# Erosion and Sedimentation Processes on Irrigated Fields

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**Abstract:** Soil erosion is sometimes excessive during furrow irrigation and under center pivot sprinkler systems. An understanding of erosion processes is required to predict and develop management practices to reduce irrigation induced erosion. Little erosion process research has been carried out under irrigation, but much of the extensive channel sediment transport and rainfall-induced erosion process research can be adapted to irrigated conditions. Soil erosion occurs when fluid in motion detaches and transports soil particles. Sedimentation occurs when the fluid transport capacity decreases to less than the sediment load. Hydraulic forces of moving water and soil factors such as aggregate stability and particle size determine erosion and sedimentation. Under furrow irrigation, the shear of the overland flow against the soil provides the detachment force and is a primary factor determining channel transport capacity. With sprinkler irrigation, water drop energy detaches particles, some of which may be transported downslope by shallow interrill flow if the water application rate exceeds the soil infiltration rate.

## IRRIGATION METHODS

Irrigation water is applied either by gravity (surface) irrigation, in which the soil surface distributes water by overland flow, from pressurized sprinklers that spray water across the soil surface, or by drip (trickle) irrigation in which water is supplied through small-diameter tubing to localized areas at very low rates. Most surface irrigation erosion occurs when the flow is concentrated in small channels called furrows or corrugates. Sprinkler irrigation can cause erosion when the application rate is higher than the soil infiltration rate, which frequently occurs near the outer end of center pivot systems. Because of low application rates, runoff and erosion do not normally occur under drip irrigation. Consequently, only furrow and sprinkler irrigation-induced erosion will be discussed. This paper deals with erosion and transport processes within the irrigated field that can result in soil redistribution on the field and soil loss from the field.

## SOIL SUSCEPTIBILITY TO EROSION

A soil's susceptibility to erosion, or erodibility, depends upon the strength of the bonds between primary particles, which determines the aggregate stability; and the amount, size, and density of loose soil particles and aggregates left by previous mechanical disturbance such as tillage. Crop cover and surface or incorporated residues may shield the soil surface from the erosive forces.

Soil aggregate stability varies with soil texture (especially clay content), organic matter content, compaction, adsorbed ions, and the chemical com-

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position of the water, time, and water content since last disruption, water content before wetting, and wetting rate. Particle-to-particle bond formation, stabilization, and disruption processes are poorly understood. Recent investigations have focused on soil bonding constituents (Kemper and Koch 1966; Lehrsch et al. 1991; Uehara and Jones 1974), the bond formation process (Blake and Gilman 1970; Utomo and Dexter 1981; Kemper and Rosenau 1984; Kemper and Rosenau 1986), bond persistence and change (Kay 1990; Lehrsch and Jolley 1992), and bond disruptive forces such as wetting (Panabokke and Quirk 1957; Kemper and Koch 1966, Arulanandum et al. 1975; Kemper et al. 1975; Kemper et al. 1985b) and freezing (Bullock et al. 1988; Lehrsch et al. 1991; Mostaghimi et al. 1988; Perfect et al. 1990). Mechanical measures of soil strength such as vane shear tests and fall cone penetrometer tests (Franti et al. 1985) have been used to attempt to quantify soil resistance to hydraulic detachment. Arulanandam et al. (1975), Kemper and Rosenau (1986), and Young (1984) describe methods of measuring soil aggregate stability under hydraulic forces in the laboratory.

## EROSION AND SEDIMENTATION PROCESSES UNDER FURROW IRRIGATION

In furrow irrigation, parallel prismatic channels are mechanically formed at regular spacings between 0.6 and 1.6 m (24 and 60 in.). Furrows usually range in slope from 0.2% to 2% and less commonly to 5%, and are usually oriented within 45° of the direction of the maximum field slope. Newly formed furrows are often V-shaped although, with use, the cross section normally evolves to a shape that can be described by a parabola or power function (Trout 1991). Water is introduced into the head (upper) end of the furrow through outlets from a pipe or open channel. Inflow must be high enough to meet initial infiltration and surface storage requirements and advance the flow across the field, which is commonly between 200 and 400 m long, in the desired amount of time—usually less than 40% of the irrigation time. Runoff at the furrow tail (lower) end normally increases with time because of decreasing infiltration rates, and may reach 40–70% of the inflow rate. Flow often continues for 12 or 24 hours.

### Soil Detachment

Flowing water exerts hydrodynamic lift and drag forces on the flow boundaries that can detach and move soil particles. The total resistive drag force, also called the tractive force, of a steady flow must equal the component of the gravitational force on the water in the direction of the flow, resulting in the commonly used tractive force equation (Duboys 1879; Graf 1971).

$$\tau = \frac{\gamma A S}{P} = \gamma R S \qquad (1)$$

where $\tau$ = the tractive force (N/m$^2$); $\gamma$ = the unit weight of water (9800 N/m$^3$); $S$ = the energy slope, essentially equal to the furrow bed slope (m/m); $A$ = the flow cross-sectional area (m$^2$); $P$ = the furrow wetted perimeter (m); and $R$ = the furrow hydraulic radius = $A/P$ (m).

The tractive force is commonly used to describe the average shear of the flow exerted on the wetted perimeter. However, a portion of the drag force is absorbed by obstructions such as crop residue, growing plants, soil clods, and bed forms such as dunes (Graf 1971). The portion absorbed by this form roughness must be subtracted from the tractive force in order to determine the shear on the perimeter particles. Otherwise, the flow in a furrow with high roughness (and thus greater flow depth and hydraulic radius) would be predicted to erode more than flow in a smooth furrow, even though the rough furrow conveys water at lower velocity.

Foster (1982) and Graf (1971) proposed partitioning the shear based on roughness coefficients for the furrow with and without the form roughness. Solving Manning's uniform flow equation, $V = R^{2/3}S^{1/2}/n$, for $R$, and inserting into (1) gives

$$\tau = \gamma V^{3/2} n^{3/2} S^{1/4} \quad \text{(2a)}$$

and

$$\tau_s = \gamma V^{3/2} n_s^{3/2} S^{1/4} \quad \text{(2b)}$$

where $\tau_s$ = the shear acting on the soil particles at the furrow perimeter (N/m²); $V$ = the average flow velocity (m/s²); $n$ = Manning's roughness coefficient; and $n_s$ = the roughness coefficient without form roughness. Note that $V$ in both (2$a$) and (2$b$) is actual velocity with form roughness. Thus

$$\frac{\tau_s}{\tau} = \left(\frac{n_s}{n}\right)^{3/2} \quad \text{(3)}$$

Furrows with relatively smooth perimeters and little form roughness have roughness values, $n_s$, of about 0.02 (Trout 1992). Irregular, cloddy furrows have $n$ values as high as 0.04, implying $\tau_s/\tau$ = 0.35. Furrows with plant residue or growing plants in the flow may have roughness coefficients as high as 0.10, yielding $\tau_s/\tau$ values as low as 0.09. Note that if the Darcy-Weisbach uniform flow equation is used instead of Manning's equation, the shear ratio is equal to $f_s/f$ where $f_s$ and $f$ = the friction factor without form roughness and the total friction factor, respectively.

The distribution of shear along the wetted perimeter of small furrows or rills will vary with furrow shape and form roughness, but generally will be maximum at the furrow bottom and decrease to zero at the water surface. Chow (1959) shows calculated shear distributions in trapezoidal channels which reach $\gamma dS$, where $d$ = the flow depth (m), in the center of the bed and decrease along the side walls from a maximum of $0.75\gamma dS$ near the bed to zero at the water surface. Foster and Lane (1983) estimated that shear stress reaches $1.35\tau$ at the center of rill beds.

The shear that causes particle detachment is so highly variable in small earthen channels in both time and space (Foster et al. 1984) that it is practically impossible to quantify in detail. Consequently, average shear, as given by the tractive force equation, is most commonly used as an indicator of flow erosivity. Two alternative hydraulic parameters that have also been used to indicate erosivity are flow velocity and stream power. Both are closely related to shear. With the Manning's uniform flow equation, shear is proportional to $V^{3/2}$ [(2)]. With the Chezy or Darcy-Weisbach equations, shear is proportional to $V^2$. Stream power is the product of shear and velocity.

If the furrow hydraulic radius, $R$, can be related to the hydraulic parameters of flow rate, $Q$ (m³/s), slope and roughness, the tractive force can be calculated for given hydraulic conditions. Rearranging Manning's equation to separate the hydraulic from the geometric parameters gives

$$\frac{Qn}{S^{1/2}} = AR^{2/3} \quad (4)$$

Thus, a relationship between $A$ and $R$ (or $A$ and $P$ since $R = A/P$) is required.

Trout (1991) found that furrows in erodible soil tend to evolve to a stable shape such that the cross-sectional shape of flow remains fairly constant and only the size varies as hydraulic conditions vary. The channel width becomes greater due to sloughing as the flow depth increases such that the top width-to-flow depth ratio and the flow shape remain fairly constant. This geometric model results in the channel wetted perimeter being proportional to the depth and the area being proportional to the depth squared. Thus, the area is proportional to the wetted perimeter squared and the right side of (4) is proportional to $A^{4/3}$ and thus to $R^{8/3}$. This compares well with measured relationships in rills (Foster et al. 1982; Meyer et al. 1975).

With this cross-sectional shape assumption, the relationship between the tractive force and flow rate, slope, and roughness is (Trout 1991):

$$\tau = \gamma RS = \gamma k_1 \left(\frac{Qn}{S^{1/2}}\right)^{3/8} S = \gamma k_1 Q^{3/8} n^{3/8} S^{13/16} \quad (5)$$

where $k_1$ = a coefficient dependent on the channel shape. Likewise, stream power, $\omega$ (W/m$^2$), can be related to $Q$, $S$, and $n$:

$$\omega = \tau V = \gamma k_1^{5/3} \left(\frac{Qn}{S^{1/2}}\right)^{3/8} QS = \gamma k_1^{5/3} Q^{5/8} n^{3/8} S^{19/16} \quad (6)$$

With (5) or (6), the relative effects of changes in the hydraulic parameters on shear and steam power can be calculated directly. Both equations show that flow erosivity should be about twice as sensitive to variations in furrow slope as to variations in furrow flow rate.

In wide channels with noncohesive beds, many researchers have observed that a critical shear or tractive force, $\tau_c$, is required before significant particle movement will occur (Graf 1971). This concept has been adopted by several researchers modeling erosion in cohesive channels (Partheniades 1972; Foster et al. 1981; Meyer et al. 1975). By this theory, particle detachment or erosion capacity, $E_c$, is related to shear by:

$$E_c = K(\tau_s - \tau_c)^b \quad (7)$$

where $K$ = a soil coefficient and $b$ = an empirical exponent. Many authors assume $b = 1$. Foster and Lane (1983) assign a value of 1.05. Both $K$ and $\tau_c$ vary with the soil type and condition.

Foster and Lane (1983), utilizing the concept of critical shear and an estimated shear distribution along the wetted perimeter, derived a stable shape which an eroding channel in a homogenous soil will approach. After reaching the stable shape, erosion continues uniformly along the perimeter to the point where the shear is less than $\tau_c$, and beyond which no erosion occurs. Thus, the channel erodes downward at a uniform rate until a less erodible layer is reached, at which time the bed flattens and width increases. The process continues at an asymptotically decreasing erosion rate until a wide rectangular channel evolves and $\tau < \tau_c$ everywhere. The final width can be predicted. Data collected on rills formed under highly erosive flows support this theory (Foster et al. 1982). In irrigation furrows where erosion usually occurs under less severe and more controlled conditions, this process is less evident.

Kemper et al. (1985a) proposed that, because of the unstable nature of dry aggregates under rapid wetting and the wide size range of unattached particles after tillage, there is no threshold shear value required to initiate erosion in furrows, and thus $\tau_c$ in (7) is zero. Such a relationship appears to fit the data presented in Partheniades (1972) and Foster et al. (1982) as well as (7) with a critical shear value. Sayler and Fornstrom (1986) used the ratio of measured shear to a baseline shear value at which significant erosion occurs to predict erosion in irrigation furrows, which is similar to assuming $\tau_c$ in (7) is zero. Note that when $\tau_c$ is assumed to be zero, the $b$ value will be larger than one and often larger than two.

By assuming $\tau_c = 0$, that $\tau$ is given by (5) and that the shear and thus erosion is evenly distributed around the wetted perimeter, Kemper et al. (1985a) derived a relationship between erosion rate per unit length, $E_c$, and $Q$, $S$, and $n$:

$$E_c = K\tau^b P = Kk_1^{(b-5/3)}\gamma^b(Q^{6b+6}n^{6b+6}S^{13b-3})^{1/16} \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

If the relationship between erosion rate per unit length and flow rate or slope is measured for a given soil and furrow condition, the $b$ value in (8) can be derived. Derived $b$ values in furrows have varied from 2.0 to 3.5 (Kemper et al. 1985a). This implies the exponent on the flow rate term ranges between 1.1 and 1.7 while the exponent on the slope term ranges between 1.4 and 2.7 and that erosion is 1.3–1.6 times more sensitive to slope changes than to flow rate changes.

Eq. (8) predicts that, as channel roughness increases, erosion increases. As discussed previously, although roughness does increase flow depth and thus tractive force, the form roughness absorbs shear and decreases the portion of the shear applied to the soil surface. Thus, (8) cannot be used to predict the effects of roughness on erosion. In fact, practices that increase roughness by use of residue or growing plants extending into the flow are commonly used to decrease furrow erosion (Miller et al. 1987; Aarstad and Miller 1981; Brown 1985; Brown et al. 1988; Carter and Berg 1991; Cary 1986).

Erosion in furrows does not occur uniformly or at a constant rate as these equations based on average shear and uniform cross sections imply. Gravity may cause sloughing of furrow side walls that have been weakened by wetting and/or undercut by erosion. Sloughed soil provides both readily moved fine sediment and difficult-to-move larger particles and aggregates that may deposit in the channel bed and result in wide and shallow furrow cross sections. Compacted subsurface layers such as tillage pans may stop scouring of the bed. Head cuts form when, at points of localized high shear, the surface seal or a resistant soil layer is eroded away and the channel bed elevation drops. The accelerating water at the drop erodes a pool that undercuts the resistant layer so that the head cut moves upstream, producing large amounts of sediment.

In furrows in cohesive soils, the quantity of sediment transported changes with time even with constant flow conditions. Israelson et al. (1946) and Gardner and Lauritzen (1946) measured exponentially decreasing sediment discharge rates with time. Mech (1949) and Kabir and King (1981) measured sediment discharge rates that decreased after 30 min of flow. The initial high sediment loss is likely the result of movement of loose particles left from tillage or previous deposition and particles produced by aggregate disintegration during rapid wetting. After this loose material is eroded away, the erodibility of the soil, represented by the $K$ value in (7), decreases and erosion decreases. Foster (1982) also explains higher initial erosion from rills as the flushing of loose soil.

Brown et al. (1988) proposed that sediment deposition on the furrow perimeter creates a low-permeability seal that increases the soil water tension at the furrow perimeter. The tension, in turn, increases deposition and stabilizes the seal. This self-perpetuating process stabilizes the furrow perimeter and decreases the erodibility of the soil with time.

Foster and Lane (1983) proposed that, after the loose sediment is removed, the channel bed will erode steadily downward until a less erodible layer is reached. The erosion rate will then decrease exponentially as the channel widens and shear decreases. This process, which will also result in decreasing erosion with time, probably occurs in furrow erosion, but becomes important only under highly erosive conditions.

The decrease in soil erodibility with time can be modeled by a $K$ coefficient that decreases with time or eroded mass. Kabir and King (1981) model this soil erodibility change with an availability function that decreases logarithmically over time.

These individual processes are complex and highly variable and are difficult to describe mathematically. Consequently, they are usually assumed to all be related to the shear of the flow and their combined effects are incorporated in the soil coefficients. The many distinct processes result in large variability in erosion data.

**Sediment Transport**

Once sediment is detached, it will be transported by the flow for some distance, dependent primarily upon the sediment particle and aggregate sizes and densities, and the transport capacity of the flow. Sediment is moved both as bed load, which rolls, slides, and bounces along the furrow bed, and as suspended load, which remains entrained in the flow.

Bed load movement depends primarily on the lift and drag of the flow. The drag force is commonly represented by the shear. Thus, bed load movement is primarily dependent on the shear and the particle size and density.

Particles are held in suspension if the upward velocity components of a turbulent flow exceed the fall velocity of the particles. Thus, suspended load capacity depends upon: (1) The flow turbulence; (2) a measure of the channel relative roughness; (3) the particle size, shape, and density; and (4) the fluid viscosity. Flow turbulence is often represented by the shear velocity, $u^* = \sqrt{\tau/\rho}$ (Graf 1971; Alonzo et al. 1981) where $\rho$ = the fluid density ($kg/m^3$). Suspended transport is often analyzed as a diffusion-dispersion process.

Since distinguishing between suspended and bed load in small channels is difficult and the complex hydrodynamic processes both depend upon similar measurable parameters, the two processes are often either lumped together or the suspended load process is ignored.

Streamflow sediment transport capacity is the upper limit of the flow's ability to transport sediment or the sediment concentration that would be reached in a long, uniform channel. Several transport capacity equations of various complexities have been developed (Graf 1971). Alonzo et al. (1981) compared the applicability of nine commonly used sediment transport equations to transport in agricultural watersheds. They, and Foster and Meyer

(1972c), concluded that the Yalin equation provided reliable estimates of transport capacity in small watersheds.

Finkner et al. (1989) proposed a simplified version of the Yalin equation to predict the transport capacity at the end of a slope. They also confirmed the earlier finding of Foster and Meyer (1972b) that transport capacity, $T_c$, varies along a channel with the 3/2 power of shear

$$T_c = k_t \tau_s^{3/2} \qquad (9)$$

where $k_t$ = a transport coefficient.

Most erosion models recognize that net erosion decreases as sediment load increases. Foster and Meyer (1972a) and Simons et al. (1977) propose that net erosion, $E$, is proportional to the difference between sediment transport capacity, $T_c$, and sediment load, $T$, resulting in

$$\frac{E}{E_c} = 1 - \frac{T}{T_c} \qquad (10)$$

Although this relationship implies that sediment load influences the erosiveness of the flow, the actual effect of load is on deposition. As discussed earlier, because earthen channels are not smooth and prismatic, flow velocity and shear varies widely. Localized points of low velocity behind soil aggregates or bed dunes and in natural depressions allow otherwise transportable particles to settle out. Because the perimeter is permeable and water is being absorbed, some particles move with absorbed water into pore spaces in the perimeter. Soil water tension at the soil surface can hold transportable particles in place (Brown et al. 1988; Segeren and Trout 1991). Neibling and Foster (1983) and Einstein (1968) have also noted the tendency of transportable fine sediments to accumulate on coarse channel beds. These processes result in gradual sediment deposition, even though the transport capacity has not been exceeded, and a smoothing of the furrow perimeter. As the concentration of sediment in the flow increases, the probability of deposition by these processes increases. Thus net erosion (detachment minus deposition) decreases as sediment load increases and the transport capacity in a channel with uniform flow is approached asymptotically rather than linearly.

Eqs. (9) and (10) along with the simplified Yalin equation form the basis for the sediment transport predictions in the water erosion prediction project (WEPP) model (Nearing et al. 1989).

The transportability of sediment, represented by $k_t$ in (9) depends on the size and density of the sediment particles. Soil particles vary in size from clays (diameter <2 μm) through sands (diameter >0.25 mm). However, most particles eroded from cohesive soils are actually microaggregates with diameters from 50 μm to larger than 1 mm, which vary in density from 1.6 to 2.0 gm/cm$^3$ (Young 1980; Foster et al. 1981). As the flow rate in furrows decreases and transport capacity begins to limit transport, the larger and heavier particles tend to deposit first, resulting in a change in size distribution of the sediment (Foster et al. 1981). Also, as bed load aggregates roll and bounce along the furrow bed, they may abrade into smaller particles, which also reduces the average transported particle size. Decreasing particle size with transport distance results in an increase in the transportability of the sediment, which may at least partially counteract a decreasing transport capacity of a furrow flow. This process will also cause differential deposition of larger particles upstream of smaller particles and result in accumulated textural differences in furrow irrigated fields.

**Furrow Erosion, Deposition, and Transport**

The sediment load, $T$ (kg/s) at any location along a furrow, $x$ (m), is given by the integral of the erosion rate, $E$ ([kg/m]/s) (assuming no sediment inflow to the furrow)

$$T = \int_0^L E\,dx \qquad (T < T_c) \quad \text{(11a)}$$

or equivalently

$$\frac{dT}{dx} = E \quad \text{(11b)}$$

Inserting (10) for the erosion rate, separating the variables and integrating, (11$b$) yields

$$T = T_c\left[1 - \exp\left(-\frac{E_c}{T_c}L\right)\right] \quad \text{(12)}$$

Eq. (12) confirms that the sediment load gradually approaches the transport capacity with distance along a furrow. The erosion rate likewise approaches zero.

However, flow rate decreases with distance along irrigation furrows as water infiltrates, and thus $E_c$ and $T_c$ also decrease. Eq. (11$a$) cannot be solved explicitly for spatially changing flow rates. As flow rate decreases, $T_c$ eventually becomes less than the sediment load, resulting in deposition, $D$

$$D = -\frac{dT_c}{dx} \qquad (T_c \le T) \quad \text{(13)}$$

Assuming flow rate decreases at a uniform rate along a furrow and inserting (9) and (5) into (13) yields

$$D = \left(\frac{9}{16}\right)\gamma^{3/2}k_1^{3/2}k_tI(Q_0 - Ix)^{-7/16} \qquad (T_c \le T) \quad \text{(14)}$$

where $I$ = the uniform infiltration rate, $Q_0$ = the furrow inflow rate and $k_1$ and $k_t$ = previously defined coefficients. Thus, deposition increases at an increasing rate with distance until $Q$ becomes zero.

These steady-state relationships are depicted along a hypothetical irrigation furrow in Fig. 1. In the figure, the flow rate decreases linearly with distance (uniform infiltration) and goes to zero at $x$ = 100. Shear is calculated by (5) and $\tau_s$ is assumed equal to $\tau$ (no form roughness). Erosion capacity is calculated by (7) with $\tau_c$ = 0 and $b$ = 2.5, and $E$ is calculated by (10). Transport capacity is calculated by (9) and sediment load is calculated numerically from (11). Both flow rate and erosion rate are set at unity at the beginning of the furrow, and initial transport capacity is set at 30 times $E_c$.

In Fig. 1($a$), the furrow slope is uniform. Although erosion capacity decreases along the furrow similar to flow rate, net erosion decreases more rapidly, due to the increasing sediment load. For this example, $T$ reaches $T_c$ at the point where $Q$ is 40% of $Q_0$. Beyond this point, net erosion ceases and net deposition begins. The figure depicts deposition increasing abruptly

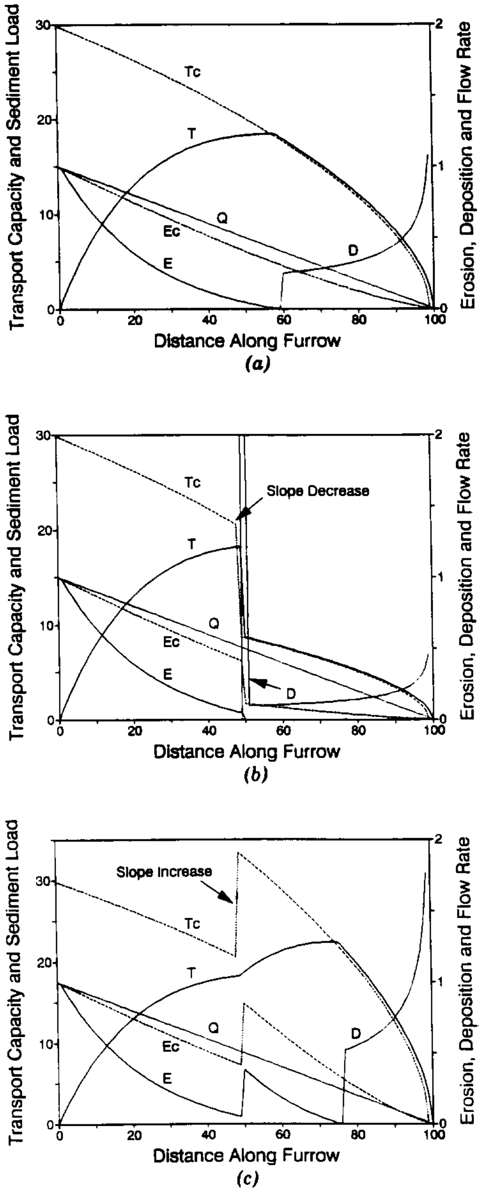


**FIG. 1. Variation in Flow Rate, $Q$, Erosion Rate, $E$, Erosion Capacity, $E_c$, Sediment Transport (Load) $T$, Transport Capacity, $T_c$, and Deposition, $D$, with Relative Distance along Irrigation Furrow with: (*a*) Constant Slope; (*b*) Abrupt Slope Decrease; and (c) Abrupt Slope Increase**

to match the decreasing transport capacity. In reality, deposition would increase more gradually as suspended particles settle.

Fig. 1(*b*) depicts a furrow with an abrupt 50% slope decrease halfway along the furrow. This decrease reduces the transport capacity by 70% and results in a large amount of sediment deposition concentrated just beyond the slope change. Fig. 1(*c*) depicts a 50% slope increase halfway along the furrow. The resulting increase in $T_c$, $E_c$, and thus $E$ causes erosion to continue until the point where $Q$ is only 25% of $Q_0$. If the slope increase had been in the tail end section where deposition was occurring, it would have stopped deposition for some length and may have resulted in erosion in that section. This commonly occurs where farmers excavate a tail water collection ditch below field level. The increased flow velocity into the ditch erodes the furrows and results in a convex end on the field (Carter et al. 1993).

Fig. 1 shows $Q$ decreasing to 0 and all eroded sediment depositing before the tail end of the furrow. In actual furrows, this process is truncated because farmers allow 10–50% of the flow to run off the tail end of the field. The sediment load at that point would be the sediment yield from the field, the quantity that is most often measured and reported in the literature. As the figure shows, outflow sediment yield measurements do not quantify the sediment movement on furrow-irrigated fields and may miss the majority of the erosion that occurs at the head end of the field but is contained and redistributed on the field surface. Head-end erosion can cause serious crop yield losses (Carter 1993) without necessarily resulting in excessive sediment yield from the field.

Note that the processes described in Fig. 1 eventually result in hydraulic leveling of furrows to a uniform, flatter slope. Soil is eroded from the initial portion of steep reaches and deposited in the initial portion of flat reaches, and soil is eroded from the inflow end of the furrow and deposited at the tail end.

Due to the several complex processes discussed previously, sediment erosion, transport, and deposition in furrows is much more difficult to quantify than is represented by these simple models. Relationships that were originally developed to model erosion and transport in large noncohesive channels cannot accurately predict erosion in small cohesive furrows, although they do provide valuable information on factors and relationships important to the process. Our lack of understanding of soil cohesion and aggregate stability further limits the effective use of analytical models. Thus, although process-based models are important for understanding the processes, the presently available models can predict soil erosion from a field no better than simple empirical models relating erosion and sediment transport to measurable hydraulic parameters such as slope and flow rate and qualitative descriptions of the soil medium.

## EROSION AND SEDIMENTATION UNDER SPRINKLER IRRIGATION

Under sprinkler irrigation, water is distributed under pressure to pipe lines (laterals) with sprinklers at regular intervals. Water sprays radially from each sprinkler and thus is applied to a strip of land along the lateral. With hand-move and side-roll laterals, after sufficient water has been applied to an area, the lateral is moved to the next location to irrigate another, usually adjacent, strip of land. Fixed-set systems are operated similar to hand move systems, although several laterals may operate concurrently.

Center pivot and linear move systems are automated to move the lateral at constant speeds radially around or linearly through a field.

Agricultural sprinklers have traditionally been impact type, which uses an impact arm to rotate the nozzle. High pressure (300–500 kPa) is used to spray the water over 10- to 20-m radius circles. With recently developed low pressure (150–300 kPa) impact sprinklers, coverage area is less (8- to 12-m radius) and special nozzle designs are used to break up the spray jet. Low-pressure spray heads (70–200 kPa) impact the jet onto a smooth or serrated plate to produce a radial spray (3–6 m wetted radius).

Because the outer sprinklers of center pivot systems move faster, they must apply water at about a 40% higher rate than the average application rate for the system, thus increasing the possibility of exceeding the soil infiltration rate and creating runoff and the potential for erosion. Low-pressure sprinklers and spray heads also increase the potential for runoff and erosion because the application rate per unit area on the smaller wetted areas must be higher to achieve the same total application. Typical application rates at the outer ends of center pivots range from 35 mm/h for high-pressure impact nozzles to 100 mm/h for low-pressure spray heads (Kincaid et al. 1990). Runoff from the outer spans of 10 low-pressure center pivots in the Pacific Northwest averaged 16% of the applications for fields with slopes between 1 and 5% (Kincaid et al. 1990).

Meyer and Wischmeier (1969) separated erosion by rainfall into four components: detachment of soil particles by falling raindrops, detachment by flowing water, transport by rain splash, and transport by flowing water. Each of these processes is present in erosion from sprinkler irrigation to one degree or another depending on waterdrop characteristics and soil, topographic, and cover factors.

**Detachment by Water Drop Impact**

The erosion process begins when water drops strike the soil surface. The explosive character of impacting drops detaches soil particles from the soil mass. The detached particles are splashed in all directions from the impact point, with net movement downslope.

In natural rainfall, detachment of soil particles by raindrop impact has been shown to be proportional to rainfall intensity squared (Meyer and Wischmeier 1969) or to the product of momentum and number of drops, both raised to a power (Park et al. 1983). Meyer (1981) and Park et al. (1983) both measured splash erosion by simulated rainfall from sprinklers and found it proportional to rainfall intensity to a power that varies, with soil type, from 1.6 to 2.1.

An alternative means of evaluating erosion from raindrop impact is to relate it to the kinetic energy of the rainfall since the size distribution and the kinetic energy produced by a number of sprinkler nozzles has been evaluated. Simulated rainfall with drop diameters of 2.2, 3.2, and 4.9 mm and several fall heights was used to study soil detachment from a silty clay, a loamy sand, and two silt loam soils (Bubenzer and Jones 1971). The regression equation relating soil splash, $ss$, to kinetic energy, $e_k$, rainfall intensity, $i$, and percent clay, $c$, was:

$$ss = 7.50 i^{0.41} e_k^{1.14} c^{-0.52} \qquad (15)$$

which had a correlation coefficient of 0.93. Kinetic energy was by far the most significant term. Additional soil parameters did not significantly improve the degree of correlation.

**Sprinkler Waterdrop Energy**

To evaluate the erosion potential of various sprinklers, the mean drop diameter can be converted to kinetic energy using the procedure of Stillmunkes and James (1982). These kinetic energy values can then be used in (15) to obtain an estimate of soil detachment by water drop splash. Erosion in the field will not be equal to splash values, but they can be used as an index of the relative erosivity of a particular sprinkler. Data on drop size distributions from various nozzle designs, and the effect of nozzle size or pressure on drop size distribution has been the object of considerable recent research (Kohl 1974; Dadio and Wallender 1985; Kohl and DeBoer 1984; Soloman et al. 1986). Drop size is important not only to splash erosion, but also to surface seal formation, and thus infiltration and runoff.

Kohl et al. (1985) converted drop size distribution data for a low-pressure sprinkler to kinetic energy distributions, using the method of Stillmunkes and James (1982). Peak kinetic energy from a smooth plate spray sprinkler with a 6.4-mm nozzle operated at 100 kPa was approximately 20 $J/m^2$-mm, comparable with the kinetic energy of rainfall of less than 10-mm/h intensity. Peak kinetic energy from the same nozzle with a serrated plate was 32 $J/m^2$-mm, comparable with that of natural rainfall of 200 mm/h, a highly erosive condition. A standard impact sprinkler with a 3.97-mm nozzle operated at 400 kPa produced an intermediate peak kinetic energy value of 25 $J/m^2$-mm.

**Transport by Shallow Overland Flow**

Although detachment processes govern the quantity of sediment produced at a particular site, sediment transport processes determine how much of that sediment may be moved from the site. The sediment is transported by overland flow, and thus erosion depends upon water application in excess of the soil infiltration rate. The same raindrop processes that detach soil particles tend to decrease the infiltration rate (Thompson and James 1985; von Bernuth 1982; Moldenhauer and Kemper 1969) and reduce surface roughness (Zobeck and Onstad 1987), thus enhancing the possibility for runoff.

When the water application rate exceeds the infiltration rate, water initially ponds in small depressions. Once surface storage is exceeded, water begins to flow downslope as shallow overland flow. This flow seldom exerts sufficient shear to detach particles, but does carry sediment detached by water drop impact. In this interrill area of broad shallow flow, considerably more sediment may be detached by raindrop impact than can be transported.

The basic bed and suspended load transport processes are described in the furrow erosion section. Streamflow transport equations have been adapted to describe transport in shallow interrill flows. Foster (1982) lists applications of the DuBoys, Meyer-Peter and Muller, Einstein, Yang, Yalin and Bagnold sediment transport equations.

The streamflow transport equations were all developed under conditions where presence of rainfall was not a significant factor. In the shallow flow case, rainfall can significantly increase flow depth (Izzard and Augustine 1943) and transport capacity (Young and Wiersma 1973; Davis et al. 1983; Neibling 1984); although insufficient data are available to develop a functional relationship.

**Detachment and Transport in Concentrated Flow Areas**

As overland flow moves downslope, it tends to concentrate because of equipment tracks, tillage marks, natural microtopography, or previous erosion. The detachment and transport processes in these rills are similar to those in furrows, described in the previous section. However, in rills, flow rates tend to increase rather than decrease with distance because the collection area increases. Thus, transport capacity tends to increase and a slope decrease is required before net deposition occurs.

As with shallow, interrill flow, the presence of rainfall can have a significant impact on the erosion rate and development of a rill (Young and Wiersma 1973; Alberts et al. 1980). Raindrop impact detachment and lateral inflow tends to round and decrease the slope of rill sidewalls, providing a significant source of sediment. Meyer et al. (1975) showed that the presence of a canopy decreased rill erosion to less than half that without canopy cover.

Flow from a number of rills tends to concentrate into a few larger channels formed in the natural drainageways of a field. The ephemeral channels or gulleys are larger than rills, but can still be obliterated by tillage. The sediment detachment and transport processes are similar to those in rills. However, since flow depths are greater in ephemeral gulleys, the effect of rainfall is small.

Typically, an ephemeral gully will erode downward to a less erodible layer and enlarge to an equilibrium width during the first significant erosion event following tillage. Unless tillage occurs, additional erosion will be minimal for subsequent events smaller or equal in size to the event that formed the channel.

**Concentrated Flow Differences with Sprinklers**

Concentrated flow under sprinklers will tend to differ from that under normal rainfall because only a small portion of a field is being irrigated at one time. The runoff area contributing to concentrated flow depends upon the orientation of the sprinkler lateral relative to the prevailing slope. When the lateral is oriented across the prevailing slope, the wetted slope length is only the width of the wetted strip. When the lateral orientation is parallel to the prevailing slope, the effective slope length is the lateral length, although the total drainage area is still a small portion of the total field. With center pivot irrigation, application rates decrease toward the center of the pivot and thus the runoff producing slope length will only be a portion (usually less than one-quarter) of the lateral length. Crop row orientation in line with the prevailing slope and lateral will also increase runoff and erosion potential.

Also with center pivot sprinkler irrigation, application depths per event are usually less than 30 mm. Large precipitation events which can cause much of the concentrated flow under rainfall do not normally occur. As a result of the controlled application depths and small effective slope lengths and collection areas, concentrated flow erosion generally is not as important a factor under sprinkler irrigation as under rainfall conditions. Most sediment produced by water drop impact is transported to local depressions by shallow interrill and rill flow.

## APPENDIX I. REFERENCES

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## APPENDIX II. NOTATION

*The following symbols are used in this paper:*

$A$ = flow cross-sectional flow area (m$^2$);
$b$ = empirical exponent [(6)];
$c$ = percent clay content;
$D$ = sediment deposition rate (kg/m/s);
$d$ = flow depth (m);
$E$ = soil erosion rate ([kg/m]/s);
$E_c$ = soil erosion capacity ([kg/m]/s);
$e_k$ = sprinkler drop kinetic energy (J/cm$^2$);
$f$ = Darcy-Weisbach friction factor;
$f_s$ = Darcy-Weisbach friction factor excluding form roughness;
$I$ = furrow infiltration rate ([m$^3$/m]/s);
$i$ = rainfall intensity (cm/h);
$K$ = rill erodibility soil coefficient [(6)];
$k_1$ = channel shape coefficient [(5)];
$k_2$ = channel shape coefficient [(7)];
$k_t$ = sediment transport coefficient [(8)];
$L$ = furrow section length (m);
$n$ = Manning's roughness coefficient;
$n_s$ = Manning's roughness coefficient without form roughness;
$P$ = wetted perimeter (m);
$Q$ = flow rate (m$^3$/s);
$Q_0$ = furrow inflow rate (m$^3$/s);
$R$ = hydraulics radius = $A/P$ (m);
$S$ = channel energy slope (m/m or %);
$ss$ = soil splash (g/cm$^2$);
$T$ = sediment transport (kg/s);
$T_c$ = sediment transport capacity (kg/s);
$t$ = time (s);
$u_*$ = shear velocity (m/s);
$V$ = average flow velocity (m/s);
$\gamma$ = unit weight of water (9800 N/m$^3$);
$\rho$ = fluid density (kg/m$^3$);
$\tau$ = tractive force or average shear stress (N/m$^2$);
$\tau_c$ = critical shear tractive force (N/m$^2$);
$\tau_s$ = shear acting on perimeter soil particles (N/m$^2$); and
$\omega$ = stream power (W/m$^2$).