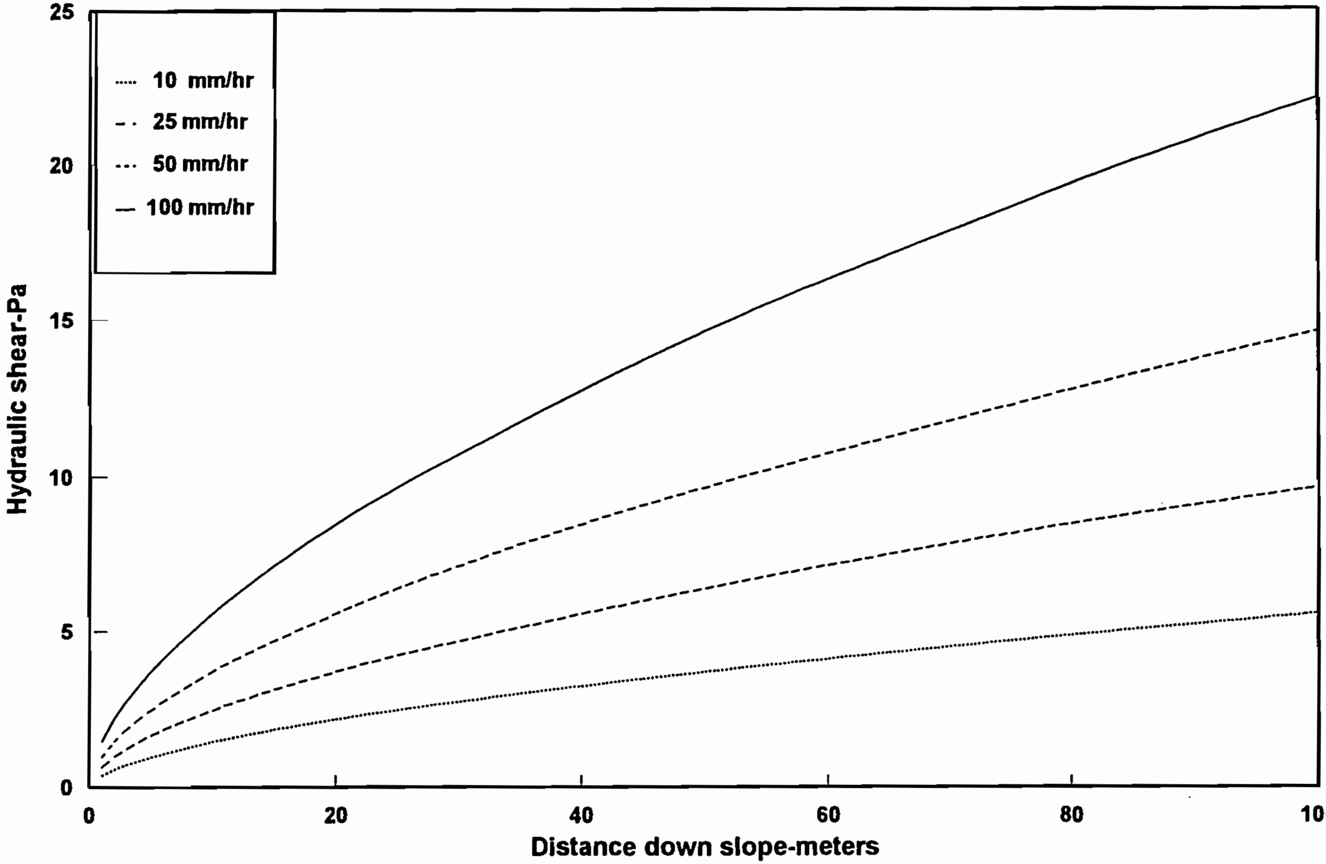

Figure 1. Change in hydraulic shear with distance down slope for runoff rates of 10, 25, 50 and 100 mm/hr for a 10 cm wide rectangular channel on a 9% slope, with 0.75 m wide contributing area.

example, hydraulic shear was quite low for this steep 9% slope when runoff rates were low (10 mm/hr) but increased quite rapidly with increased runoff rates.

Total transport capacity at a rill cross section can be approximated by (Finkner et al., 1989)

$$Tc = w_r \, B \, t^{1.5} \tag{12}$$

where Tc is transport capacity (kg s^{-1}), w_r is rill width (m) and B is a transport coefficient ($m^{.5}$ s^2 $kg^{-.5}$) that is usually in the vicinity of 100. For high slopes, transport capacity generally exceeds sediment load.

The rill detachment rate was calculated for the conditions in Figure 1 for a typical silt loam soil with a rill erodibility of 0.01 s m^{-1} and a critical hydraulic shear of 3 Pa. These are plotted in Figure 2. Note that detachment began at different points down the slope, depending on runoff rate. The point of initiation of detachment is the point where the hydraulic shear exceeds the critical hydraulic shear, which in this case was 3 Pa. If the soil was highly compacted and critical hydraulic shear was increased, erosion would be reduced substantially for the low flow rates. As shown in Table 1, soils high in sand and very fine sand tend to have the higher rill erodibilities and lower critical shears.

Ephemeral gullies are a common occurrence on many fields. They are small gullies that are fleeting in nature because they are filled by tillage (Thomas and Welch, 1988; Thomas et al., 1995) and are not visible much of the time. They can usually be crossed with field machinery. These are an important source of sediment, and they contribute greatly to soil degradation, removing from some fields more soil than that estimated by the Universal Soil Loss Equation (Laflen et al., 1986). Ephemeral gullies develop quickly, with potential deepening rates in the order of several centimeters per minute, depending on flow rates, slope and soil.

Foster (1982) developed a model for erosion in ephemeral gullies that was incorporated in the CREAMS model (Knisel, 1980). Erosion was modeled as an eroding rectangular channel. Erosion was computed as above for a rill. When the channel eroded to a layer that had a high critical shear–usually to the depth of the last primary or secondary tillage, it was assumed to begin widening. The rate of widening at the time widening began was the rate that would give the same sediment discharge rate as when the channel was deepening. The rate of widening decreased exponentially until the channel reached a width where the hydraulic shear of the flowing water was less than the critical hydraulic shear of the material on the sides of the channel or flow decreased to the point where the critical hydraulic shear on the sides of the channel exceeded the hydraulic shear of the flowing water. At that point, widening ceased. Later larger flow events might widen the channel further, or if the channel had been obliterated by tillage, initiate a new ephemeral gully at the same location.

Estimates of erosion from ephemeral gullies have been made using CREAMS (Kniesel, 1980). Watson et al. (1986) developed a model based on CREAMS technology for estimating average annual erosion from ephemeral gullies on fields. The WEPP model (Laflen et al., 1991a) also computes ephemeral gully erosion.

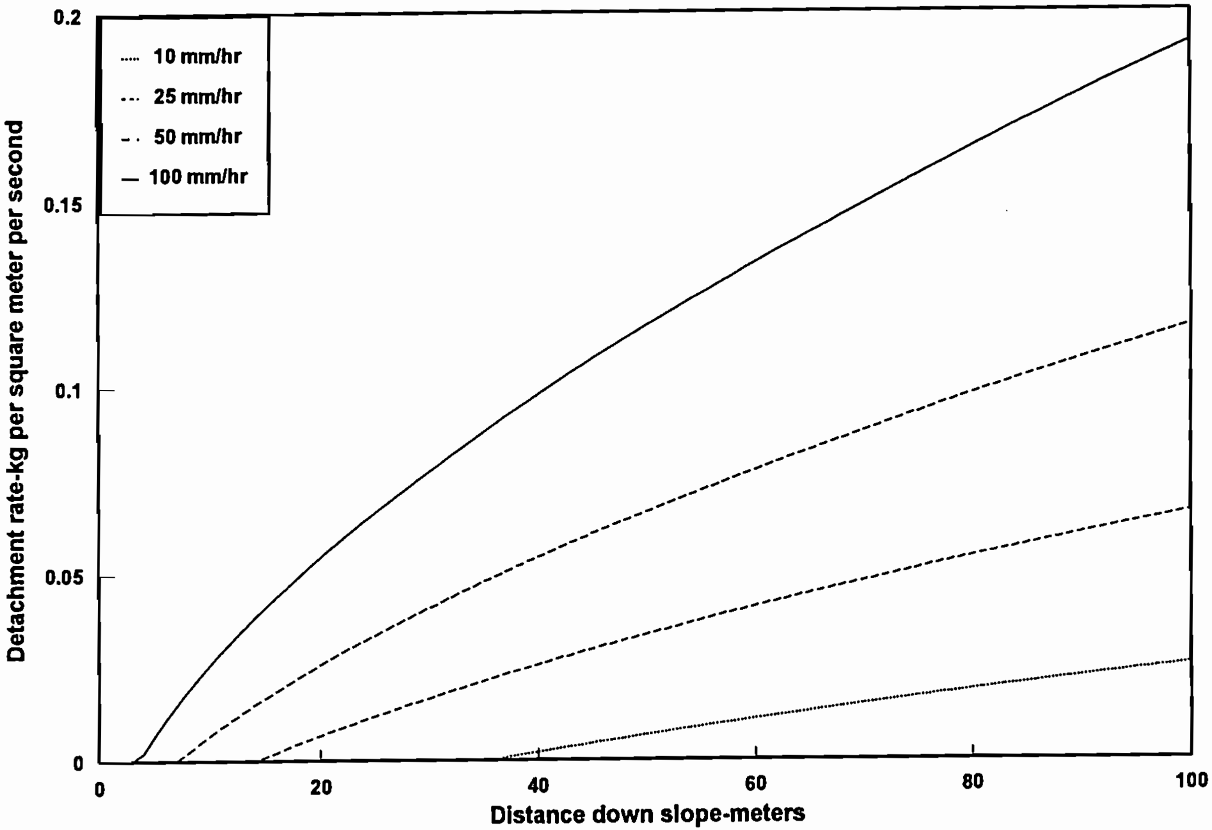

Figure 2. Detachment rate in rill versus distance down slope for the conditions shown in Figure 1.

Gullies are a major source of land degradation, their presence is a strong indicator that erosion is out of control and that the land is entering a critical phase that threatens its productivity. Lal (1992) discussed methods of restoring tropical lands that had been degraded by gully erosion. Grissinger (1996b) described rehabilitation techniques for reclaiming severely eroded lands. Both mechanical and agronomic reclamation techniques were described.

The gully erosion process has been described by Roose (1994). He described three processes of gully formation–the formation of a V-shape gully where the weathered material from the gully sides is moved from the gully bottom and additional material is moved from the gully bottom due to hydraulic shear; a U-shaped gully due to gully wall failure due to the pressure of a watertable; and tunneling in soluble material or because of burrowing animals. Bradford et al. (1973) described gully erosion has having three phases: (i) failure of gully head and gully banks, (ii) cleanout of the debris by streamflow, and (iii) degradation of the channel. They indicated that the resisting forces of the gully walls decrease to a point at which the steep gully wall collapses, creating a more stable slope geometry. If the debris is not cleaned out, the reduced slope will grass over and gully development will cease. Their observations were made in the loessial area of western Iowa. Bradford et al. (1978) concluded that the failure sequence of gullies began with a weakening of the soil material at the base of the gully wall. This weakening was a result of wetting. Once the base failed, overhanging material sloughed and then eroded material was transported downstream. The depth to water table in relation to the geometry of the gully bank played an important role in gully head and gully bank failure. They noted that soil strength decreases with increasing moisture content, that seepage forces may be important, and that the increased unit weight of the soil mass with greater water content exerts more force. Huang and Laflen (1996) have recently found that rill erosion and its initiation are greatly influenced by seepage forces.

The process of gullying seems to be well understood. Many of the factors that affect gullying and that are responsible for it are quite well understood. Still, it is extremely difficult to predict where and when gullies will occur, how fast they will develop, and whether or not they will be a factor in soil degradation for a particular site. Erosion rates can be extremely high, a 30 ha watershed continuously farmed to corn in the loessial hills of western Iowa had a gully erosion rate from a major gully of about 1000 t/yr per square km of the entire watershed, with a combined total of sheet and rill and gully erosion of over 3000 t/km^2 from the watershed (L. Kramer, personal communication). In China, Jiang et al. (1980) reported sediment delivery rates (which included sheet and rill and gully erosion) of 1000 to 18600 t/yr/km^2 to the Wuding river in the Loess Plateau. Trimble's (1974) estimates of soil erosion on the southern Piedmont, a major part of which was gully erosion, were slightly less that 1000 t/yr/km^2 over 270 years covering the period from the initiation of settlement of that area until it had essentially been destroyed for cropping. However, in very general terms, it appears that the erosion rates when land degradation was worst were well in excess of 2000 t/yr per square km. Rates have greatly declined as the land use has shifted from cultivation to a much less intensive use.

C. Limits on Channel Erosion

Limits on any kind of erosion, as discussed in the section on limits on interrill erosion, are very difficult to set. While most limits are established on the basis of the effect of erosion on productivity, there are other considerations. For the effect of erosion on crop productivity, the reader is referred to the papers cited under interrill erosion limits. In this section we will focus on channel erosion and its effect on man's ability to use the land.

Rill erosion usually has a relatively small impact on field operations, and seldom affects the use of the land except from a productivity viewpoint. Rills are usually easily obliterated by subsequent tillage operations after the rill forming events. Rills are usually shallow, even when rill erosion rates are extremely high. Rills are the source of much of the sediment originating on agricultural lands, and must be considered in any studies on the effect of erosion on productivity. Rill erosion rates at the end of long slopes could result in deepening of rills at the rate of up to about 0.5 mm per second when runoff rates are extremely high, when slopes and lengths are great, and when the soil has a high rill erodibility. The highest erosion rate for the soils shown in Table 1 resulted in a rate of deepening of the rill of about .15 mm per second. In most field situations, rates of runoff that result in these deepening rates exist for a few minutes, and only in rare storms. For extreme events, rill deepening is restricted to the depth of the most recent tillage.

Ephemeral gullies are transient channels that can cause major problems in field operations that are highly mechanized. Such gullies do not occur every year. It is assumed that they are restricted in depth to the latest tillage depth, but this is not always true. Such gullies can be much deeper than the latest tillage depth, and can form after the crop covers the ground, making it difficult to detect them when performing harvest operations. In cases of reduced tillage, and particularly where there is no tillage, ephemeral gullies may not be obliterated every year. They may become permanent gullies that cannot be crossed with most farm equipment, and may require considerable rehabilitation before mechanized agriculture can be used efficiently.

Ephemeral gullies generally form in the same location as previous ephemeral gullies, and should be replaced with nonerodibile channels-usually a grassed waterway. The formation of ephemeral gullies is a strong indication that soil erosion is not being controlled on a field, and depending on conditions, is a threat to continued use of the field for agricultural use.

The more common indication that the land is being destroyed is the presence of gullies, which range from very shallow gullies common on much cropland to the extremely deep gullies found in loessial areas such as the loess plateau in China. There are no limits to gully erosion, for their presence alone demonstrates that the limits have been exceeded. Trimble (1974) described the progression of erosion in the southern Piedmont as "sloping land was cultivated until no longer productive, abandoned, and then extremely dissected by erosion before vegetation could become established." The erosion that Trimble referred to was too often gully erosion.

Almost every area of land has some surface runoff that must be discharged from that land, hence, since channels carry surface runoff, channels will exist on nearly all lands. And, these channels will be either erodible or nonerodible. Soil conservation practices generally have a channel component that for most storms will allow surface runoff that will not allow channel erosion to destroy the land.

D. Indicators of Susceptibility to Channel Erosion

The major indicators of the susceptibility of a particular site to channel erosion are climate, topography, soil and cover.

As with interrill erodibility, the soil factors important in determining a soil's susceptibility to channel erosion involve soil characteristics related to cohesion and aggregation-clay, organic matter and very fine sand content (Alberts et al., 1995). But, there are additional considerations related to subsurface layers and subsurface hydrology that become increasingly important as channel erosion grows beyond ephemeral gullies (Bradford et al., 1973; Bradford et al., 1978). Also of increasing importance are soil characteristics related to their effect on surface runoff, for surface runoff becomes of increasing importance in channel erosion.

Surface cover, both canopy and residue, are indicators of the susceptibility of a specific site. Canopy is important because it determines to a great extent surface runoff. When canopy is great, runoff volumes are frequently low because plant water use is high and antecedent moisture is low (there are notable exceptions). Residue has a major impact on channel erosion, particularly rill erosion. Residue reduces runoff velocities (Kramer and Meyer, 1969), and serves as a storage location for sediment with deposition above residue occurring very similarly to that in other impoundments (Brenneman and Laflen, 1982). Residue tends to fail in effectiveness as channels increase in size, and generally has little effect on detachment and transport within ephemeral and larger size gullies.

Climate, as in interrill erosion, determines to a great extent the importance of the other factors. Climate determines surface runoff rates and volumes, the driving force in channel erosion. Climate, as in interrill erosion, determines the existence of surface cover and organic matter. And, climate determines the timing of runoff events along with the occurrence of surface cover.

Topography, like climate, is a necessary requisite to channel erosion. The most severely degraded lands in the world, at least as far as quantity of eroded material is concerned, are in areas with exceptionally high relief. Loessial areas are nearly always prone to high channel erosion rates, mostly because of the very high slopes in channels.

V. Control of Soil Degradation Due to Water Erosion

Soil erosion by water is basically a process of detachment and transport (Ellison, 1947). The soil is detached and then transported until it reaches a point of deposition. For either interrill or rill erosion, control methods usually then take the form of some combination of practices that do one or more of the following:

1. Reduce the magnitude of detaching forces acting on erodible surfaces.
2. Reduce the fraction of an area subject to erodible forces.
3. Increase the resistance of the erodible surface to detachment.
4. Reduce the ability of flow to transport detached materials, and induce deposition of transported materials.

The application of detaching forces to erodible surfaces can be reduced by reducing both the magnitude of the forces and by protecting the surfaces from direct application of detaching forces. For interrill erosion, forces are reduced by canopy and residue. For channel erosion, practices that decrease surface runoff reduce the detaching forces. One of the most effective means for controlling both interrill and channel erosion is to increase crop yields; this generally increases crop water use, reduces runoff volumes, increases canopy and increases residue on the soil surface. In Ohio, no-till nearly halted surface runoff (Harrold and Edwards, 1974). Effective contouring reduces shearing forces of runoff water by reducing the slope of rills and channels carrying runoff water. Ridge tillage on the contour reduces surface runoff volumes (L. Kramer, personal communication), again reducing the forces for sediment detachment. Properly designed, constructed and maintained waterways reduce the forces flowing water exerts so that channels and gullies are not formed. In some cases, grade control structures in channels are necessary to control detachment forces.

Reducing the susceptibility of the surface to detachment can be accomplished in a number of ways. The use of no-till (direct drilling) increases the resistance of the soil to detachment in interrill and channel areas. Improving soil aggregation and the use of some soil amendments also increase the resistance of the soil to detachment. Grassed waterways have a soil surface that is greatly resistant to detachment by flowing water. Soil that remains undisturbed for long periods usually increases in resistance to detachment, but this is dependent on soil properties. The ability to transport detached material is reduced in many practices through reduction of runoff velocity. In conservation tillage, even small amounts of residue can greatly reduce runoff velocity (Kramer and Meyer, 1969). In ridge tillage, rows at low slopes will greatly reduce runoff velocity. In grassed waterways, dense grass serves to reduce runoff velocity. Grade control devices in channels will control runoff velocity and reduce the energy available for sediment transport. In most channels, locations where runoff velocity is reduced results in immediate deposition of much transported material. In conservation tillage, deposition sites can be found above individual pieces of crop residue (Brenneman and Laflen, 1982). Deposition is also induced when runoff water enters small impoundments above terraces (Laflen et al., 1978), or when runoff water slows as it passes through a strip of grass. A regular maintenance of grassed waterways is to remove deposited soil. Other deposition sites can be found where water flows from a row crop or small grain into a strip of meadow on a strip cropped field.

While the examples given above are those related to agricultural use of the land, the same principles apply for soils having other land uses. As Ellison (1947) stated, erosion is a process of detachment and transport. Erosion control then involves reducing detachment and transport.

VI. Conclusions

Soil erosion by water is the major cause of soil degradation on the planet earth. As the earth's population increases, soil degradation inevitably leads to reduced food supplies for those that inhabit this planet. The scale of soil degradation is difficult to grasp, but at least a billion ha of the earth's soil has been seriously degraded because of water erosion. The estimated costs of water erosion exceed $400 billion dollars per year.

Soil erosion by water can be measured and estimated. Estimation techniques have been developed and applied on most of the earth's lands. Measurement of soil erosion has helped evaluate and apply these estimation techniques. Measurement techniques are available for a broad range of applications from detailed research studies to broad-based assessment techniques.

Soil erosion limits are usually based on the effect of soil erosion on the productivity potential of the soil. An additional consideration is the dissection of the landscape, making use of the land very difficult. Future limits may well be based on off-site effects.

Erosion control methods are based on the fundamental principles of soil erosion by water. Soil erosion is a process of detachment of materials and their transport to another location. Erosion control practices are those that reduce the susceptibility of soil to detachment, that reduce the magnitude of detaching forces, that reduce the fraction of the surface to which detaching forces can be applied, and those that induce deposition. An understanding of these principles is important in developing erosion control practices for the many situations where soil erosion exceeds allowable limits.

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