Furrow Erosion and Water and Soil Management

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ABSTRACT

EFFECTS of basic water and soil interactions on erosion are reported. The effects of flow rate and slope on perimeter shear stress are outlined for channels in which the ratio of breadth and depth of the flow cross section stay reasonably constant. Effects of the resulting shear stress on erosion are discussed in terms of coefficients for the equations developed and several data sets. For furrows with a relatively constant breadth to depth ratio, erosion appears to be related to the shear stress by an exponent which varies between two and four depending on the range of cohesive forces holding the soil particles to underlying soil. The data sets studied indicate continuous exponential relationships rather than a "critical shear stress" below which there is no erosion.

Following disruption of Portneuf silt loam by tillage or compaction, cohesion increases with time. Maximum rate of cohesion increase occurs when the soils are moist, but have sufficient tension in the water to draw the particles firmly together. Rapid wetting of dry soils disrupts a majority of the bonds between particles, allowing aggregate disintegration which reduces infiltration rates and substantially increases erosion. Considering erosion as an independent factor, not affected by sediment load and carrying capacity, allowed development of equations which appear to describe the whole erosion-deposition process.

These findings indicate several management options which can decrease furrow erosion.

INTRODUCTION

Soil erosion by water is a major factor reducing fertility of the world's soils, fish production, river navigability, and useable reservoir storage. High intensity natural precipitation and resulting runoff are the common cause of major erosion events. However, irrigation waters leaving furrow irrigated fields in the Western United States commonly remove 5 to 50 tons of soil/ha/yr, thereby removing about 4 to 40 cm of topsoil per century (Berg and Carter, 1980). Erosion on the top ends of many irrigated fields is over 100 t/ha/yr. This occurs when the high flow rates at the upper ends of furrows detach sediment and move it down to lower portions of the field where part of the sediment deposits as stream size decreases. Sand contents at the lower ends of such fields are higher than at the middle and top indicating that the finer particles have moved off in the tail water. Productivity at the top ends of these fields has decreased substantially as a result of erosion (Carter, 1984).

Since the farmer controls water application to his fields, this erosion may appear to be unnecessary and thoughtlessly self inflicted. However, if the farmer is to obtain good crop production in arid region soils, he must supply water to those furrows at a rate sufficient to at least match the furrow infiltration capacity and reach the end of the furrow. This rate of supply is often large enough to cause erosion at the top end.

Shortening the furrow length by adding a midfield supply ditch or pipeline is an obvious way to reduce the required water supply rate by a factor of two. However, this doubles the water supply cost in terms of length of pipe or concrete ditch, land use, and labor required to distribute the water. It also doubles tractor turn around time and decreases crop production in the turning areas. To avoid these costs, farmers use relatively large flow rates and tolerate substantial amounts of erosion. Another erosion reducing option for the irrigation farmer is to use pressurized water distribution systems. However, with the high energy and capital costs of sprinkler and trickle systems, this option will not be economical for many farmers unless crop prices increase significantly.

To help motivate the farmers to reduce erosion, the furrow erosion process must be understood and cost effective means for its reduction must be identified. This paper reports steps in that direction.

FACTORS AFFECTING SHEAR ON THE FURROW PERIMETER

Supply Rate and Slope

The furrow flow rate, and to some extent the slope, are manageable factors which affect erosion. As discussed above, shortening runs is a means of decreasing required supply rate. Furrows compacted by tractor wheels commonly have infiltration rates about 40% lower than uncompacted furrows (Kemper et al., 1982). Consequently, supplying water to wheel-packed rather than unpacked furrows can reduce the needed supply rate by about 40%. However, some of that benefit is lost, because at the reduced infiltration rate, water must run in the furrow for a longer time period to supply sufficient water to the crop. If the exponent relating the furrow flow rate to erosion is greater than 1.0, utilizing compacted furrows and cutting back on the flow rates accordingly can reduce erosion. Whether or not this reduction occurs also depends on time and the soil water content since the packing occurred. The immediate effect of packing is destruction of a major portion of existing solid particle-to-particle bonds which increases erodability. However, compaction also increases the

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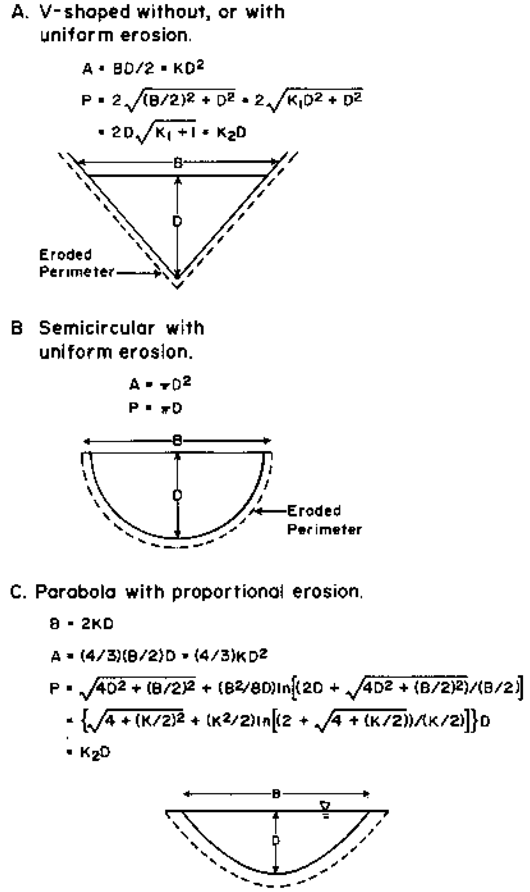

Fig. 1—Furrow geometries where breadth and depth remain approximately proportional as flow rate increases or erosion occurs.

number of particle-to-particle contacts at which bonds can form. Under moist conditions these bonds form (Kemper and Rosenau, 1984) and strengthen rapidly so that in a few weeks the ability of the compacted soil to resist detachment by water can be greater than that of uncompacted soils.

Furrow slope can be reduced by orienting the furrows at an angle rather than directly in the downslope direction. This may be costly in terms of requiring earth moving to maintain proper grades on some fields and may result in more point rows, but will be feasible for some fields. Clean, adequately sized furrows are necessary to prevent overtopping and sidewise flow.

Recognizing at least some degree of manageability in both furrow slope and supply rate and possibilities for tradeoffs between them, their effects on shear at the wetted perimeters of furrows is analyzed as follows.

The most commonly used and generally verified equation defining the relation between flow rate, Q, flow cross sectional area, A, wetted perimeter, P, and furrow slope, S, is Manning's equation.

$$Q = A^{5/3}\ S^{1/2}/nP^{2/3} \quad \text{[1]}$$

where n is a roughness coefficient. For flow cross sections such as those assumed in Fig. 1 the flow cross section breadth, B, and depth, D, increase when the furrow capacity increases (i.e., the shape remains constant). Consequently, the ratio of B/D remains practically constant over the normal furrow flow ranges and

$$B = K_3D \quad \text{[2]}$$

For such shapes the cross sectional area

$$A = K_4D^2 \quad \text{[3]}$$

and the wetted perimeter

$$P = K_5D \quad \text{[4]}$$

The constants K_3, K_4, and K_5 are derived for the specific geometric shapes shown in Fig. 1.

Substituting the values of A and P from equations [3] and [4] in Manning's equation,

$$Q = (K_4D^2)^{5/3}\ S^{1/2}\ /n(K_5D)^{2/3}$$

$$= (K_4{}^{5/3}/K_5{}^{2/3})\ D^{10/3}\ S^{1/2}\ /nD^{2/3},$$

$$\text{defining } K_6{}^{8/3} = K_5{}^{2/3}/K_4{}^{5/3}$$

$$D = K_6(Qn/S^{1/2})^{3/8} \quad \text{[5]}$$

As water flows through a channel of slope, S, the force due to gravity acting on the water per unit channel length is

$$F_g = \rho gSK_4D^2 \quad \text{[6]}$$

where ρ is the mass density of water and g is the gravitational constant.

This gravity induced force is opposed by drag, or shear forces, T_i, acting on each unit area of the wetted perimeter, P, of the channel. The development of Manning's equation assumes that this shear force is approximately uniform and has an average value

$$T = \sum_{i=1}^{N} T_i/N \quad \text{[7]}$$

over the wetted perimeter. The uniform shear force depicted in equation [7] is an exact solution, neglecting drag at the air-water interface, for semicircular cross sections (e.g. Fig. 1B) and is obviously a better approximation for cross sections of this type than the tractive force treatment which is a relatively exact treatment of infinitely wide cross sections and concludes that shear forces are proportional to the depth of water over the specific section of the perimeter. Assuming uniform distribution of the shear force over the wetted perimeter, P, shear, F_s, per unit length of channel is

$$F_s = PT \quad \text{[8]}$$

which from equation [4] gives $F_s = K_5DT$.
In sections where there is no acceleration $F_g = F_s$.
Therefore, $\rho gK_4SD^2 = K_5DT$, and the average shear, T, per unit area of perimeter is

$$T = (\rho gK_4/K_5)DS \quad \text{[9]}$$

Substituting D from equation [5], and defining

$k = \rho g K_4 K_6 / K_5$

$$T = kS(Qn/S^{1/2})^{3/8} \quad [10]$$

The same relationship results from inserting these hydraulic (equation [1]) and geometric (equations [4] and [6]) relationships into the tractive force relationships ($T = \rho gRS$ where R, the hydraulic radius is defined as A/P, as in Chow, 1959).

Considering unit flow width in an infinitely wide, relatively shallow channel of depth, d, the flow cross section A = d and the wetted perimeter, P, is unity. Then Manning's equation yields

$$Q = d^{5/3} S^{1/2} / n \quad [11]$$

and

$$d = (Qn/S^{1/2})^{3/5} \quad [12]$$

Gravity induced force, f_g, acting to move this element of unit width, unit length, and depth, d, along the channel is

$$f_g = \rho gSd.$$

Opposing this motion is the drag or shear force which, on a unit width and length on the bed of a wide channel, is $f_s = T_w$, where T_w is the shear per unit area on a wide channel bed.

When flow is steady, $f_s = f_g$, and consequently

$$T_w = \rho gSd \quad [13]$$

Substituting for d from equation [12], in equation [13]

$$T_w = \rho gS(Qn/S^{1/2})^{3/5} \quad [14]$$

Shear and Erosion

During initial rapid wetting of a dry or recently cultivated soil, entrapped air, swelling pressures and gravitational forces often detach particles and small aggregates from the soil mass and incorporate them in the moving water. Following this initial wetting phase, soil particle and aggregate detachment from the channel perimeter is primarily a function of the shear force. Under low flow velocities there may be practically no detachment. As velocities increase, shear forces increase, and eventually exceed the critical shear stress (Foster and Lane, 1983) required to overcome cohesion of some soil aggregates and particles to adjacent and underlying soil. The number and strength of the bonds causing this cohesion are a function of factors discussed in the following section. They cause a range of cohesions varying from zero for particles detached by air bubbles emerging from soil as it is wetted quickly by advancing water, to high values for particles which have been forced into intimate contact with, and have had time to bond to, adjacent particles and have been wetted slowly by capillarity thereby avoiding disruption. The unattached soil particles and microaggregates lying on the furrow perimeter also vary widely in size and force required to move them. The broad range of cohesions and sizes of soil units encountered in furrow irrigation preclude an analytical prediction of effect of shear force on erosion.

Equations such as equations [10] and [14] can be correlated with measured rates of furrow erosion, in studies where flow rates and/or slopes have been varied to estimate the functional relation between shear, T, and erosion rate, E, for that particular soil with the cohesive characteristics that it has at that point in time. In general, good fits (e.g., data sets in Table 1) have been obtained with equations of the type

TABLE 1. DATA SETS RELATING EROSION (E) TO SLOPE (S) AND FLOW RATE (Q) COMPARED IN TERMS OF THE a AND b COEFFICIENTS IN THE EMPIRICAL EQUATION $E = k_7 S^a Q^b$, WHERE k_7 CAN BE EITHER k_3 OR k_6 IN EQUATIONS [17] OR [21] RESPECTIVELY.

Investigators	a	b	a/b	Location
Israelson et al (1946)	1.8	1.5	1.2	Utah Farm
Israelson et al (1946)	1.6	1.2	1.3	Utah Farm
Israelson et al (1946)	1.4	1.0	1.4	Utah Flume
Gardner & Lauritzen (1946)	1.5	1.0	1.5	Flume
Evans & Jensen (1952)	2.3	1.5	1.5	No. Dak. Field
*Carter et al	2.7	1.8	1.5	Idaho Farms
*Trout, Brown & Rosenau	2.1	1.4	1.5	Idaho Farm

*Unpublished data from Snake River Conservation Research Center

$$E = k_2 PT^M \quad [15]$$

where k_2 and M are constants for soil at that time.

For the wide shallow channel consideration, leading to equation [14], the wetted perimeter was assumed constant and equal to unity. Substituting T_w from equation [14] for T in equation [15] and assuming P = 1.0,

$$E_w = k_2[\rho g(Qn)^{3/5} S^{7/10}]^M \quad [16]$$

provides good approximation of the erosion rate E_w for wide shallow channels.

Writing equation [16] in a generalized form where

$$k_3 = k_2(\rho gn^{3/5})^M,$$

$$E_w = k_3 S^a Q^b \quad [17]$$

where a = 7M/10, b = 3M/5, and a/b = 7/6.

When the depth of the channel is more than 20% of its breadth and channels are of the types shown in Fig. 1, which led to equation [10], the wetted perimeter is not constant, but also varies with flow rate and slope.

From equations [4] and [6] it can be concluded that

$$P = K_5 K_6 (Qn/S^{1/2})^{3/8} \quad [18]$$

Consequently, if

$$E = k_4 T^M P \quad [19]$$

and $k_5 = K_5 K_6$, from equations [10] and [18]

$$E = k_4 k_5 k^M [n^{6M+6} S^{13M-3} Q^{6M+6}]^{1/16} \quad [20]$$

where a/b = (13M − 3)/(6M + 6).

$$\text{For } M = 2,\ E = k_4 k^2 k_5 n^{1.13} S^{1.44} Q^{1.13},\ a/b = 1.3 \quad [20a]$$

$$M = 3,\ E = k_4 k^3 k_5 n^{1.50} S^{2.25} Q^{1.50},\ a/b = 1.5 \qquad [20b]$$

$$M = 4,\ E = k_4 k^4 k_5 n^{1.88} S^{3.06} Q^{1.88},\ a/b = 1.6 \qquad [20c]$$

Correlation with Field Data

The quotient, a/b, of the exponents of the slope and flow rate factors increases as M increases in equation [20] which is for furrows with shapes similar to those in Fig. 1. In equation [17] which was developed for wide shallow furrows, $a/b = 7/6$ for all values of M. Equations [20] through [20c] for rate of erosion in a section of the furrow can also be written in the general form

$$E = k_6 S^a Q^b \qquad [21]$$

where $k_6 = k_4 k_5 k^M n^b$, $a = (13M-3)/16$ and $b = (6M+6)/16$.

The degree to which B/D is constant as flow rates and slope vary and furrows erode, is difficult to predict or quantify. However, several data sets are available in which effects of slope and flow rate, on erosion have been related. The ratios of the slope and flow rate exponents (a and b in equation [16]) are compared for these data sets in Table 1.

Pictures in the Israelson et al. publication indicate that the furrows with a/b values of 1.2 and 1.3 had broad flat bottoms. Many furrows in the studies where a/b was 1.5 ± 0.1 also developed relatively flat bottoms, but the assumption of B/D being constant was apparently close enough to reality for a/b to be in the ranges predicted by equation [19] when M varies from two to four. The data sets in Table 1 indicate that erosion is commonly about a third power function of the shear stress, i.e., $M=3$. Data sets needed to estimate M are rates of runoff, sediment content of the runoff water and wetted perimeter (1) on a known slope at two rates or (2) at a known flow rate on two measured slopes. Data collected by Berg and Carter (1980) indicate that the pertinent slope is that which is immediately upstream from the sediment measuring station.

Values of M and the other coefficients are more easily derived from such data sets if equations [9] and [19] are combined to give

$$E = k_M (Q^{3/8} S^{13/16})^M P \qquad [22]$$

where $k_M = k_4(kn^{3/8})^M$, and P is measured, or calculated from equation [18]. An equation derived from equation [22] that may be used for calculating M from two data sets where Q is different and S is constant is

$$M = (8/3)\log(E_2 P_1 / E_1 P_2)/\log(Q_2/Q_1) \qquad [23]$$

The value of k_M can then be determined from either data set using equation [22] and the common value of M.

Water flowing fast on steep slopes often erodes cultivated soil rapidly and then stops at the more cohesive plow pan or other layers in which stronger cohesion withstands the shear. In analyses of the Trout et al, and Carter et al data, erosion measurements were not used to determine the exponents if the furrow had eroded down to an obviously more cohesive underlying soil layer.

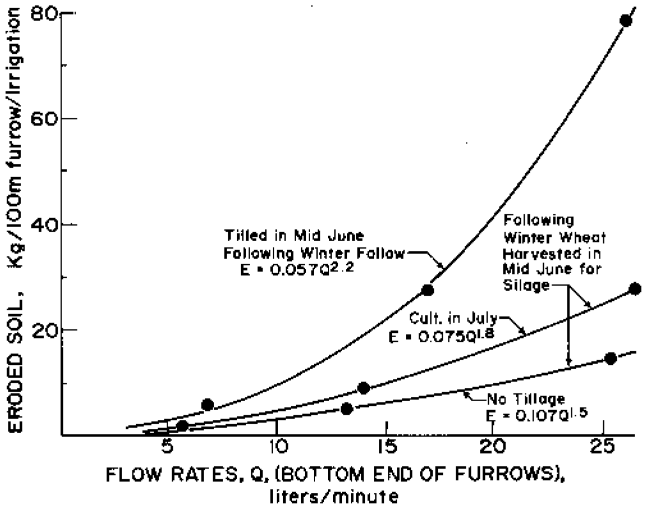

Fig. 2—Effects of tillage and the preceding crop on erosion from furrows on bean fields.

The relatively limited ranges of a and b in Table 1 are a result of using data points which were averages of summations involving enough observations to smooth out the effects of other variables. Evaluating deviations of actual datum points from these equations indicated about 40% of the deviations from the mean were associated with slope and flow rate.

Factors which probably account for substantial portions of the remaining deviations are discussed in the following sections.

ROOT FABRIC AND TIME AND WATER CONTENT SINCE CULTIVATION

Kemper et al. (1985) observed that during successive irrigations the exponent relating associated flow rate to erosion decreased as the remaining soil in the high flow rate channels became more cohesive and consequently more resistant to the shear stress. Part of this increased resistance may have resulted from the furrow bottom encountering soil consolidated by wheat root fabric. Such root fabric appeared to be part of the reason for the differences in erosion shown in Fig. 2 between the furrows in soil following winter wheat and those following winter fallow. These curves (Fig. 2) are averaged for irrigations throughout the growth periods of two successive summer bean crops.

However, another factor causing decreased erosion in the non tilled soil in Fig. 2 is the tendency of this soil to become more cohesive with time (e.g., Blake and Gilman, 1972; Utomo and Dexter, 1981; Kemper and Rosenau, 1984). Increases of wet sieve aggregate stability with time for this soil are shown for moist and air dry Portneuf silt loam in the two left curves in Fig. 3.

A major portion of the solid-to-solid bonds in this soil were broken by shear and compression as they were forced through a 2 mm sieve when moist. Some of the aggregates were then air-dried to a water content, w, of 0.04 g/g ($w=0.04$) and the others kept moist ($w=0.21$) for the indicated times. Values of 10^5 hours were obtained from a soil sample which was sieved and air dried 11 years prior to the time when the rest of the study was conducted. Some of the dried aggregates were then moistened slowly to water levels of $w=0.13$, and 0.31 by passing moist air from a vaporizer through them before

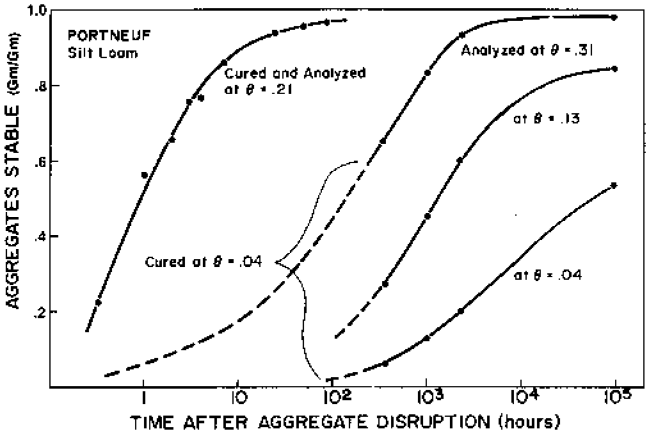

Fig. 3—Increases in aggregate stability with time of moist and dry air soil Portneuf silt loam.

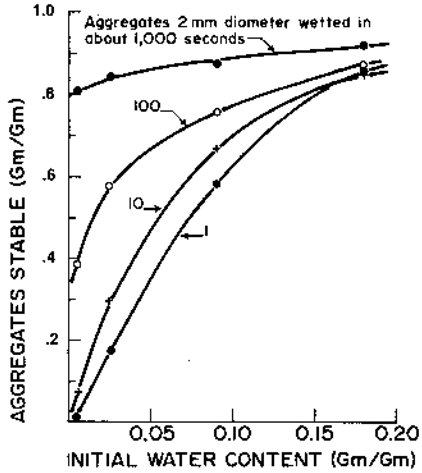

Fig. 4—Aggregate stability of Portneuf silt loam as a function of initial water content and rate of wetting prior to immersion.

they were submerged in the wet sieving analysis. Solid-to-solid bonds reformed and cohesion increased rapidly in aggregates with 0.21 water content. In the air dry soil, ($\theta=0.04$) which had about one molecular layer of water on the mineral surfaces, reformation of these bonds took about 100 times as long. These differences in rates are about the same as the difference in diffusion rates measured (e.g., VanSchaik and Kemper, 1966) in soils at these water contents, indicating that diffusion of ions and molecules through the liquid phase to particle-to-particle contacts where they bond the particles together may be the rate controlling mechanisms.

The rapid increase, during the first ten hours, in the fraction of aggregates stable when cured at a water content of $\theta=0.21$ indicates rapid bond strengthening in this time period. After 20 h of curing at $\theta=0.21$ only a few of the aggregates do not have bonds strong enough to resist the forces causing disruption during immersion and the subsequent sieving process. However, when greater disruptive forces were applied during immersion by drying the aggregates to a lower water content (i.e., $\theta=0.04$) prior to immersion, most of the aggregates did not remain intact. The right hand curve in Fig. 3 indicates that bonds binding particles together strengthen slowly over extended time periods when the soil is air dry ($\theta=0.04$). The water content favoring most rapid strengthening of bonds appears to be about 0.20 g/g for these Portneuf aggregates. When the aggregates were near saturation, bonds did not strengthen with time, indicating a need for tension in the soil water to pull the soil particles into firm contact so the bonding process can proceed.

Since wheel compaction and cultivation are effective in the disruption of such bonds it is probable that cultivation and lack of time and optimum water content to regain cohesion played a major role in the higher erosion of the tilled soil (Fig. 2).

INITIAL WATER CONTENTS AND WETTING RATES

Runoff and erosion were measured from furrows in a bean field (Portneuf silt loam) during six successive irrigations by Kemper et al. 1985. Sediment contents of water during the third and fourth irrigations were much lower than in the other four irrigations. The only apparent cause for this difference was traces of precipitation recorded by the weather station during the previous evening or afternoon and high humidities during the night. Kemper, Rosenau, and Nelson (1985) found that traces of precipitation, followed by clear nights and heavy dew, can increase the water content of the immediate soil surface to 0.05 to 0.10 g/g from its normal 0.01 to 0.02 g/g during hot afternoons.

Differences in aggregate stability of this Portneuf soil having different initial water contents prior to immersion are indicated in Fig. 4. Aggregates (1-2 mm diameter) with these initial water contents were wetted to saturation at different rates by placing them on filter paper and applying water at different rates to a point on the filter paper that was about 10 cm from the aggregates. Time from when the paper contacting the aggregates became moist to when the last dry spot on the aggregates disappeared was determined and used as an index of the wetting rate in Figs. 4 and 5. For the portion of the furrow in Portneuf silt loam wetted quickly by direct contact with the flowing water, increasing the initial water content from 0.03 to 0.10 g/g would increase the aggregate stability from about 21% up to 63%. For aggregates on portions of the furrow where

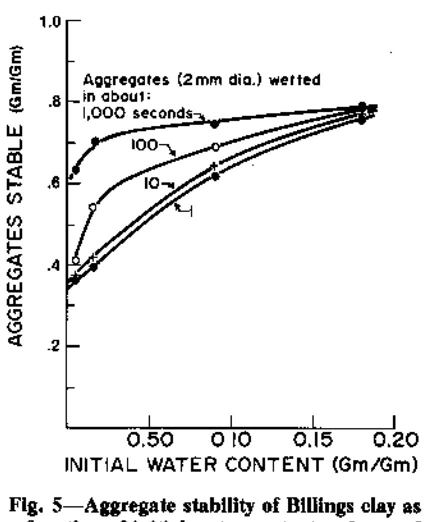

Fig. 5—Aggregate stability of Billings clay as a function of initial water content and rate of wetting prior to immersion.

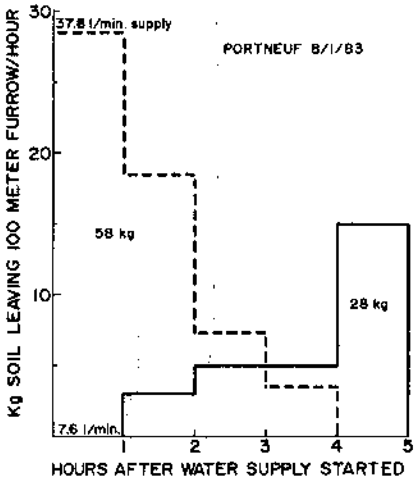

Fig. 6—Effect of wetting rate on furrow erosion (Portneuf 8-1-83).

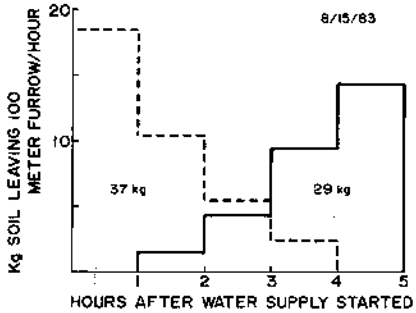

Fig. 7—Effect of wetting rate on furrow erosion (Portneuf 8-15-83).

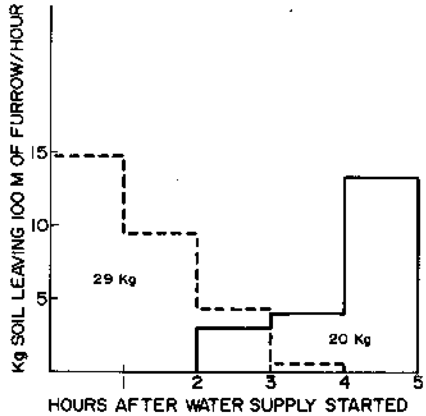

Fig. 8—Effect of wetting rate on furrow erosion (Portneuf 9-7-83).

wetting by capillary action took about 100 s, the stabilities of soils with initial water contents of 0.03 and 0.10 g/g would be about 59 and 77%, respectively.

When Portneuf aggregates were wetted slowly, taking 30 min or more to bring them to water contents >0.3 g/g (Fig. 4), the water content prior to this wetting had little effect on the stability of the aggregates when wet sieved.

Not all soils have as broad a range of aggregate stabilities under these conditions of initial water content and rate of wetting. For instance, a sample of Billings clay from near Grand Junction, CO (Fig. 5), has greater cohesion than Portneuf and substantial aggregate stability (i.e., 35%) when dry soil is immediately wetted. Maximum aggregate stability of this soil is about 80% which is significantly lower than that of Portneuf (92%). This persistent instability of a small fraction of the Billings aggregates may be a result of about 3% exchangeable sodium in this soil.

Rate of wetting the soil is, to some extent, a manageable factor in furrow erosion. The normal recommendation, designed to minimize differences in intake opportunity time, has been to start irrigating a furrow with a large supply rate to wet the whole furrow as quickly as possible and then reduce this supply rate to reduce runoff. To determine whether more rapid wetting increases erosion, two pairs of furrows each 100 m long, were irrigated with identical amounts of water. One of each pair had an initial supply rate of 37.8 L/min for 1 h which was then dropped to 80, 60, 40, and 20% of this rate in successive hours. The other furrow of each pair was provided with 20% of 37.8 L/min for the first hour and this was raised to 40, 60, 80, and 100% of 37.8 L in successive hours. Erosion measured during these five hours of irrigation for these quick wetted and slow wetted furrows is shown for the third, fourth, and fifth irrigations in Figs. 6, 7, and 8. The third irrigation was preceded by cultivations. The faster wetting rate more than doubled the erosion during the 8-1 irrigation. Differences in erosion due to different rates of wetting were not as large, but were substantial during successive irrigations. The faster wetting rate reduced water intake to 68, 83, and 81% of that which occurred with slow wetting during the 8-1, 8-15, and 9-6 irrigations, respectively. The resulting greater runoff rate, indicated in the second column of Table 2 was thus a contributing factor to more erosion.

This study was conducted on the plot from which the data for Fig. 2 was taken. For irrigations on 8-1, 8-15, and 9-6 in 1983, the values of b in the equation $E = AQ^b$ were 2.5, 1.4, and 1.0. These values, listed in the third column of Table 2 were used to calculate the percentage increase in erosion (shown in the fourth column) expected, due to more runoff from the plots which were wet quickly as compared to those wet slowly. Erosion increases measured are shown in the last column of Table 2. The average increase was 60%, compared to 38% increase expected due to increased runoff. These data on Portneuf soil indicate that greater disintegration of clods and aggregates by fast wetting has at least two effects on erosion. Fragments resulting from the disintegration are smaller and more easily carried. Those fragments are also smaller and more effective in filling and blocking the pores which results in lower intake rates, more runoff and therefore more shear force exerted by the water on the furrow perimeter.

EROSION AND DEPOSITION

Equation [21] can be used to describe the rate, E_i, of erosion, i.e., detachment and removal of soil fragments from a furrow section in terms of the flow rate, slope of the furrow and soil characteristics in that furrow section.

TABLE 2. INCREASED RUNOFF, DUE TO FAST WETTING INCREASED EROSION EXPECTED DUE TO RUNOFF INCREASE AND MEASURED INCREASE IN EROSION.

Date	Ratio of runoff, Fast wet / Slow wet	Exponent relating flow rate to erosion	Calculated increase in erosion due to increased runoff	Measured erosion increase
8-1	1.24	2.5	71%	106%
8-15	1.17	1.4	25%	28%
9-6	1.17	1.0	17%	45%
Average			38%	60%

Most theoretical treatments of erosion have their background in river transport of non cohesive sediments. In those treatments, detachment of the sediment from the stationary bed requires no significant amount of energy and the primary limitation on the net rate of removal of the sediment is the degree to which carrying capacity of the stream is filled. When it is filled the rate at which sediment settles on the bed of the stream is equal to the rate at which turbulence induced forces are lifting sediment off the bed. When the sediment load of the water is less than its carrying capacity the net rate at which sediment will be removed from a bed of unconsolidated sediment is generally proportional to the carrying capacity minus the sediment load. Consequently as sediment load increases, net rate of loss of sediment from the bed decreases. While there are data which substantiate the inverse relation of sediment in the water to sediment removal from channels in non cohesive sediment. We were unable to find data which support its extension to channels in cohesive soils. In fact, since sediment in air increases ability of wind to erode soil, it seems likely that soil fragments in the moving water will provide more abrasion and loosening of soil fragments from the wetted perimeter than would sediment-free water.

Until there are data to characterize the effect of sediment in the water on erosion of cohesive soil, the easiest way to treat this factor is to assume that sediment in the water has practically negligible effect on the rate of detachment and removal of soil fragments from a cohesive soil bed. This assumption is a deviation from most previous treatments and facilitates the following development.

The sediment load, L_j, or rate of sediment leaving any section, j, of the furrow may be expressed by equation [24]

$$L_j = L_o + \sum_{i=1}^{i=j} E_i - \sum_{i=1}^{i=j} D_i \quad \ldots\ldots\ldots\ldots\ldots\ldots [24]$$

where E_i and D_i are the erosion and deposition rates in the respective upstream sections and L_o is the rate at which sediment is entering the furrow in the supplied water.

When the flow rate and/or slope decrease and reduce the carrying capacity to below the sediment load, deposition, D_i, takes place in that section.
In equation form,

$$D_i = L_{i-1} - C_i \text{ except} \ldots\ldots\ldots\ldots\ldots\ldots [25]$$

$D_i = 0$ when $C_i > L_{i-1}$.

The carrying capacity C_i in the ith section is related to the velocity and turbulence of the flow and can probably be approximated by another exponential function of furrow slope and flow rate, i.e.,

$$C_i = k_8 S_i^d Q_i^f \ldots\ldots\ldots\ldots\ldots\ldots [26]$$

where k_8 involves factor such as the particle size and roughness coefficient. This "carrying capacity" is the ability of the flowing water to keep loose sediment moving.

Equation [26] has the same general form as the equations [17], [20], and [21] for erosion rates. However, since erosion of cohesive soils generally involves breaking bonds which hold the soil fragments to underlying soil, the rate of erosion by a specific flow rate on a specific slope is less than the transport capacity under those same conditions and the exponents associated with the S and Q terms in equation [21] are smaller than those in equation [26].

Equations [21], [24], [25], and [26] can be used to represent the erosion, transportation and deposition of sediment.

Sediment transport and flow rate measurements were made at 32 M intervals along furrows 192 M long during seven irrigations of a bean field with a convex end. Elevations were also determined at the measurement stations and these data are presented in Fig. 9.

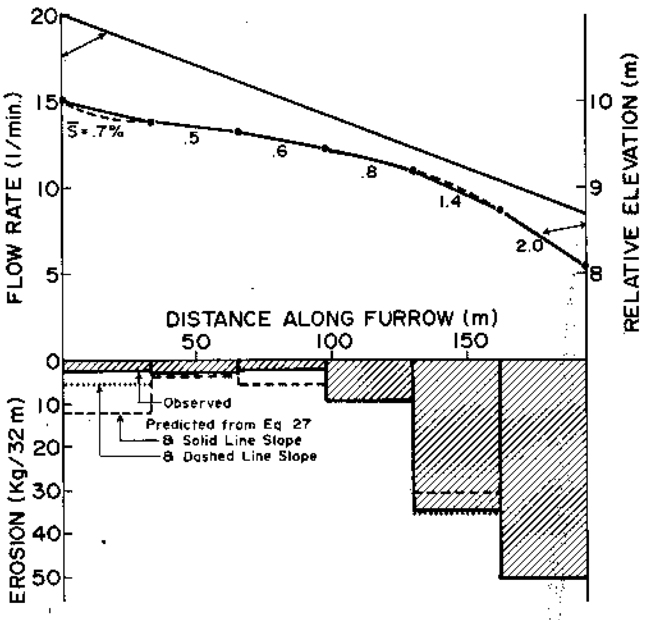

Fig. 9—Effects of slope and flow rate on erosion on Portneuf silt loam (average of seven irrigations on each of two furrows). (Sections 4 and 6 were used for calibrating the equation so predicted values = observed values.)

Using the a = 1.5b approximation in equation [21] and the slopes, average flow rates and the average erosion per irrigation in the fourth and sixth sections, indicated by the solid lines in Fig. 9, the coefficient and exponents for the equation

$$E_i = 0.3\, S_i^{2.4} Q_i^{1.6} \ldots\ldots\ldots\ldots\ldots\ldots [27]$$

were obtained. The erosion per irrigation predicted by this equation is shown by the dashed lines in the bottom of Fig. 9. These dashed lines are coincident with the solid lines in sections 4 and 6 because values in those sections were used to define the coefficient and exponents in equation [27]. The agreement between measured erosion and that predicted by equation [27] was fair, but there was considerable discrepancy in the first and fifth sections. Reinspection of the first section showed a detailed elevation profile indicated by the dashed line in the top portion of Fig. 9, with the slope being 0.3 or less in the 10 m next to the bottom end of that section. This concave profile in this first section is maintained as a result of plowing up hill each year. A major portion of the sediment eroded from the top end of this first section settles out in the middle. When such changes of slope

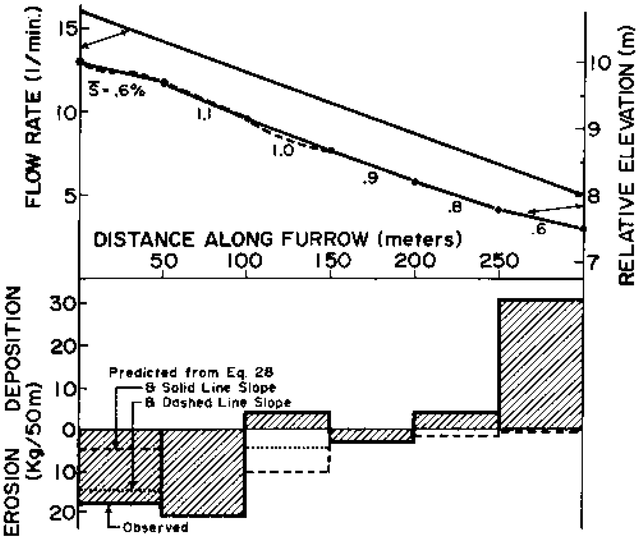

Fig. 10—Effects of slope, flow rate, and incoming sediment on erosion and deposition of Portneuf silt loam (average of eight irrigations on each of two furrows). Segments 2 and 4 were used for equation calibration so predicted values = observed values.

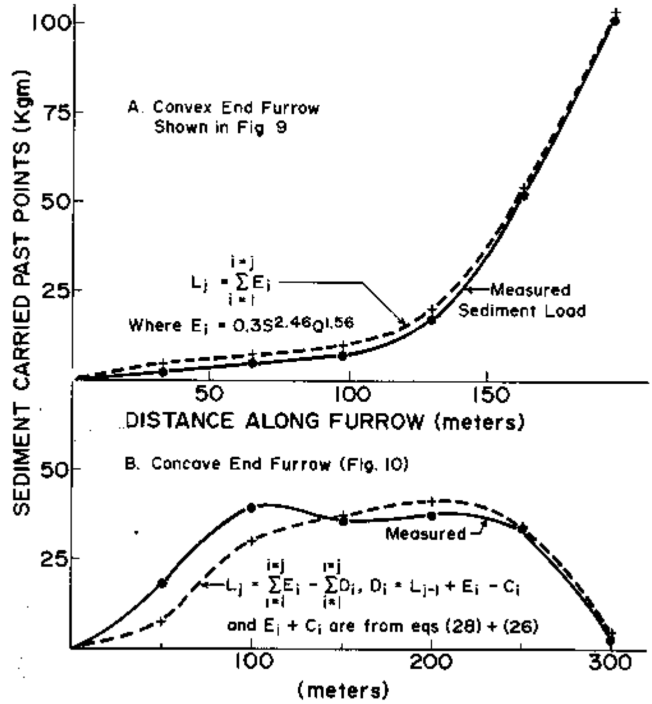

Fig. 11—Measured and estimated sediment transport at intervals along furrow.

occur within a section, the slope in the 10 m immediately upstream from the measuring station can determine the rate of soil removal from that section. Using a slope of 0.5% for this first section instead of 0.7% in equation [27] yields erosion indicated by the dotted line.

A smooth curve fitting all the elevations in the vicinity of the fifth section indicates that the slope in the 7.5 m upstream from the measuring station at the bottom end of the section was closer to 1.5% than the 1.4% indicated by the straight line. Using 1.5% slope in equation [27] yields the erosion indicated by the dotted line for the fifth section. With these refinements of the slope, agreement between erosion measured and predicted by equation [27] is good.

Sediment transport, water flow rates and elevation measurements were also measured at 50 M intervals on rows 300 M long with slightly concave bottom ends. The flow rates and erosion and deposition per irrigation indicated in Fig. 10 are the averages on four rows for eight irrigations.

Slopes, and flow rates and erosion per irrigation, were taken from sections two and four and used in equation [21] along with the approximation a = 1.5b to determine the coefficient and exponents in the following equation,

$$E_i = 0.087\ S^{3.0}Q^{2.0} \quad [28]$$

The dashed lines in the bottom of Fig. 10 represent the average erosion per section per irrigation predicted by this equation. The major discrepancies in the first and third sections may again be reconcilable by more detail of the elevation profiles, which appear to have the waves indicated by the dashed line in the top half of Fig. 10.

Deposition which occurred in the last two sections of these furrows occurred because the carrying capacity in those sections was less than the sediment load which the water brought into them. In sections of this type where erosion is practically negligible, if deposition is taking place fast enough, the sediment load will be just slightly larger than the carrying capacity. Consequently, the loads leaving the last two sections were used as estimates of the carrying capacities, C_5 and C_6 along with the respective slopes and flow rates and the approximation d = 1.5f in equation [26] to obtain the coefficient and exponents in the following equation

$$C_i = 0.032 S_i^{5.7} Q_i^{3.8} \quad [29]$$

If significant deposition had occurred in at least three sections, use of the d = 1.5f approximation would not have been necessary to obtain the three unknowns. The exponents associated with the slope and flow rate are about twice as large for the carrying capability as they were for the erosion rate equations [27] and [28].

Using equation [27] to generate E_i values for equation [24] and recognizing that L_0 and D_i were all practically zero for the convex end furrows, the sediment loads at intervals down the furrow were calculated and are plotted as the dashed line in the top of Fig. 11. The points on the solid line represent the measured sediment load (average kg per furrow per irrigation).

Using equation [28] to generate E_i values, the sediment loads were calculated with equation [24] for the first four sections of the furrows with concave ends where deposition was zero and there was practically no sediment in the incoming water. In the last two sections the limited carrying capacity limits the amount of sediment which the water can carry out of the furrow and equations [25] and [26] can be used to calculate the deposition (D_i) in the last two sections which are shown at the bottom right of Fig. 10. They were also used along with equation [28] in equation [24] to determine the sediment load per furrow per irrigation passing the last two sections. The measured and calculated sediment load carried past these sections are represented by the solid and dashed lines respectively in the bottom half of Fig. 11 for these furrows with concave ends in Portneuf silt loam. The slopes used in these calculations are the values given by numbers in the top half of Fig. 10. More detailed elevation profiles could probably provide a better fit of the two curves in the first two sections.

The general treatment involving separate consideration of erosion rate (detachment) as an independent phenomenon related to sediment load, carrying capacity and deposition, appears to be capable of describing the spectrum of erosion-deposition phenomena.

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS FOR MANAGEMENT

Erosion can be decreased by reducing shear stress exerted by the water on the furrow perimeter and by increasing cohesion of the soil particles. The average shear stress, T, on the perimeter of furrows where breadth of the water surface is proportional to depth is related to the furrow slope, S, and flow rate, Q, by the equation

$$T = kn^{3/8}Q^{3/8}S^{13/16} \qquad [30]$$

where n is Manning's roughness coefficient.

Erosion, E, is related to the shear stress, and wetted perimeter P, by the equation $E=k_4T^MP$ [19] where M and k_4 are functions of the soil cohesion. Available data sets indicate that M is commonly between two and four and its value can be determined from measurements of furrow erosion rate and wetted perimeter at two known flow rates.

Erosion is commonly about a 1.5 power function of flow rate. For soils with this relationship erosion will be reduced if infiltration rate and furrow supply rates are proportionately reduced even though the flow must be continued for longer to obtain the desired amount of infiltration. If the change in infiltration rates is not accompanied by a change in cohesion in such soils, erosion will be proportional to the half power of the infiltration and furrow flow rates. That is, reducing infiltration and furrow flow rates by a factor of four can reduce erosion rates by a factor of two. Infiltration rates in wheel compacted furrows are commonly about 60% of infiltration rates in noncompacted furrows. Avoiding tillage avoids immediately subsequent extremely high infiltration rates but favors long term increases in interconnected macropores created by roots, worms, etc.

Erosion is commonly about a 2 to 3 power function of furrow slope so reducing slope is highly effective in reducing erosion.

A large portion of the solid bonds, which hold soil aggregates together are broken when moist soils are tilled or compacted. Under moderately moist conditions bonds reform between particles and strengthen with time. Consequently, allowing as much time as possible between cultivation and irrigation allows the soil to develop more cohesion and results in less erosion. Elimination of tillage allows more cohesion to develop in the aggregates and substantially reduces erosion.

Rapid wetting entraps air which breaks bonds between aggregates and facilitates erosion. Slower wetting of the soils decreases erosion, but increases differences in intake opportunity times between the top and bottom ends of the furrows. Methods to decrease furrow intake rates at the top ends could help make total intake more uniform while allowing slower wetting and decreasing erosion.

Soils with appreciable amounts of water in them prior to wetting are disrupted less by wetting than soils which are initially completely dry. Consequently, irrigation following light rainfall events, or even started while the soil is still slightly moist following a night's dew will cause less erosion than irrigation initiated on soils during hot dry afternoons.

Furrow erosion rates in no till bean fields following winter wheat were only 18 to 30% of those in bean fields following winter fallow and normal seed bed preparation. Both increased soil cohesion and root fabric from the previous wheat crop helped keep the erosion low.

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