#539

EROSION BY CONCENTRATED FLOW IN FARM FIELDS
by G. R. Foster and L. J. Lane

from

PROCEEDINGS
OF THE
D.B. SIMONS SYMPOSIUM
ON
EROSION AND SEDIMENTATION

CO-EDITED BY
RUH-MING LI
PETER F. LAGASSE
SIMONS, LI & ASSOCIATES, INC.

IN COOPERATION WITH
COLORADO STATE UNIVERSITY
AND
WATERWAY, PORT, COASTAL AND OCEAN DIVISION
OF THE
AMERICAN SOCIETY OF CIVIL ENGINEERS

TABLE OF CONTENTS

For information, correspondence, and to order:

Simons, Li & Associates, Inc.
P.O. Box 1816
Fort Collins, CO 80522 U.S.A.

Phone: (303) 223-4100

Checks payable to: Simons, Li & Associates, Inc.

or

CSU Engineering Development Office
Engineering Building
Colorado State University
Fort Collins, CO 80523

Phone: (303) 491-5877

Checks payable to: CSU Foundation

EROSION AND SEDIMENTATION

September 1983

Published by D. B. Simons Symposium on Erosion and Sedimentation. Printed in the United States of America. This publication is printed and bound by BookCrafters, Inc., Chelsea, Michigan, U.S.A.

EROSION BY CONCENTRATED FLOW IN FARM FIELDS

By G. R. Foster and L. J. Lane, A. M. ASCE*

I. Abstract

A variety of channels occur in farm fields; some are formed by erosion and others like terraces are constructed specifically to prevent erosion. These channels range from small rills to large gullies. Topography causes overland flow on many farm fields to collect in natural waterways, intermediate sized channels. Immediately after seedbed preparation, these concentrated flow areas may be highly susceptible to erosion, and erosion in them may be as great as sheet and rill erosion for the field. Processes of erosion by concentrated flow in farm fields are discussed, and equations describing these processes are developed. Erosion rates calculated with the equations are compared with observed data.

KEY WORDS: RILL EROSION, CHANNEL EROSION, GULLIES, CONCENTRATED FLOW, AGRICULTURAL FIELDS, SEDIMENT CHARACTERISTICS.

II. Introduction

Erosion on farm fields reduces the crop productive potential of soils and produces sediment that may leave the fields to cause off-site environmental damage. Gullies, eroded channels that cannot be crossed with farm equipment, hinder farming operations, especially the use of large tillage and planting equipment, and reduce land value. Severe erosion may force land from cultivated crops to pasture and forest.

Sheet, rill, and gully erosion are the usual types of soil erosion by water on farm fields. Rill and gully erosion are forms of channel erosion. Rill erosion is often defined as erosion that occurs in small channels that can be obliterated by tillage while gully erosion is defined as erosion that occurs in channels that can not be obliterated by tillage (19). However, intermediate sized natural or constructed waterways exist in many fields which fit the definition of a rill but behave hydraulically as a larger channel. The purpose of this paper is to review definitions and features of eroded channels within farm fields and to develop equations describing these processes.

Sheet erosion, interrill erosion as it is sometimes called, is from the soil surface and can produce large quantities of sediment. This somewhat uniform detachment of soil often proceeds unnoticed until extensive damage has occurred. Runoff, however, is not uniform across farm fields but is concentrated in tillage marks and micro-channels. Erosion in these small channels, defined as rill erosion, depends primarily on overland flow hydraulics. These small eroded channels or rills, typically about 50 to 300 mm wide and up to about 300 mm deep, vary greatly in frequency across fields depending on the

---

* Hydraulic Engineer, USDA-Agricultural Research Service, and Associate Professor, Agricultural Engineering, Purdue University, W. Lafayette, IN (on assignment to Los Alamos National Laboratory, Sept. 1982-July 1983); and Hydrologist, USDA-Agricultural Research Service, Tucson, AZ.

frequency of preformed tillage marks, land slope, and the resistance of the soil to rill erosion. A typical frequency is about one rill per meter (25). Rills imply numerous small channels across a hillslope such that the removal of a single rill has minimal effect on the erosion response of a field, while a flow in a waterway implies one of a few major channels in a field (7). Flow in rills is frequently analyzed as broad sheet overland flow. In special cases, flow in an individual rill may be analyzed as channel flow to represent the flow in a group of rills having very similar characteristics (21).

Topography frequently causes overland flow to concentrate in a few major natural waterways before leaving a field. Where excessive erosion occurs in natural waterways, constructed channels such as diversions, terrace channels, and grassed waterways are installed to collect runoff and convey it off the field at nonerosive velocities. Severe erosion by flow in waterways results in gully erosion.

Tillage equipment can till across eroding waterways in many fields. Immediately after seedbed preparation, the waterway areas may be highly susceptible to erosion. Even though channels formed by erosion in these waterways are obliterated by subsequent tillage, fitting the popular definition of a rill, they should be treated as individual channels in erosion analyses (14). Runoff in these types of waterways has sometimes been called concentrated flow, and erosion by this flow has been called concentrated flow erosion (14).

Since overland flow often converges in waterways, sediment yield from fields is normally by flow in waterways. Depositon by flow occurs when the sediment load is greater than the flow's sediment transport capacity. The gradient along many waterways decreases from a fairly steep grade at the head of the channel to almost level at the edge of the field. In such cases, erosion may occur on the upper end of the waterway where transport capacity is greater than the incoming sediment load from the overland flow areas. As flow moves down the channel, sediment load accumulates while transport capacity increases due to accumulation of flow. At further distances, the transport capacity then begins to decrease because the decreasing gradient has more effect on transport capacity than does the accumulation of runoff. Frequently the gradient flattens so much that large quantities of sediment are deposited within the field. Deposition may also occur in backwater at field outlets due to vegetation or ridges around fields retarding or damming the flow (22).

Not all channels have both erosion and deposition along their length. Deposition may occur everywhere along low gradient channels such as terraces (8), or erosion may occur everywhere along steep channels having unrestricted outlets. In some channels, however, neither erosion nor deposition occur; the channels simply translate the incoming sediment from overland flow areas.

Frequently the question is asked, "Is this channel a rill, waterway (concentrated flow), or a gully?" Definition of rills, waterways (concentrated flow areas), and gullies continues to be a problem. The definitions given above, though too imprecise to eliminate the problem, provide guidance. In the context of the above definitions, erosion in rills, waterways (concentrated flow areas), and gullies are all forms of channel erosion. Rills imply micro-channels, gullies imply channels too large to traverse with tillage equipment, and waterways imply intermediate sized channels. Furthermore, gullies imply deep channels with steep sidewalls relative to waterways which are shallow without well defined sidewalls. The emphasis of the following discussion is on waterways because they occur in most fields, and they have received little attention in erosion literature. Since rill erosion processes are similar to those occurring in waterways, much of the following discussion applies to rills, and information from rill erosion studies is used to describe erosion in waterways.

III. Erosion by Flow

1. Fundamental Concept

A fundamental concept in erosion mechanics is that flow has the potential for either erosion or deposition depending on the relationship of sediment load to sediment transport capacity (7). If sediment load is greater than transport capacity, deposition occurs at a rate proportional to the difference between the transport capacity and the sediment load. If the sediment load is less than the transport capacity, the flow has a potential for detaching soil from the boundary of the channel. Shear stress of flow in the channel is frequently used as a measure of the erosivity of the flow. However, no erosion is assumed until the flow's shear stress exceeds a critical shear stress, a measure of the soil's resistance to erosion.

2. Critical Shear Stress

With the exception of grassed waterways, farmers regularly till across most waterways. Tillage greatly reduces the resistance of soil to erosion by flow. Measured rill erosion rates immediately after tillage were about three times those measured before tillage (12). Foster et al. (15) suggested that the critical shear stress for flow to initiate erosion of a typical midwestern silt loam soil might vary over a cropping year from about 5 N/m^2 for a freshly prepared seedbed to 25 N/m^2 for a well consolidated soil that had not been tilled for three months. Several of the factors influencing critical shear stress are soil texture, compaction, drying, type of tillage, and degree of pulverization by tillage (15, 18). Smerdon and Beasley (27) found that critical shear stress for a soil with 55 percent clay was five times that for a soil with 10 percent clay, and Laflen and Beasley (23) found that an increase in void ratio by 50 percent decreased critical shear stress by 40 percent.

Most field soils are cohesive. Clay content ranges from about 10 percent for sandy loam soils to about 35 percent for clay loam soils. Silt content ranges from about 30 percent for clay loam soils to about 90 percent for silt loam soils. Sand content varies from about 20 percent for silt loam soils to about 70 percent for sandy loam soils. Although much attention has been given to clay as an indicator of critical shear stress, the role of silt, sand, organic matter, and chemical constituents may also be important. However, the influence of these factors on the erosion of tilled agricultural soils has not been studied extensively.

Erosion in waterways in farm fields differs distinctively from erosion of noncohesive sediment from alluvial stream channels. A critical shear stress to initiate movement of noncohesive sediment of the size of soil particles for silt loam field soil is about 0.5 N/m^2 in comparison to measured values of 3

N/m^2 required to detach soil particles in rill erosion studies immediately following tillage (9). In other words, less shear stress is required to initiate sediment transport once the sediment is detached than is required to initially detach the sediment.

3. Selectivity of Erosion by Flow

Flow in waterways on agricultural soil does not selectively erode either clay, silt, or sand based on results from rill erosion studies (2, 25). While large particles like gravel and stone may not be eroded, they do not significantly armor the soil and affect the erosion of sand, silt, and clay. Gravel and stone are generally a small fraction of tilled agricultural soils, and any surface armor that might develop over time is buried and mixed with the underlying soil by tillage.

4. Effect of Nonerodible Layers

Immediately after seedbed preparation, the surface zone tilled by secondary tillage may be much more erodible than both the underlying zone tilled only by primary tillage or lower zones undisturbed by tillage (15). When resistance to erosion is great in zones beneath the tilled surface zone, flow in tilled waterways erode the soil to the depth of secondary tillage. Downward erosion then ceases, and the channel begins to widen from lateral erosion, the widening and erosion rates decreasing as the channel widens. When discharge is steady, the channel widens to a final width and erosion almost stops (10). A subsequent smaller discharge rate causes little or no erosion. However, a subsequent discharge rate greater than the one that initially formed the channel will cause further erosion. As before, the erosion rate decreases as the channel approaches its final width for the new discharge. The erosion rate of uniform soils is constant for a constant discharge (10, 24).

IV. Sediment Characteristics Produced by Erosion

Sediment eroded by rill erosion on farm fields is a mixture of aggregates and primary particles (2, 7, 31). The aggregates,, conglomerates of primary particles and organic matter, are larger than the primary particles making up the aggregates, and the average size of the aggregates is larger than the average size of the primary particle making up the soil. Aggregate diameter may range from clay size, <0.002 mm, to larger than coarse sand size, 2.0 mm (2, 24). The specific gravity of aggregates (31) may range from 1.6 to 2.65 (the specific gravity of the primary particles) and influences the transport of aggregates by shallow flow more than diameter (4, 6, 11).

The size of eroded particles depends on the primary particle size distribution of the soil, recency and type of tillage, and ground cover (16, 31). Clay fraction in the soil is an important factor in the aggregation of the eroded sediment and the size of the eroded aggregates. Generally, the higner the clay fraction, the greater is the amount of aggregated sediment and the larger are the aggregates (16, 31). Since much of the sediment is aggregated, much of the eroded clay is contained in the aggregates. Clay as a primary particle in the sediment may be no more than 20 percent of the clay fraction in the soil (2, 16) unless deposition has enriched the sediment in the fraction of fine particles.

Clay and organic matter are highly important in the transport of soil adsorbed chemicals because of their large surface area relative to that of sand and silt. Most sediment associated nutrients, herbicides, pesticides, and insecticides leave the field attached to clay and organic matter (1).

V. Mathematical Equations for Erosion by Concentrated Flow

Numerical evaluation of erosion in channels requires mathematical equations to describe these processes. In the past, if erosion in a natural waterway was visually judged to be excessive, a grassed waterway was installed as a replacement channel to prevent erosion. Diversion and terrace channels are usually designed to be noneroding. Design of stable channels is discussed by Graf (17).

Channel design methods based on stability criteria do not estimate erosion rates needed to assign erosion reduction benefits from protection of eroding waterways in fields. In the case of rill erosion, common predictive equations include it with interrill erosion (7). Recent interest in nonpoint source pollution has resulted in several models including CREAMS (21) for estimating erosion, deposition, and sediment transport rates within farm fields (3, 5, 20, 28). Relationships in CREAMS are summarized to illustrate equations for describing erosion by flow in rills and waterways.

1. Detachment

Detachment of soil particles from the wetted perimeter may be described by (10):

$$D = K\,(\tau_s - \tau_c)^{1.05} \tag{1}$$

where D = detachment rate at a point on the wetted perimeter (mass/unit area of wetted perimeter · unit time), K = a soil erodibility factor for erosion by flow, τ_s = shear stress acting on the soil at a point on the wetted perimeter, and τ_c = a critical shear stress. Equation 1 has been verified with field research for rill erosion (10). Grass or mulch cover protects the soil from erosion by reducing the shear stress τ_s acting on the soil (13, 29). Shear stress τ_s is assumed to control both erosion and sediment transport. It may be estimated with concepts used in sediment transport analysis (17) that divide a flow's total shear stress into that acting on grain roughness (equivalent to that acting on the soil) and that acting on form roughness (equivalent to that acting on soil cover). Shear stress increases around the wetted perimeter from zero at the water surface to a maximum at the middle of the channel (17). The shear stress distribution around an eroded channel in a farm field is described by:

$$\tau_* = \tau_s/\bar{\tau}_s = 1.35[1 - (1 - 2x)^{2.9}] \tag{2}$$

where τ_* = normalized shear stress, $\bar{\tau}_s$ = the cross sectional average shear stress acting on the soil, and x = the ratio of distance from the water surface along the wetted perimeter to a particular point on the wetted perimeter to the length of the wetted perimeter. Equation 2 has the properties of: $\int_0^{0.5} \tau_e dx = 0.5$; $d\tau_e/dx = 0.0$ and $\tau_e = 1.35$ at $x = 0.5$ (location of maximum shear stress); and $\tau_e = 0.0$ at $x = 0.0$.

2. Erosion before Channel Reaches a Nonerodible Layer

The above equations were used in a dynamic model to study eroded channel development from an initial cross section by computing erosion rate at closely spaced points around the perimeter of the channel. Displacement normal to the wetted perimeter is given by:

$$\Delta z = D\Delta t/\rho_s \tag{3}$$

where Δz = the displacement for the time interval Δt and ρ_s = the bulk density of the soil. If a nonerodible layer is sufficiently deep and discharge is steady, erosion develops an equilibrium channel shape. Erosion rate is unsteady during the initial incisement of the channel, but it becomes steady after the equilibrium channel is reached and remains steady until the nonerodible layer is reached.

If an equilibrium cross section exists, the channel must erode downward so that all points along the eroding portion of the channel move downward at the same rate. This requirement is met when:

$$D_y = D_m \tag{4}$$

where D_y = the vertical erosion vector at x and D_m = the vertical erosion vector at the middle of the channel, where $x = 0.5$. The vertical erosion vector is given by:

$$D_y = D/\cos\theta \tag{5}$$

where D = the erosion rate normal to the wetted perimeter at x and θ = the angle between the normal to the wetted perimeter and the horizontal. The equation for the channel boundary is therefore:

$$\cos\theta = D/D_m \tag{6}$$

Substitution of Eqs. 1 and 2 into Eq. 6 gives:

$$\cos\theta = [(\tau_e - \tau_{ec})/(1.35 - \tau_{ec})]^{1.05} \tag{7}$$

where τ_{ec} = normalized critical shear stress and x_c = the x where $\tau_e = \tau_{ec}$. Equation 7 applies from $x_c \le x \le 0.5$, and for $x \le x_c$, $\theta = 90.0°$ so that the wetted perimeter from the water surface to where shear stress equals critical shear is vertical. This assumes that the channel walls can stand vertically, an appropriate assumption for rills in many cohesive soils. According to Eq. 7, the shape of the channel cross section at equilibrium is a function of x_c and the shear stress distribution τ_e. The variable x_c is a measure of cross-sectional average shear stress to critical shear stress. Equation 7 was numerically solved to construct a range of cross sections so that wetted perimeter, flow area, hydraulic radius, and width could be determined as a function of x_c as shown in Fig. 1.

Erosion rate E for a cross section can be computed from:

$$E = D_a W_e \qquad (8)$$

where E = erosion rate per unit channel length and W_e = the equilibrium width of the channel since all erosion rates in the vertical direction across the width of the rill are equal. Substituting in Eq. 5 for D_a gives:

$$E = W_e K(1.35\bar{\tau}_s - \tau_c)^{1.05} \qquad (9)$$

The average shear stress $\bar{\tau}_s$ is given by:

$$\bar{\tau} = \gamma RS \qquad (10)$$

where γ = the specific weight of the flow, R = hydraulic radius, and S = grade along the channel. Shear stress acting on the soil is assumed to equal total shear stress. Otherwise, the shear stress $\bar{\tau}_s$ is reduced from $\bar{\tau}$ for the effect of cover.

Solution of Eqs. 9 and 10 requires determining a value for x_c in order to use Fig. 1 to obtain values for W and R. The value for x_c is implicitly determined from:

$$\tau_c = \gamma R S \tau_{*c} \qquad (11)$$

Hydraulic radius R is related to the discharge rate in the channel by Manning's equation:

$$Q = (AR^{2/3}S^{1/2})/n \qquad (12)$$

where Q = discharge rate, A = flow area, and n = Manning's n. By the definitions, A = R P and r = R/P, Eq. 12 becomes:

$$Q = (R^{8/3}S^{1/2})/nr \qquad (13)$$

By Eq. 11, R equals:

$$R = \tau_c/\gamma S\tau_{*c} \qquad (14)$$

which substituted in Eq. 13 gives:

$$Q = [(\tau_c/\gamma S\tau_{*c})^{8/3}S^{1/2}]/nr \qquad (15)$$

Rearranging Eq. 15 gives a conveyance function:

$$g_{xc} = (Qn/S^{1/2})^{3/8}\gamma S/\tau_c = 1/\tau_{*c}r^{3/8} \qquad (16)$$

Since Eq. 16 cannot be solved explicitly for x_c, the function:

$$g_{xc} = 1/\tau_{*c}r^{3/8} \qquad (17)$$

was computed and plotted in Fig. 2.

For a particular problem, x_c is read from Fig. 2 after g_{xc} is computed from Eq. 16. Values for normalized hydraulic radius r = R/P and width w = W/P

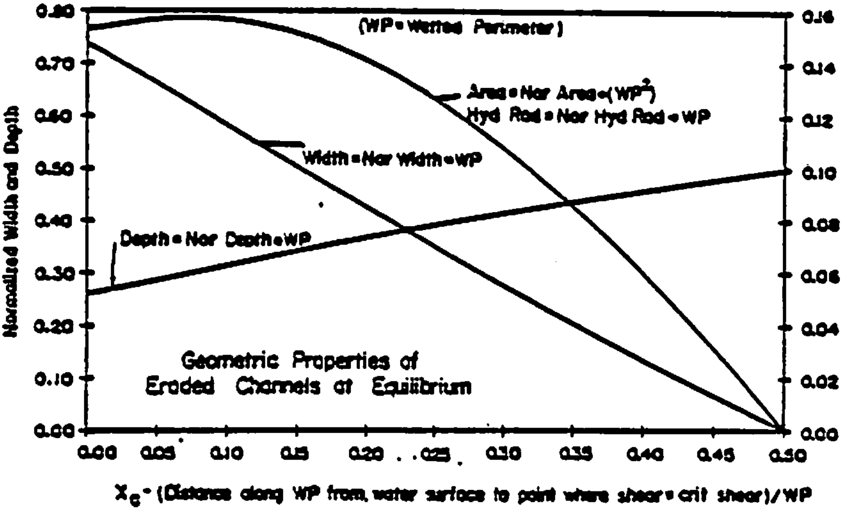

Fig. 1. Geometric properties of an eroding channel at equilibrium.

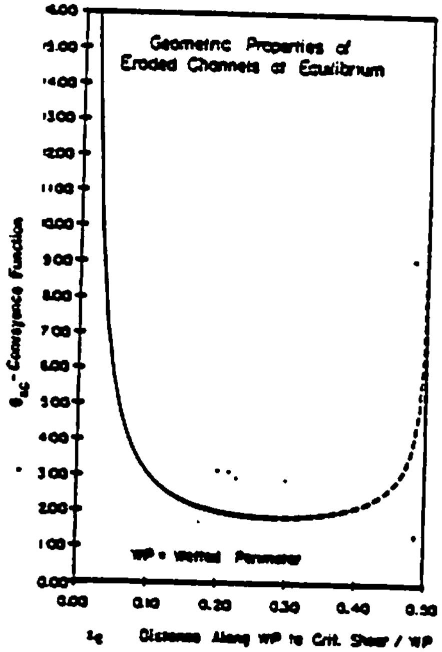

Fig. 2. Function g_{xc} for an eroding channel at equilibrium.

are read from Fig. 1. A value for W is calculated from Eq. 18, a result of combining Eq. 13, P = R/r, and v = W/P:

$$W = [(Qn/S^{1/2})^{3/8}]v/r^{5/8} \tag{18}$$

The equation for hydraulic radius is obtained from P = W/v, P = R/r, and Eq. 13:

$$R = (Qnr/S^{1/2})^{3/8} \tag{19}$$

The following example illustrates how the equations are used to compute an erosion rate. Assume $Q = 0.0011\ m^3/s$, $n = 0.03$, $S = 0.09$, and $\tau_c = 4.8\ N/m^2$. The value computed for g_{xc} from Eq. 16 is 6.0. From Fig. 2, $x_c \cong 0.05$ and values of 0.155 and 0.66 are obtained from Fig. 1 for r and v_c respectively. Hydraulic radius is 0.0163 m from Eq. 19 giving a value of 14.4 N/m^2 for average shear stress, $\bar{\tau}$. The value for width W from Eq. 18 is 0.0694 m. If K in Eq. 9 is 11, the erosion rate from Eq. 9 is 12.8 g/m s. These values of K and τ_c apply to rill erosion data of Foster and Lane (10). Results from the same computations for the data from field erosion experiments (10, 24) are shown in Tables 1 and 2. Values for K were 2.76 and 2.34 for no canopy and canopy, respectively, and values for τ_{cr} were 2.87 and 4.16 N/m^2 for no canopy and canopy, respectively, in the study by Meyer et al. (24).

Table 1. Observed and calculated rill erosion rates at the initiation of discharge for study by Foster and Lane (10).

Discharge Rate $\times 10^4$	Manning's n	Rill Grade	Rill Erosion Rate Per Unit Length of Rill: Observed	Rill Erosion Rate Per Unit Length of Rill: Calculated
(m^3/s)			(g/m.s)	(g/m.s)
2.07	0.039	0.100	1.59	2.83
3.00	0.040	0.095	3.03	4.02
3.85	0.040	0.099	5.36	5.51
5.83	0.030	0.083	7.65	5.06
8.07	0.035	0.097	13.03	10.28
12.49	0.035	0.094	15.56	14.90
17.16	0.031	0.085	22.96	16.24
21.75	0.026	0.096	49.60	19.21

An advantage of the equations derived for the eroding equilibrium channel width is that computation of erosion rate does not require the assumption of a particular hydraulic geometry. This is especially important where rills develop and become incised on a relatively flat surface rather than developing in preformed channels such as tillage marks. Further field and analytical research is needed on the initialization of rills and their geometry, erosion rate, and hydraulics during initiation. Also, experiments are needed to determine soil erodibility and critical shear stress values for a wide range of conditions.

where W = channel width at time t and W_i = the initial channel width. Time t was normalized as:

$$t_* = t(dW/dt)_i/(W_f - W_i) \tag{23}$$

where $(dW/dt)_i$ = the rate that the channel is widening at the beginning of a time period and is given by:

$$(dW/dt)_i = 2K(\tau_b - \tau_c)^{1.05}/\rho_s \tag{24}$$

where τ_b = the shear stress at the intersection of the channel sidewall and the nonerodible layer at t_i. The relation of W_* to t_* as evaluated with the dynamic erosion model for steady discharge was for practical purposes:

$$W_* = 1 - \exp(-t_*) \tag{25}$$

Erosion rate is determined by considering the change in channel width for the time t measured from the beginning of the time period. The equation for change in width is obtained by rearranging Eq. 22 to give:

$$\Delta W = W - W_i = W_*(W_f - W_i) \tag{26}$$

The average erosion rate for the time period t is:

$$E = \Delta W \, H_{sw} \rho_s / t \tag{27}$$

where H_{sw} = the height of the channel sidewall. Computed erosion rates from these equations are shown in Fig. 3 with observed erosion rates.

Table 3. Observed and calculated final eroded rill widths for study by Foster and Lane (10).

Discharge Rate $\times 10^4$	Final Eroded Rill Width	
	Observed	Calculated
(m^3/s)	(mm)	(mm)
3.00	82	88
3.85	113	101
5.83	131	104
8.07	134	143
12.49	177	183
17.16	207	201
21.75	238	213

VI. Magnitude of Erosion by Concentrated Flow

Erosion by concentrated flow may be practically nonexistent, or it can produce much of the sediment leaving a field. This type of erosion is greatest on steep and long slopes where shear stress of the flow is great. Also, it is greatest when the soil is most susceptible to to erosion by flow,

Table 2. Observed and calculated rill erosion rates for study by Meyer et al. (24).

Discharge Rate $\times 10^4$	Rill Erosion Rates Per Unit Length of Rill	
	Observed	Calculated
(m^3/s)	(g/m.s)	(g/m.s)
1.85	0.26	0.45
3.51	0.81	0.90
5.49	1.45	1.41
7.97	2.37	2.01
4.36	0.38	0.71
8.22	0.94	1.44
10.78	1.56	1.86

3. Erosion after Channel Reaches a Nonerodible Layer

Once a channel reaches a nonerodible boundary, it widens as a rectangular channel at the rate that the sidewall is eroded at its intersection with the nonerodible boundary. As the channel widens, erosion rate decreases because of reduced average shear stress and reduced shear stress on the sidewall. The dynamic model used to study initial channel development was also used to study erosion rate as a channel widens.

The analysis indicated that erosion rate exponentially approaches zero as the channel exponentially approaches a final width. The final width depends on discharge rate, channel grade, and critical shear stress. The condition for the final channel width is given by:

$$(Qn/S^{1/2})^{3/8}(\gamma S/\tau_c)=\{[x_{cf}(1-2x_{cf})]^{3/8}\tau_{*cf}\}^{-1} \tag{20}$$

where x_{cf} = the relative distance from the water surface down the sidewall to the nonerodible layer and τ_{*cf} = the shear stress distribution function evaluated at x_{cf}. Shear stress at x_{cf} equals the critical shear stress, the condition for the channel reaching a final width. Given a value for x_{cf} determined implicitly from Eq. 20, a value for the final width W_f can be found from:

$$W_f = [(Qn/S^{1/2})[(1-2x_{cf})/x_{cf}^{5/3}]]^{3/8} \tag{21}$$

Values of W_f were computed and given in Table 3 with observed widths for field data (10).

We did not find a simple analytical expression for the decrease of erosion rate with time as the channel widened. Instead, a wide range of values for the controlling variables was substituted into the dynamic erosion model to generate a family of curves for channel width W normalized by:

$$W_* = (W-W_i)/(W_f-W_i) \tag{22}$$

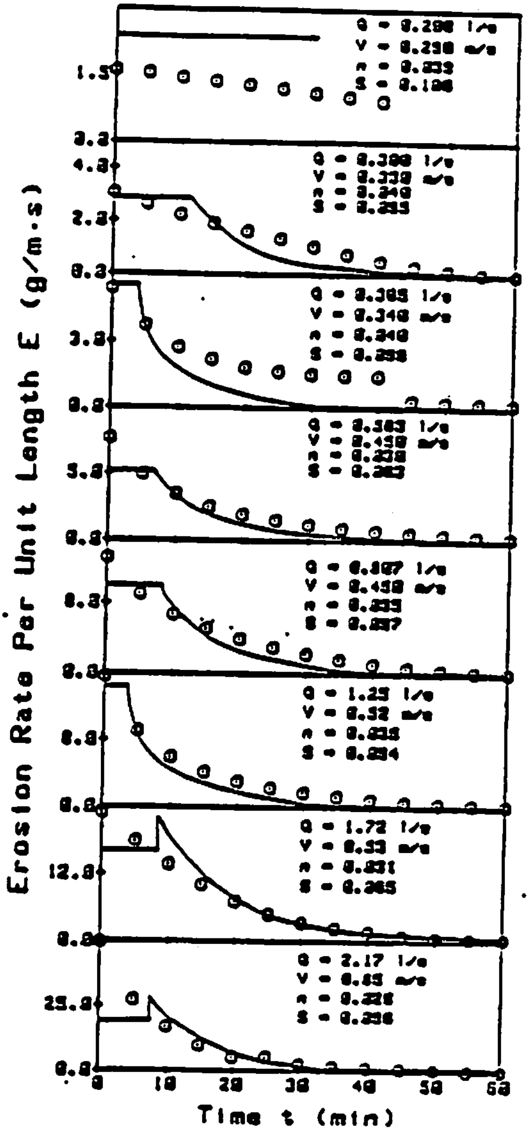

Fig. 3. Observed and computed rill erosion rates for data of Foster and Lane (10) showing the effect of a nonerodible layer.

usually immediately after seedbed preparation on tilled land, a period of intense midwestern spring rains producing large rates and amounts of runoff. Erosion by concentrated flow in natural waterways has seldom been measured, but early indications from a program recently initiated by the USDA-Soil Conservation Service (SCS) to measure this type of erosion on farm fields in several states suggest that this erosion may equal or exceed sheet and rill erosion. Such observations agree with estimates from CREAMS for a typical field in Georgia (22). A better understanding of erosion by concentrated flow was identified as a high priority research need in 1982 by the USDA-SCS, and research has been initiated by the USDA-Agricultural Research Service and others to learn more about this type of erosion and how to better estimate it.

VIII. Summary

A variety of channels occur in farm fields; some are formed by erosion and others are constructed specifically to prevent erosion. Eroded channels range from small rills several millimeters wide and deep to large gullies several meters wide and deep. Intermediate sized natural channels in areas where topography has caused overland flow to concentrate can be eroded if not protected with grass or crop residue. Constructed channels include grassed waterways, terrace channels, and diversions.

Channel erosion within farm fields degrades the soil and reduces the yield potential of the field for growing crops. Furthermore, when channel erosion becomes so severe that farm equipment cannot cross the eroded areas, farm operations are inconvenienced, efficiency drops, costs increase, and land values fall. If channel erosion within fields becomes extremely severe, the field may be forced out of cultivated crop production into pasture, idle land, or forest land.

Farmers regularly till over most channels in fields except for gullies and permanently vegetated waterways. Tillage greatly decreases the resistance of channel areas to erosion. Following tillage, resistance to erosion increases over a cropping season due to traffic compaction, wetting and drying, vegetative growth, and other processes. Untilled soil below the tilled zone also reduces erosion by restricting downward erosion of channels. Once a channel erodes to the untilled soil, downward erosion ceases, and widening begins. The widening rate is relatively fast at first but decreases to zero as the channel width approaches an equilibrium width. Erosion in a channel for a given stormflow is a function of the amount of downward and lateral erosion from previous storms. Therefore, channel erosion within cultivated fields often decreases during a cropping season for two reasons: increased resistance to erosion with time and restriction of downward erosion by untilled soil beneath the tilled zone.

Sediment eroded from channels in farm fields is a mixture of primary particles and aggregates made up of primary particles. Aggregates may be much larger than their primary particles, and their densities may be significantly less than that of primary particles.

Mathematical relationships for these processes are available for estimating erosion by concentrated flow in farm fields. These equations assume that erosion rate is proportional to the difference between shear stress of the flow and critical shear stress of the soil for resisting erosion. Channel width is calculated as a function of flow shear stress, critical shear stress, and distribution of shear stress around the channel boundary.

VIII. Acknowledgement

This paper is a contribution from the USDA-Agricultural Research Service, National Soil Erosion Laboratory, W. Lafayette, IN and Southwest Rangeland Watershed Research Center, Tucson, AZ; in cooperation with the Purdue Agricultural Experiment Station, W. Lafayette, IN and the Los Alamos National Laboratory, Los Alamos, NM (Contract W-7405-ENG.36 with the U. S. Department of Energy).

Appendix I. References

1. Alberts, E. E., "The Nitrogen and Phosphorus Content of Eroded Soil Aggregates and Sediment," thesis presented to Purdue University, at W. Lafayette, Ind., in 1979, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

2. Alberts, E. E., Moldenhauer, W. C., and Foster, G. R., "Soil Aggregates and Primary Particles Transported in Rill and Interrill Erosion," *Soil Science Society of America Journal*, Vol. 44, No. 3, 1980, pp. 590-595.

3. Alonso, C. V., DeCoursey, D. G., Prasad, S. N., and Bowie, A. J., "Field Test of a Distributed Sediment Yield Model," *Proceedings of ASCE, 26th Hydraulics Division Specialty Conference*, 1978, pp. 671-678.

4. Alonso, C. V., Neibling, W. H., and Foster, G. R., "Estimating Sediment Transport Capacity in Watershed Modeling," *Transactions*, American Society of Agricultural Engineers, Vol. 24, No. 5, 1981, pp. 1211-1220.

5. Beasley, D. B., Monke, E. J., and Huggins, L. F., "ANSWERS: A Model for Watershed Planning," *Transactions*, American Society of Agricultural Engineers, Vol 23, No. 4, 1980, pp. 938-944.

6. Davis, S. S., "Deposition of Nonuniform Sediment by Overland Flow on Concave Slopes," thesis presented to Purdue University, at West Lafayette, Ind., in 1978, in partial fulfillment of the requirements for the degree of Master of Science.

7. Foster, G. R., "Modeling the Erosion Process," *Hydrologic Modeling of Small Watersheds*, American Society of Agricultural Engineers, St. Joseph, Mich., 1982, pp. 294-280.

8. Foster, G. R., and Ferreira, V. A., "Deposition in Uniform Grade Terrace Channels," *Crop Production with Conservation in the 80's*, American Society of Agricultural Engineers, St. Joseph, Mich., 1981, pp. 185-197.

9. Foster, G. R., and Lane, L. J., discussion of "Modeling Rill Density," *Journal of the Irrigation and Drainage Division*, ASCE, Vol. 107, No. IR1, 1981, pp. 109-112.

10. Foster, G. R., and Lane, L. J., "Simulation of Erosion and Sediment Yield from Field-Sized Areas," *Tropical Agricultural Hydrology,* John Wiley and Sons, New York, N. Y., 1981, pp. 375-394.

11. Foster, G. R., and Meyer, L. D., "Transport of Soil Particles by Shallow Flow," *Transactions,* American Society of Agricultural Engineers, Vol. 15, No. 1, 1972, pp. 99-102.

12. Foster, G. R., Johnson, C. B., and Moldenhauer, W. C., "Critical Slope Lengths for Unanchored Cornstalk and Wheat Straw Residue," *Transactions,* American Society of Agricultural Engineers, Vol. 25, No. 4, 1982, pp. 935-939, 947.

13. Foster, G. R., Johnson, C. B., and Moldenhauer, W. C., "Hydraulics of Failure of Unanchored Cornstalk and Wheat Straw Mulches for Erosion Control," *Transactions,* American Society of Agricultural Engineers, Vol 25, No. 4, 1982, pp. 940-947.

14. Foster, G. R., Lane, L. J., and Knisel, W. G., "Estimating Sediment Yield from Cultivated Fields," *Proceedings of the ASCE Symposium on Watershed Management,* 1980, pp. 151-163.

15. Foster G. R., Lane, L. J., and Nowlin, J. D., "A Model to Estimate Sediment Yield from Field Sized Areas: Selection of Parameter Values," *CREAMS - A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems,* Conservation Report No. 26, Volume 2: Users Manual, Chapter 2, USDA-Science and Education Administration, Washington, D. C., 1980, pp. 193-281.

16. Foster, G. R., Lane, L. J., Nowlin, J. D., Laflen, J. M., and Young, R. A., "Estimating Erosion and Sediment Yield on Field-Sized Areas," *Transactions,* American Society of Agricultural Engineers, Vol. 24, No. 5, 1981, pp. 1253-1262.

17. Graf, W. H., *Hydraulics of Sediment Transport,* McGraw-Hill Book Co., New York, N. Y., 1971.

18. Grissinger, E. H., "Resistance of Selected Clay Systems to Erosion by Water," *Water Resources Research,* Vol. 2, No. 1, 1966, pp. 131-138.

19. Hutchinson, D. E., and others, "Resource Conservation Glossary," *Journal of Soil and Water Conservation,* Vol. 31, No. 4, Soil Conservation Society of America, Ankeny, Iowa, 1976.

20. Khaleel, R., Foster, G. R., Reddy, K. R., Overcash, M. R., and Westerman, P. W., "A Nonpoint Source Model for Land Areas Receiving Animal Wastes: III. A Conceptual Model for Sediment and Manure Transport," *Transactions,* American Society of Agricultural Engineers, Vol. 22, No. 6, 1979, pp. 1356-1361.

21. Knisel, W. G., *CREAMS - A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems,* Conservation Research Report No. 26, USDA-Science and Education Administration, Washington, D. C., 1980.

22. Knisel, W. G. and Foster, G. R., "CREAMS: A System for Evaluating Best Management Practices," *Economics, Ethics, Ecology: Roots of Productive Conservation,* Soil Conservation Society of America, Ankeny, Iowa, 1981, pp. 177-194.

23. Laflen, J. M. and Beasley, R. P., "Effects of Compaction on Critical Tractive Forces in Cohesive Soils," *Research Bulletin 749,* University of Missouri Agricultural Experiment Station, Columbia, Mo., 1960.

24. Meyer, L. D., Foster, G. R., and Nikolov, S., "Effect of Flow Rate and Canopy on Rill Erosion," *Transactions,* American Society of Agricultural Engineers, Vol. 18, No. 5, 1975, pp. 905-911.

25. Meyer, L. D., Foster, G. R., and Romkens, M. J. M., "Source of Soil Eroded by Water from Upland Slopes," *Present and Prospective Technology for Predicting Sediment Yields and Sources,* Report No. ARS-S-40, USDA-Agricultural Research Service, Washington, D. C., 1975, pp. 177-189.

26. Partheniades, E. "Results of Recent Investigations on Erosion and Deposition of Cohesive Sediments," *Sedimentation (Einstein),* Chapter 20, Colorado State University, Fort Collins, Colo., 1972.

27. Smerdon, E. T. and Beasley, R. P., "Critical Tractive Forces in Cohesive Soils," *Agricultural Engineering,* Vol. 42, No. 1, 1961, pp. 26-29.

28. Smith, R. E., "Field Test of a Distributed Watershed Erosion/Sedimentation Model," *Soil Erosion: Prediction and Control,* Special Publication No. 21, Soil Conservation Society of America, Ankeny Iowa, 1977, pp. 201-209.

29. Temple, D. M., "Tractive Force Design of Vegetated Channels," *Transactions,* American Society of Agricultural Engineers, Vol. 23, No. 4, 1980, pp. 884-890.

30. Yalin, Y. S., "An Expression for Bed-Load Transportation," *Journal of the Hydraulics Division,* ASCE, Vol. 89, No. HY3, 1963, pp. 221-250.

31. Young, R. A., "Characteristics of Eroded Sediment," *Transactions,* American Society of Agricultural Engineers, Vol. 23, No. 5, 1980, pp. 1139-1142, 1146.

Appendix II. - Notation

The following symbols are used in this paper:

A = flow area;
D = detachment rate at a point on the channel wetted perimeter;
D_m = erosion vector in middle of channel;
D_y = vertical erosion vector;
E = erosion rate per unit channel length;
f_{xz} = conveyence function;
H_{sw} = height of channel sidewall;
K = soil erodibility factor for erosion by flow;
n = Manning's n;

P = length of wetted perimeter;
Q = discharge rate for total width of channel;
r = R/P;
R = A/P, hydraulic radius;
S = grade along channel;
t = time;
t_n = normalized time;
w = W/P;
W = channel width;
W_e = equilibrium channel width;
W_f = final channel width;
W_i = initial channel width;
W_n = normalized channel width;
x = normalized distance around wetted perimeter;
x_c = x to where $\tau_s = \tau_c$ for equilibrium channel;
x_{cf} = x to where $\tau_s = \tau_c$ for final channel;
γ = weight density of flow;
Δt = time interval;
ΔW = change of width;
Δz = displacement normal to wetted perimeter;
θ = angle of channel boundary with horizontal;
ρ_s = bulk density of soil;
$\overline{\tau}$ = cross-sectional average total shear stress;
τ_b = shear stress at bottom of channel sidewall;
τ_c = critical shear stress for initiation of erosion by flow;
τ_s = shear stress acting on soil at a point on wetted perimeter;
$\overline{\tau}_s$ = cross-sectional average shear stress acting on soil;
τ_n = normalized shear stress distribution around channel;
τ_{nc} = τ_{ncf} = $\tau_c/\overline{\tau}_s$.