37

Soil Erosion on Irrigated Lands

D. L. CARTER
USDA-ARS
Kimberly, Idaho

Soil erosion is a serious agricultural problem. Most of the available literature on the subject concerns nonirrigated cropland where natural precipitation and snowmelt water produce the forces needed to erode soil and transport sediment. Most of the water providing those forces for erosion on irrigated land is that applied by humans to supply water to growing crops. The purpose of this chapter is to provide a review of irrigation-induced soil erosion and to supply some insight into its hazards and control.

I. GENERAL OBSERVATIONS

A. Irrigation-Induced Erosion Began With Irrigation

Irrigation-induced erosion began when water was first applied to the soil surface where the land slope was sufficient that the moving water had enough shear force energy to detach soil particles from the soil mass and transport them as suspended sediment or bedload. Some of the first irrigating was by wild flooding (see chapter 16 in this book). Using this method to irrigate grass meadows seldom caused much erosion, but when farmers began to till the soil to produce crops of greater value, serious erosion resulted from wild flooding.

Most high-value crops are planted in rows, and to surface irrigate them, small ditches are made parallel to these crop rows; thus, furrow irrigation has become a common method. The concept that water could be controlled by these parallel furrows has extended the use of furrow irrigation to nonrow or solid stand crops, such as alfalfa (*Medicago sativa* L.) and cereals. Today, furrow irrigation is widely practiced and in most areas where it is practiced, furrow erosion is a problem.

Sprinkler irrigation has been developed to irrigate areas that cannot be irrigated by other methods and to improve irrigation efficiency. Soil erosion can also be serious under sprinkler irrigation if the water application rate exceeds the soil infiltration capacity.

Irrigation of Agricultural Crops—Agronomy Monograph no. 30.

B. Recognizing Erosion as a Problem on Irrigated Land

Furrow erosion was recognized as a serious problem more than 50 yr ago in Utah. Isrealson et al. (1946) reported that furrows near the head ditches eroded 2.5 to 10 cm in one irrigation season. These researchers, along with Gardner et al. (1946) and Gardner and Lauritzen (1946), developed graphic relationships and equations relating erosion to stream size and furrow slope. They discouraged furrow irrigating slopes that were too steep and encouraged the use of smaller stream sizes to reduce erosion. Even earlier, Taylor (1940) published information on the mean furrow stream velocities at which different sizes of soil aggregates began to be transported.

Following the early work in Utah, investigations were conducted in other western states (Mech, 1949; Evans & Jensen, 1952). The USDA Soil Conservation Service, Division of Irrigation conducted tests throughout the western USA from 1948 to 1952 to determine the maximum nonerosive stream size as a function of slope.

Mech (1949) conducted several studies of the effect of stream size and slope on furrow erosion in Washington, and his results were similar to those reported earlier in Utah. All of these researchers indicated that erosion was not a serious problem on slopes $<1\%$, and that by carefully controlling stream size, furrow erosion can be controlled reasonably well on slopes up to 2%. Irrigation erosion research conducted before 1967 was been reviewed by Mech and Smith (1967), and their paper should be consulted for more detailed information before that date.

Renewed interest in irrigation-induced erosion arose from water quality legislation in the early 1970s, directed at cleaning up rivers and streams. Sediment was recognized as the most serious pollutant in most rivers and streams (Robinson, 1971; Wadleigh, 1968), and some of that sediment was traced to irrigation erosion. Brown et al. (1974) investigated sediment inflows and outflows for two large irrigation tracts and found a net sediment loss of 1.42 t/ha for an 82 000-ha tract and a net sediment inflow for a 65 350-ha tract. This study stimulated further investigations on individual fields and small watersheds. Results from these studies supported the need for developing and implementing erosion control practices.

C. Differences in Erosion on Irrigated and Nonirrigated Cropland

Erosion on nonirrigated cropland occurs when the rainfall or snowmelt rate, or both, exceed the soil infiltration capacity. Serious erosion occurs when the soil is frozen and has an infiltration rate near zero, and rain falls on snow, causing melting, or when unseasonably high temperatures occur suddenly and snow melts rapidly on frozen soil. Under these situations, water moves downslope, and the streams become larger from the addition of more water from the source. Usually rainfall and snowmelt involve the entire soil surface. An exception is where water from melting snowdrifts runs downslope on to non-frozen soil. The crop canopy also plays an important role in reducing erosion on nonirrigated cropland. As the canopy cover increases, it has a continuously greater reducing effect on erosion because it intercepts more and more of the raindrops, thereby reducing the raindrop impact effects on the soil surface.

Erosion on irrigated land can occur by the same processes as described for nonirrigated land, but because irrigated land generally receives less precipitation, this type of erosion is infrequent. On these lands, irrigation-induced erosion is the primary erosion problem.

Erosion on furrow-irrigated land is different from that on nonirrigated land because when water is placed in furrows, only the furrows erode. The water source is at one point, and the streams become smaller as a result of infiltration as they move downslope. Sprinkler irrigation is similar to rainfall except that only a portion of a field receives water at any given time. If water is applied by the sprinklers at a rate greater than the soil infiltration capacity, concentrated flow may begin downslope. If these concentrated flow streams run out of the area being irrigated, they begin to decrease in size as a result of infiltration.

II. FURROW EROSION

Furrow erosion is a dynamic process influenced by many factors and having multiple impacts. The following sections will discuss the furrow erosion process, factors influencing it, the impact of furrow erosion on crop yield, practices to control furrow erosion, and measures to lessen the effect of furrow erosion. The approach will be to report what is known today and project what can be expected in the future.

A. The Furrow Erosion Process

Furrow erosion begins when water enters the furrow, creating forces caused by soil wetting and water flow that exceed cohesive forces holding soil particles together and in place. The condition of the soil in the furrow when it is contacted by water largely determines if erosion will occur. When soils are dry, O_2 and N_2 are adsorbed on the internal surfaces of aggregates. When dry soils are wetted suddenly, water molecules rapidly displace the adsorbed O_2 and N_2 molecules. These gases join entrapped air in the gaseous phase, causing pressure forces sufficient to break soil aggregates apart along planes which constitute their internal surface area. The bursting of small clods resembles tiny explosions. Many times, I have observed dust in the air from this process along the flowing front of furrow streams. When water is applied in the early morning after a cool night, much less erosion results than when the water is applied during or following hot, dry afternoons (Kemper et al., 1985a). As the relative humidity rises above 50% during cool nights, more strongly adsorbed water molecules displace O_2 and N_2 molecules gradually.

Other forces involved are shear forces caused by the flowing water and transported materials and the opposing cohesive factors that bind soil aggregates and their combinations together. When shear forces exceed cohesive forces, erosion occurs. In contrast, soils are stable when cohesive forces exceed shear forces. These two counteracting forces are discussed below.

1. Cohesion factors

Bonds between primary soil particles hold soil aggregates together. The strength of these bonds represents the soil cohesion or stability which varies with clay content and type, organic matter content, compaction, adsorbed ions, time and water content since the last disruption, the wetting rate, and the chemical composition of the water wetting the soil. Soil bond formation and disruption processes are not yet well understood, but recent research has provided considerable enlightenment about factors controlling bond strength or cohesive forces. Kemper and Rosenau (1984) demonstrated that soil cohesion increases with time since the last disruption. Soil disintegrated less in water if a few days were allowed between cultivation and irrigation than when irrigation immediately followed cultivation. Dry soils, high in clay concentration, had greater cohesion than silty soils. Gums and resins from decomposing plant residues also tend to form organic bonds that increase soil stability.

Aggregate stability increases in the spring and summer months in areas where soils freeze (Bullock et al., 1988). In contrast, when minimum daily temperatures fall below 0 °C during winter and early spring months, soil cohesion—as measured by aggregate stability—decreases because of compacting and shearing forces caused by freezing and thawing at high water content. As a result, furrow erosion is higher in the spring when the first and second irrigations are applied and then decreases as the season progresses into summer and fall (Berg & Carter, 1980; Brown et al., 1974). Spring tillage also breaks soil bonds and contributes to greater early-season erosion, particularly when excessive tillage is done.

Conclusions about the erosivity of specific soils at specific sites from single time measurements can be misleading. For example, a measurement made in the spring may give much higher erosion and soil loss values than a similar measurement at the same site in the fall. Similarly, soil may be more erosive immediately following tillage than a week or so later.

2. Shear Forces

The furrow stream size and the slope are factors affecting water velocity that causes the shear forces on the furrow perimeter. Under slow velocities there may be practically no particle detachment. Erosion begins when flow velocities increase, causing shear forces to increase and eventually exceed the critical shear stress (Foster & Lane, 1983; Kemper et al., 1985b; Trout & Neibling, 1989) required to overcome cohesion of soil aggregates and particles. Because there is a wide range of soil cohesion, there is also a wide range of critical shear stresses to be overcome before erosion begins. Because of these variations, analytical predictions of this effect of shear forces on erosion have not been accomplished (Kemper et al., 1985b; Trout & Neibling, 1989).

B. Factors Affecting Furrow Erosion

There are several factors that affect furrow erosion. Some of these have been recognized for more than 50 yr while others have been discovered recently. These factors are difficult to quantify because most of them are complexly interrelated, and the literature contains mostly qualitative statements about them. Recent attempts to quantify some of these factors and their relationships to others have greatly expanded our understanding of irrigation furrow erosion. Following are discussions of some factors known to have significant impacts on furrow erosion.

1. Slope Along the Furrow

The slope along the irrigation furrow was recognized as one of the most important factors in furrow irrigation erosion in the 1930s, and the first attempts to develop relationships between slope and erosion were initiated (Gardner & Lauritzen, 1946; Isrealson et al., 1946). These relationships usually also included the furrow stream size.

A misconception about the relationship between slope and furrow erosion resulted from the fact that measured papameters were generally field slopes taken as an average from the head to the lower end of the furrow, and the sediment loss from the lower end of the furrow was called erosion. This simplification has resulted in the misconception for several reasons. First, few fields have uniform slope along the full furrow length, and erosion along a furrow is dynamic. Where the slope is steeper than the average, erosion will be greater than average, and where the slope is less than average, erosion will be less than average. Another factor is that the furrow stream size decreases from the point of entry to the furrow outlet. The furrow stream size, combined with the slope, determines if the stream will generate sufficient velocity to produce the shear force required to cause erosion along any furrow segment and maintain enough energy to transport the sediment load it has accumulated.

A second reason for this misconception is that convex end patterns have developed on most furrow-irrigated fields (Carter & Berg, 1983). A convex end is an increasing slope beginning approximately 5 to 15 m upslope from the lower end of the furrow. This pattern developed because farmers generally maintained drainage ditches deeper than the furrow ends along the lower ends of fields to allow for free flow of drainage water. As a result, eroding head-cuts begin at the drainage ditch and move along the furrow in response to the increased energy of water because of the increased slope. This is a self-perpetuating process that becomes more severe with time. On many fields, the majority of the sediment loss from the field is from this portion.

A third reason involves factors not fully understood. Brown (1985b) found that erosion may occur along a specific furrow segment during one irrigation and deposition may occur along that same segment during a subsequent irrigation, with the same stream size. These single irrigation effects

Table 37-1. Estimated sediment losses from fields of different crops irrigated from concrete-lined ditches with siphon tubes. Run length was 200 m.

	Average field slope, %							
	0.5-1		1-2		2-3		>3	
Crop	N†	S	N	S	N	S	N	S
	t/ha							
Alfalfa	0.0	0.0	1.6	2.7	5.2	9.2	12.6	22.0
Cereal grain or pea	2.5	4.0	7.2	12.6	14.3	25.1	23.3	40.8
Dry bean or corn	5.6	9.9	19.5	34.3	41.2	72.2	62.8	109.8
Sugarbeet	7.2	12.6	27.1	47.5	59.2	103.6	98.6	172.6

† N = No convex end; S = severe convex end.

are often hidden when only seasonal totals are reported, but they do indicate that there are factors involved that we do not yet understand.

Kemper et al. (1985b). concluded that erosion is approximately a two- to three-power function of furrow slope. They reached this conclusion from studies where sediment losses at the end of the furrows were measured for different slopes. More appropriately, the conclusion should be that sediment loss is about a two- to three-power function of the average furrow slope, and a better definition of the length of the slope concerned should be given. Carter and Berg (1983) reported considerably higher sediment losses for fields with convex ends than from fields without convex ends with the same average slope (Table 37-1).

2. Stream Size

The furrow stream size or flow rate is an important erosion factor. As the stream size diminishes along the furrow length, its energy to erode and capacity to transport sediment decreases. Hence, erosion is greatest on the upper one-third of the furrow and sedimentation generally results on the lower half (Carter et al., 1985; Carter, 1989; Farnstrom et al., 1985).

The furrow stream must be large enough to supply adequate water to irrigate the entire furrow length. Furthermore, the infiltration time should be, as nearly as possible, the same over the entire furrow length to provide uniform amounts of water to the crop. A stream large enough to flow to the lower end of the furrow in a few hours is almost always erosive over the upper one-third of the furrow. Once water has reached the lower end of the furrow, the stream can be cut back to reduce future erosion. Some automated stream size cutback systems have been developed (Humpherys, 1971).

Kemper et al. (1985b) concluded that erosion is commonly about a 1.5-power function of stream size. Again, this relationship should more appropriately be stated as one between furrow stream size and sediment loss.

The variability in stream sizes among furrows averages about 25% and the infiltration rate in a wheel track furrow may be only half that in a non-travelled furrow (Trout & Mackey, 1988; Trout & Kemper, 1983). These two factors add to the difficulty of controlling erosion on any particular field.

The normal response of the irrigator is to apply large enough streams to assure that the water reaches the lower end in all furrows within 2 to 4 h. This practice usually assures erosive stream sizes along the upslope reaches on most fields. As a result, erosion, sediment loss, and runoff are greater than necessary.

Changes in infiltration rate during an irrigation can cause problems. If the furrow stream is reduced after water has reached the lower end of the furrow to reduce runoff, and then the infiltration rate increases (Trout & Mackey, 1988), the stream may no longer reach the lower end of the furrow. Thus, farmers use streams large enough to protect against such an event they believe may occur because of past experience.

3. Residue

Small quantities of straw or other crop residue in irrigation furrows reduce soil erosion and increase infiltration. Aarstad and Miller (1981) showed that as little as 60 kg straw/ha placed in clumps along the furrow greatly reduced sediment loss from irrigation furrows along a 3% slope. Berg (1984) applied small amounts of straw uniformly along 4% slope sections of furrows in a corn (*Zea mays* L.) field to reduce erosion on that portion of the field and to reduce sedimentation downstream where the slope decreased to about 1.5%. This practice not only decreased erosion and sediment loss but also increased corn silage yields. The more uniform infiltration along the furrows improved the irrigation effectiveness in supplying water needed by the corn crop. Brown (1985a) placed 1.5 kg straw/100 m of furrow and measured both infiltration and sediment loss for six irrigations with two stream sizes. The straw increased 10-h infiltration by 50% and decreased sediment loss by 52% at a furrow inflow rate of 13.2 L min^{-1} as compared to furrows without straw and with an inflow rate of 10.3 L min^{-1}. Differences were even greater at higher inflow rates. Brown and Kemper (1987) later demonstrated that the increased infiltration resulting from placing straw in furrows significantly increased dry bean (*Phaseolus vulgaris* L.) yields. They concluded that cereal straw in furrows conserves soil, water, and plant nutrients, reduces labor, and increases crop yields.

4. Surface Roughness

When furrow surfaces are rough, water flow is retarded, and generally the water depth in the furrow is increased. The slow flow velocity decreases erosion. The deeper furrow stream increases the infiltrating area, thereby increasing infiltration. This reduces the furrow stream size and velocity, further decreasing erosion. Furrow roughness can be caused by purposely tilling soils and forming furrows at selected water contents wet enough to form clods (Kemper et al., 1982).

The effective roughness or the roughness coefficient is increased by crop residues and by crop plants or weeds growing in furrows. Plant foliage hanging into the furrow stream, as often occurs with sugarbeet (*Beta vulgaris* L.), dry bean, potato (*Solanum tuberosum* L.), and alfalfa late in their growing seasons, increases the roughness coefficient and reduces erosion. Plant roots can also increase furrow roughness, as well as physically hold the soil against shear forces.

Where soils have high infiltration rates and farmers have difficulty forcing the water to the lower ends of the furrows, implements are pulled along the furrows to reduce surface roughness. Such a practice may increase furrow erosion because furrow stream flow velocities are higher in smooth than in rough furrows when the same stream size is applied. The higher kinetic energy associated with higher flow velocities results in greater shear forces.

5. Tillage

The kind and amount of tillage determine the fineness of the soil aggregates in the furrow, or the roughness of the furrow surface as previously discussed. Extensive tillage physically breaks bonds holding soil particles together, decreases aggregate size, and increases soil erodibility. One of the first cautions issued to irrigators to reduce erosion was to avoid pulverizing the soil by excessive tillage operations (Taylor, 1940). We might consider that warning as the first recommendation for use of reduced tillage on furrow-irrigated land, and it is still applicable today. Tillage also affects furrow roughness through its effect on crop residues. Where moldboard plowing buries all crop residues, erosion is greater than where tillage practices leave residues in the irrigation furrows to increase the resistanct to water flow and reduce shear forces.

The kinds of tillage implements used today are diverse compared to those used a few decades ago. Chisel plows, roller harrows, sweeps, rototillers, slot planters, various disks, no-till planters, provide a wide range of soil and residue conditions. Some tillage operations reduce crop residues to small pieces, while others leave rather large pieces. Soils may be left either highly pulverized or cloddy, depending upon the implements used and the soil water content at the time of tillage. Other operations disrupt soils to depths of 30 cm or more, whereas others may reach to only 10 cm. Furrow erosion depends upon the extent to which soil particle-to-particle bonds have been broken and the condition of the remaining crop residue.

6. Cropping Sequence

The erosion and sediment loss from any given field of any particular crop depends upon previous cropping, particularly the most recent crop. Where significant quantities of crop residue remain in the furrows, erosion will be less than where none remains. During studies to determine sediment loss rates for various crops at different slopes and stream sizes, sediment loss was always greater where dry beans followed dry beans than where dry beans followed cereals (Berg & Carter, 1980). The impact of the previous crop on erosion is always greater for row crops than for cereals. Cereal plants slow the furrow stream flow velocity and reduce erosion sufficiently such that previous crop effects are masked and of little significance.

The kind of tillage used influences the previous crop effect on erosion and sediment loss. Generally, the less tillage used, the greater the effect. Hence, the greatest influence will be manifested with no-tillage cropping. Reduced tillage and no-tillage practices have only recently been introduced to furrow-irrigated land (Aarstad & Miller, 1979; Allen et al., 1976; Musick et al., 1977; Carter et al., 1989b).

C. The Impact of Erosion on Crop Yield

Reduced crop yields generally accompany decreases in topsoil depth resulting from soil erosion. There have been recent reports of 40% productivity loss from erosion of some USSR soils, 30% less production on eroded than noneroded Haiti soils, and a 50% yield decline from erosion of 5 cm of surface soil from some Nigeria soils (Wolman, 1985).

Most reports of the detrimental impact of soil erosion on crop production in the USA have been made in the 1980s, and they represent all regions of the country. White et al. (1985) reported that severely eroded southern Piedmont soils produced crop yields only 50% as high as on adjacent, noneroded areas of the same soils. McDaniel and Hajek (1985) found that crop yields were reduced on moderately eroded sites in 65% of the fields studied in Alabama, with an average yield decrease of 22%. Erosion reduced corn yields 12% on Maury soil (fine, mixed, mesic Typic Paleudalf) and 21% on Crider soil (fine-silty, mixed, mesic Typic Paleudalf) in Kentucky, and the yield decreases for winter crops on the eroded Maury soil ranged from 17 to 36% (Frye et al., 1985). Krauss and Allmaras (1982) reported that a loss of 13 cm of topsoil over 90-yr at a site in Whitman County, Washington, decreased wheat (*Triticum aestivum* L.) yields 50%. Papendick et al. (1985) reviewed research results for the northwestern USA and reported both linear and curvilinear relationships between wheat yield and topsoil thickness. White et al. (1985), Bruce et al. (1987), and Daniels et al. (1987) reminded us that the effect of erosion upon the crop productivity of the landscape is difficult to accurately estimate, particularly with depth of topsoil criteria. In some situations, soil water is the controlling factor, and soybean [*Glycine max* (L.) Merr.] and gain sorghum [*Sorghum bicolor* (L.) Moench] yields are about equal on severely and slightly eroded sites. In other cases, correction of nutrient deficiencies can restore yield potential. Therefore, caution should be exercised to avoid drawing incorrect conclusions in these kinds of studies.

The foregoing reports were for nonirrigated lands. The impact of irrigation erosion on crop yield has been reported by Carter (1985b, 1988) and Carter et al. (1985). After 80 yr of furrow irrigation, 75% of the fields in the study area exhibited exposure of subsoil evidenced by a whitish color from the head ditch or pipe downslope for approximately one-third of the field length (Fig. 37-1). The actual distance varied, but commonly ranged from 50 to 100 m. The whitish color came from the topsoil being eroded away and moldboard plowing mixing the white subsoil with topsoil. Crop yields were severely reduced on these areas where topsoil and subsoil were

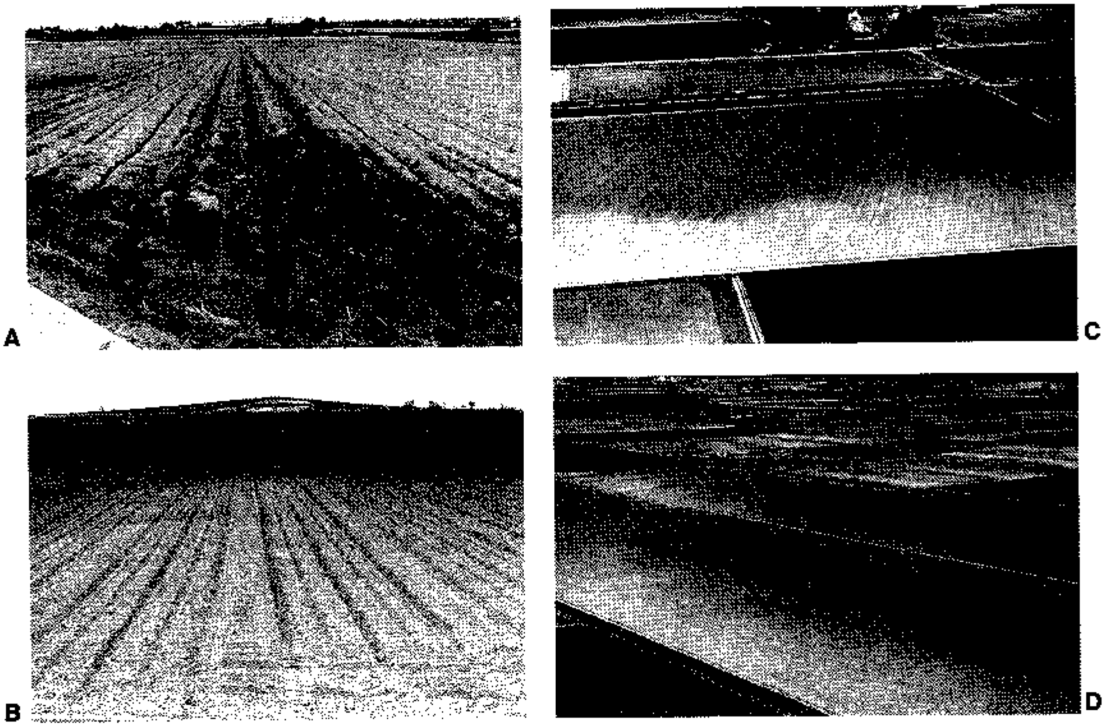

Fig. 37-1. Erosion along the (A) upper ends of furrows where reduced topsoil thickness allows plowing to mix topsoil and subsoil. Where subsoils are almost white, the effects of these processes becomes visible. (B) Ground level. (C) Aerial of one field. (D) Aerial of several fields.

mixed as well as on areas where the topsoil depth was reduced—but not sufficiently for plowing to mix subsoil with topsoil. Crop yield potential has been reduced 25% by 80 seasons of irrigation furrow erosion on approximately 1 million ha of furrow-irrigated land (Carter et al., 1985).

1. Topsoil Redistribution

Erosion on the upper portion and sedimentation on the lower portion of fields redistributes topsoil. The results of these processes become visible when the color of the subsoil differs from that of the topsoil (Fig. 37-1). The visual evidence of topsoil redistribution would be lacking where subsoil and topsoil are nearly the same color. Furrow erosion can cause a major topsoil redistribution on any field and have a simultaneous, severe, negative impact on crop production.

Typical fields that have been irrigated for about 80 yr are illustrated in Fig. 37-1, showing the color change as whitish subsoil is mixed with darker topsoil. The topsoil distribution varies depending upon the field length and irrigation practice used over the 80 yr. The deepest topsoil areas, resulting from deposition, vary from field to field from about the midpoint to the extreme lower end. Also, there has been a net topsoil loss from most fields, thereby negatively impacting crop yield.

Topsoil depth originally averaged 38 cm in the study area when irrigation began in 1905. The gray topsoil, underlain by a nearly white, caliche and silica-cemented hardpan, varies in thickness from 0 to 30 cm. The hardpan may contain as much as 30% $CaCO_3$. Root growth is limited by this hardpan layer over much of the area. Below the hardpan layer is nearly white subsoil with little structure. Before irrigation was introduced, soil below the hardpan was seldom wetted with water from precipitation and was powdery. The natural fertility of the hardpan and the subsoil beneath is low, but can be corrected. Phosphorus requirements to raise available P to adequate levels are high. Zinc is also needed for dry bean production, and N has to be added according to the crops grown. Other nutrients are adequate according to soil test values, and deficiencies have not been noted in growing crops.

The first fields exhibiting the exposure of subsoil were generally those of slopes exceeding 3%, which were among the steepest irrigated. Gradually, fields having lower slopes began to exhibit the color change until today almost all fields with slopes along the furrows $>1\%$ exhibit the phenomenon, as well as some fields with slopes $<1\%$. Studies (Carter et al., 1985) have shown that some fields have lost as much as 90 to 100 cm depth of soil near the head ditch and have deposition as much as 180 cm deep. Commonly, 30 to 40 cm have been lost from the upper ends and 20 to 40 cm have been deposited at some point downslope.

2. Effects on Yields of Major Crops

Investigations indicated that a topsoil depth of about 38 to 40 cm is the minimum depth for maximum yields of all crops in one large study area (Carter et al., 1985). Where topsoils are deeper because of deposition, no significant yield increases are found for any crop. In contrast, significant crop production decreases are evident for all crops where topsoil depth is <38 cm. The relationship between topsoil depth and crop yield is approximated by the Mitscherlich-Spillman type equation, $y = a + b\ (1 - e^{cx})$, where y is yield, x is topsoil depth, and a, b and c, are contants (Carter, 1988). Dry bean and corn are the crops most detrimentally affected by reduced topsoil depth, followed by wheat. Barley (*Hordeum vulgare* L.) and alfalfa are less severely affected and sugarbeet is least affected by decreased topsoil depth (Fig. 37-2).

The factors responsible for the yield reduction are not known. In efforts to restore productivity, adequate plant nutrients were applied on the many fields studied. None of the crops exhibited nutrient deficiencies. Soil water was monitored in some of these studies and adequately supplied by irrigation toa void moisture stress. Several organic matter amendments were tried without significant response. The only effective treatment was to replace 30 to 40 cm of topsoil. This restored yields to levels where topsoil had not been removed by erosion.

The soil erosion topsoil redistribution process is progressing in all areas where irrigation furrow erosion is occurring. Impacts on crop yields will not be as pronounced where the crop yield potential of subsoil is nearly that of topsoil. However, the overwhelming evidence indicates that topsoil losses will ultimately lead to serious crop yield losses, because subsoils are generally less productive than topsoils. There are many areas in the western USA

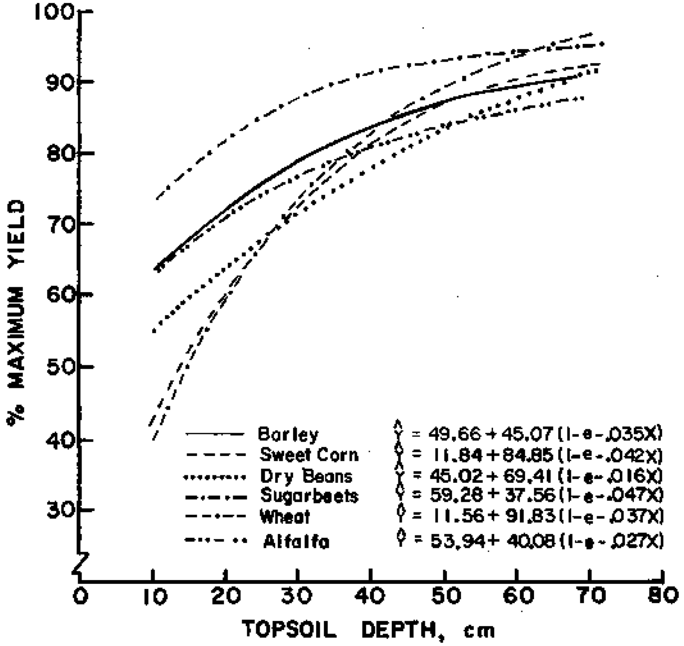

Fig. 37-2. Effect of topsoil depth on relative crop yield for six crops and associated Mitscherlich—Spellman type equations.

where soils have been furrow irrigated for <80 yr. We hope that our findings will stimulate both interest and action towards applying conservation practices to prevent the potential crop yield loss already experienced.

D. Controlling Furrow Erosion and Soil Loss

The concern for improved water quality during the late 1960s, and since that time, stimulated legislation aimed at reducing water pollution and improving water quality. Sediment was recognized as the most important nonpoint source water pollutant from the standpoint of quantity (Robinson, 1971; Wadleigh, 1968). Irrigation return flows were identified as serious nonpoint pollution sources and attempts were made during the 1970s to require permits based upon quality standards before irrigation return flows could be discharged to navigable streams.

Brown et al. (1974) reported sediment balances from two large furrow irrigated tracts. Subsequently, Carter (1976) reviewed the available literature and published some guidelines for controlling sediments in irrigation return flows. Continued interest has resulted in many studies aimed at developing practices to control irrigation erosion and sediment loss. The earlier efforts were on controlling the quality of drainage water after leaving a field. More recently, efforts have been aimed at controlling furrow erosion on the field.

1. Sediment Retention Basins

Basins or ponds constructed in drainage ways to temporarily pond irrigation runoff water can effectively trap sediment and prevent sediment loss into streams and rivers. These basins range in size from about 1.0 ha on main drains to minibasins receiving runoff from only a few furrows. They vary in size and shape, and have been given different names. All are effective, and each type has its best application. Large basins on main drains are usually formed by constructing an earthen dam across a drainage at a suitable site and installing a proper outlet. These large basins trap or remove 65 to 95% of the incoming sediment (Brown et al., 1981; Carter, 1985a). This sediment removal efficiency depends upon the sediment concentration, the particle size of the sediment, and the time required for water to pass through the basin (Brown et al., 1981; Carter et al., 1989a).

Medium-sized sediment retention basins are often excavations in drain ditches receiving runoff water from one or more fields. Their sediment removal efficiencies range from 75 to 95%. Often they are placed at the lowest corner of a field. Unfortunately many of them are undersized and fill with sediment as a result of one or two irrigations. As a basin fills with sediment the water retention time decreases, resulting in a decrease in sediment removal efficiency. The capacity of these basins to remove sediment can change rapidly during a single irrigation as they fill with sediment.

Minibasins are formed by excavating a sequence of small basins along the lower end of a field or by placing earthen checks across the tailwater drainage ditch. If each basin has an outlet into a separate drainage ditch, sediment removal efficiencies range from 85 to 95%. If the water is allowed to pass from one basin to the next, each successive basin becomes less efficient, and the overall sediment removal efficiency of a series of basins is only 40 to 70%. Often the accumulated flow volume washes out earthen checks and basins (Brown et al., 1981; Carter & Berg, 1983).

A common disadvantage of all sediment retention basins is that costly cleaning is required for them to remain effective. In some instances basins are constructed in low areas and fill with sediment. Fields can then be combined or expanded by rerouting the water after a basin is filled and farming the sediment accumulated as part of the field.

Where farmers own equipment, the sediment may be economically hauled back to the upper ends of fields, or onto a rocky, nonfarm area to expand cropping area.

Sediment retention basins have been an effective educational tool for encouraging farmers to implement erosion and sediment control practices. Few farmers are aware of the quantity of sediment they are losing from their fields until they construct a sediment retention basin and watch it fill with sediment. As they learn how much soil they are losing, they become more interested in implementing practices to reduce soil loss.

2. Buried Pipe Erosion and Sediment Loss Control System

A system comprised of a buried pipe with vertical inlets at intervals to correct the convex field end erosion problem has been developed (Carter & Berg, 1983). The buried pipe replaces the tailwater drainage ditch, and the vertical inlets serve as indivdual outlets for minibasins formed by placing earthen dams across the convex portion of the field, as illustrated in Fig. 37–3.

The minibasins of this system initially function the same as other minibasins with individual outlets, but with a sediment removal efficiency of 80 to 95%. As these minibasins fill with sediment, their efficiency decreases. At the same time, the convex end of the field is being corrected by filling with sediment. This decreases the erosion rate on the convex end. The sediment deposition depth is controlled by the elevation of the top of the vertical inlet into the buried pipe. The convex end was entirely eliminated by the end of the first irrigation season in all but two of 40 systems studied.

After the minibasins are filled with sediment and the convex end corrected, the sediment removal efficiency of this system decreases to about 70%. However, the sediment involved is from further upslope instead of that generated from the convex end. The sediment load in the water is usually much lower than before. The end of the field becomes flat, and that flat area gradually extends further upslope. Drainage water is carried away through the inlets and the buried pipe, preventing water ponding in these flat areas. Several systems have been in operation for 10 yr and continue to function effectively.

The buried pipe erosion and sediment loss control system has been shown to be a cost-effective practice. Initially, installation costs are higher than for some other sediment loss control practices. But, in contrast to some other

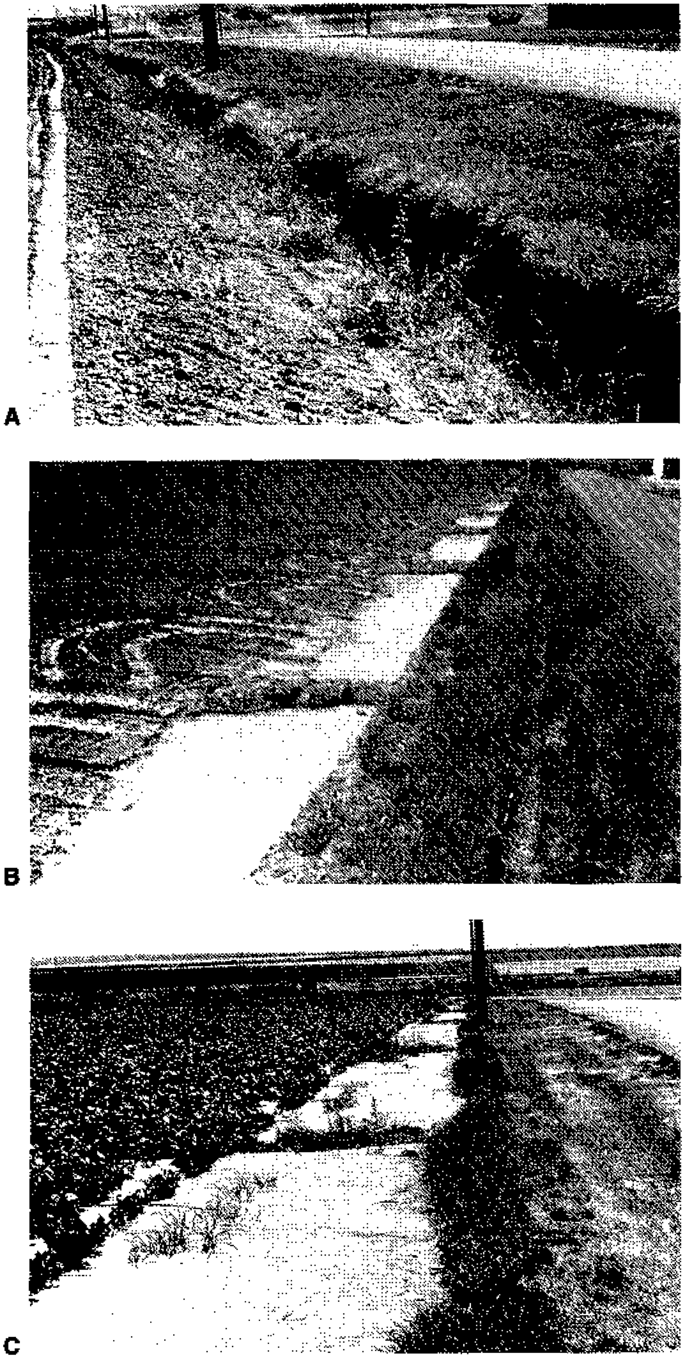

Fig. 37-3. Convex field end showing (A) waste water ditch, (B) operating buried pipe erosion and sediment loss control system during the first irrigation, and (C) convex end corrected after four irrigations.

systems, this alternative increases the productive area of fields by eliminating the tailwater ditch. This also facilitates ingress and egress of farming equipment. With the open drainage ditch, equipment could not enter or leave the field except at constructed crossings,and also had to turn around inside the field perimeter (Fig. 37-3). Eliminating the ditch also improves convenience for cultivating part of the field while another part is being irrigated, and reduces weed problems associated with wet drainage ditches (Carter & Berg, 1983).

Correcting convex ends improves crop production near the lower ends of fields. Many fields with convex ends often erode to the plow depth, resulting in furrow streams 20 to 30 cm below the soil surface, where lateral water movement doesn't reach the roots of small plants. These plants die from drought, and commonly the lower few meters of these areas produce little or no crops. Correcting the convex end eliminates this problem.

Increased crop yields resulting from increasing the harvested area and reducing drought losses increased income sufficiently to pay the costs of installing a buried pipe system in 4 to 8 yr. After that, the increased returns will add to farm profits (Carter & Berg, 1983).

3. Vegetative Filters

A simple, inexpensive erosion and sediment loss control practice is planting a strip of cereal, grass, or alfalfa along the lower end of a field in row crops. These densely planted crops at the lower ends, and in a few cases the upper ends of fields, are called *vegetative filters*. When properly placed and managed, these vegetative filters remove 40 to 60% of the sediment from furrow runoff water when at the lower end of a field and can reduce erosion when at the upper end, but no quantitative data are available for the later

Fig. 37-4. Vegetative filter strip of wheat along the downslope end of a dry edible bean field.

situation. Proper placement and management include planting the vegetative filter close to the drainage ditch and forming the irrigation furrows about one-half the way through the filter strip. Leaving the last 1 to 2 m between the furrow end and the drainage ditch allows the water to spread out through the densely planted crop before entering the drainage ditch. If furrows are made all the way through the vegetative filter, effectiveness is lost. If the furrows are not pulled far enough into the densely planted filter strip, sediment soon accumulates in the upslope side of the strip and water accumulates just ahead of the filter strip. This generally results in eroding a new channel immediately upslope from the strip, parallel to the drainage ditch.

The advantages of vegetative filter strips are simplicity, low cost, and the filter crop can be harvested. An example of a wheat filter strip at the lower end of a dry bean field is illustrated in Fig. 37–4.

4. Placing Straw in Furrows

The effectiveness of straw placed in irrigation furrows for reducing erosion and increasing infiltration was discussed earlier in this chapter. The most effective application of this practice is to apply straw to the steeply sloping segments of the furrows. Berg (1984) and Brown and Kemper (1987) reported significant crop yield increases, infiltration increases, and sediment loss decreases using this approach. Based upon this research, a commercial machine is now available to spread straw in furrows.

The application of straw to furrows should be viewed as an alternative when residues from the previous crop are not available on the field. Where previous crop residue is present, it is better to alter tillage operations to keep some of that residue in the soil surface than to expend the cost and time to bring straw from a source outside the field and spread it in the furrows.

5. Irrigation Management

The relationships among the furrow stream size, furrow slope, and sediment loss were discussed earlier. These relationships illustrate that the larger the furrow stream size, the greater the amount of erosion. One irrigation management tool is to apply the smallest possible stream to accomplish the irrigation. The required stream size is determined by the infiltration rate, slope along the furrow, and the run length. In some instances, reducing the run length by adding a midfield gated pipe may be the best alternative. Other situations may be better controlled by compacting furrows to reduce the infiltration rate. This compacting can be accomplished by traversing the furrow with the tractor wheel or with furrow packers on a tool bar (Kemper et al., 1982; Trout & Mackey, 1988). Another approach is to use surge flow (Kemper et al., 1988), surge flow with crop residues (Evans et al., 1987), or to use a manual or automated stream-size cut-back system (Humpherys, 1971). Automated cut-back systems generally apply furrow streams to one set of furrow until the water reaches the lower furrow ends, then to another adjacent equal number of furrows for the same amount of time. After that the water is applied to all these wetted furrows simulatneously, resulting in a stream size one-half the original, until sufficient water is infiltrated for crop needs.

Cablegation systems (Kemper et al., 1987) provide for a gradual stream-size reduction. Sediment loss is significantly reduced by cablegation as compared with irrigating with the same stream size for a given set time.

Carefully controlling the stream size in each furrow and selecting either wheel track or non-wheel track furrows are important parameters. The minimum required furrow stream sizes to irrigate adjacent wheel track and non-wheel track furrows are different because of differing infiltration rates (Kemper et al., 1982; Trout & Mackey, 1988). Also furrow-to-furrow variability is 25% greater using gated pipe than using siphon tubes from a cement-lined ditch. Knowing the furrow condition relative to the wheel tracks and knowing the best system for controlling stream size help to make decisions about the stream size to use.

Unfortunately, many farmers operate on a highly regimented time schedule and are limited by the particular irrigation system they have on each field. The general tendency is to apply streams that are erosive to assure that the water transverses the entire furrow length in 2 to 4 h so that adequate infiltrating time to add the appropriate amount of water to the soil reservoir will be certain. When this approach is used, 40 to 50% of the applied water runs off the field as surface drainage, and furrow erosion is often severe (Berg & Carter, 1980).

Changing the direction of irrigating a field to one of less slope can reduce erosion and sediment loss. Also, where slopes exceed 3%, consideration should be given to converting to sprinkler irrigation.

6. Conservation Tillage

Conservation tillage, including no-tillage and reduced or minimum tillage systems, has been applied successfully to rainfed cropland. Until recently, there has been little interest in trying these systems on furrow-irrigated lands. Farmers have long practiced clean tillage to provide clean furrows for irrigation, and it has been unthinkable to consider a tillage system that leaves residue on the soil surface.

Conservation tillage was first introduced to furrow-irrigated land in Washington (Aarstad & Miller, 1979; Miller & Aarstad, 1983). These authors found that conservation tillage significantly reduced sediment losses from furrow-irrigated land. Carter et al. (1989b) introduced no-tillage practices to the Northwest where irrigation furrows are so small that some farmers call them "marks in the soil." These furrows, commonly called *corrugates*, are generally 5 to 8 cm deep and 6 to 8 cm wide at the top. The initial study area in southern Idaho produces garden and commercial bean seed, sugarbeet, and corn as row crops, and alfalfa and cereal as dense-stand crops.

Alfalfa is generally grown in rotation with other crops in this area, and preparing the land for a row crop following alfalfa usually involves 8 to 12 tillage operations, including moldboard plowing when using conventional methods. The first study (Carter et al., 1988b) demonstrated that wheat and corn could be successfully produced without tillage after killing alfalfa with herbicide (Fig. 37-5). Both winter and spring wheat and silage corn produced the same yields when grown without tillage as when grown under conventional tillage. It was necessary to clean the small furrows to remove rodent mounds and clumps of grass that had invaded the alfalfa and had been killed by herbicide. Wheat was seeded with a conventional, irrigated land-type double-disk drill. Corn was seeded with a double tool bar arrangement with small, chisel-type bull tongues on the leading bar to make a groove in the soil. Flex-type corn planters were attached to the second tool bar, so that they followed directly behind the bull tongue chisels. These no-tillage crops irrigated with better uniformity and required only about one-half as much water as the adjacent, conventionally tilled plots for the first irrigation (Carter et al., 1989b).

Subsequent no-tillage studies have included no-tillage corn following cereal, cereal following corn, and a variety of investigations involving dry bean, corn, cereal, and sugarbeet. The general conclusions from 3 yr of study are that furrow erosion and sediment loss can be reduced 80 to 100% by no-tillage systems and 50 to 80% by reduced tillage systems. Direct crop production costs can be reduced 20 to 30% by using no-tillage practices and 10 to 20% by using reduced tillage practices.

Wide application of conservation tillage on furrow-irrigated land has the potential to reduce erosion and sediment loss 80 to 90%. Such widespread acceptance could almost eliminate the need for the erosion and sedi-

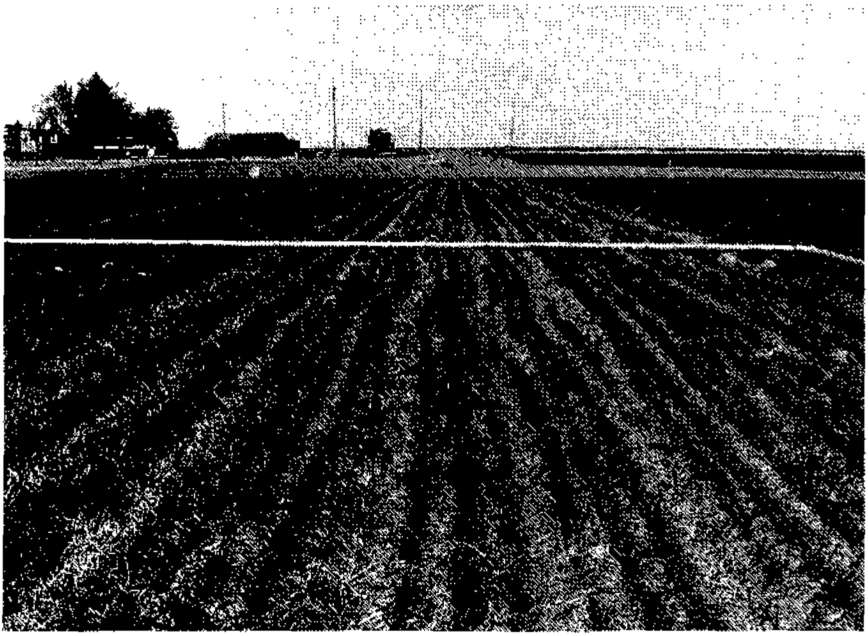

Fig. 37-5. No-till winter wheat growing in a herbicide-killed alfalfa field.

ment loss control practices discussed earlier in this chapter. However, such wide acceptance will require many years of educating farmers, if it is to ever be achieved (Carter et al., 1989b).

III. EROSION UNDER SPRINKLER IRRIGATION

Soil erodes under sprinkler irrigation by processes similar to those reported under rainfall. These are soil particle detachment caused by falling water drops and flowing water, and transport by water drop splash and flowing water (Meyer & Wischmeier, 1969; Trout & Neibling, 1989). However, conditions are often quite different under sprinkler irrigation than under rainfall because: (i) only a small part of a field is receiving water at any given time, (ii) water drops from sprinklers vary considerably depending upon the type of system used, and (iii) sprinkler irrigation is generally applied only when the soil water reservoir needs replenishing for a growing crop or in preparation for tillage. These systems can be properly designed for any particular soil conditions to minimize runoff and erosion.

The most serious erosion under sprinkler irrigation usually occurs with center pivot systems where the application rate at the outer end may exceed the soil infiltration capacity, creating runoff and the potential for erosion. Recently developed low-pressure sprinklers and spray heads also increase the potential for runoff and erosion because the application rate per unit area on the smaller wetting areas must be greater to achieve the same total application. In any case, sprinkler irrigation systems should be designed and operated according to soil characteristics of the field to be irrigated.

A. The Erosion Process

When water drops strike the soil surface, erosion may result. Impacting water drops may detach soil particles from the soil mass. Detached particles are splashed in all directions from the impact point, with a net movement downslope.

Soil particle detachment by water drop impact is proportional to the intensity squared (Meyer & Wischmeier, 1969), or to a product of the momentum and number of drops, both raised to a power (Park et al., 1983). Splash erosion measured by simulated rainfall is proportional to rainfall, or sprinkler intensity to a power that varies with soil type from 1.6 to 2.1 (Meyer, 1981; Park et al., 1983).

An alternative method of evaluating erosion from raindrop impact is to relate it to the kinetic energy of the rainfall. Simulated rainfall with drop diameters of 2.2, 3.2, and 4.9 mm from several heights has been used to study soil detachment from a silty clay, a loamy sand, and two silt loam soils. The regression equation relating soil splash (SS) to kinetic energy (KE), rainfall intensity (I), and percent clay (PC) was

$$SS = 7.50\ (I)^{0.41}\ (KE)^{1.14}\ (PC)^{-0.52}$$

with a correlation coefficient of 0.93. Kinetic energy was by far the most significant of these three parameters. Adding other soil parameters did not significantly improve the correlation coefficient (Bubenzer & Jones, 1971).

The general erosion potential from various sprinklers can be evaluated by converting the mean drop diameter to kinetic energy using the procedure of Stillmunkes and James (1982). The kinetic energy values can then be used in the above equation to estimate soil detachment by drop splash, and the relative erosivity of any particular sprinkler can be estimated by this method. Recent research has provided limited information on drop size distribution from various sprinkler nozzle designs and the effects of nozzle size or pressure on drop size distribution (Dadio & Wallender, 1985; Kohl & DeBoer, 1984; Kohl et al., 1985).

The preceding discussion concerned the processes governing the sediment produced at a particular site. Sediment transport processes generally determine how much of that sediment is moved from the site. The sediment transported by overland flow depends upon the water application rate in excess of infiltration. The infiltration rate can be reduced by water drop impact and increase the amount of runoff.

When the water application rate exceeds infiltration, water ponds in small surface depressions until they become full. Then water begins to flow downslope as shallow overland flow. This flow seldom produces sufficient shear forces to detach particles, but it does transport some sediment detached by water impact. Usually considerably more soil particles are detached by water drop impact than are transported by this shallow overland flow. Many transport equations have been applied in attempts to describe this part of the overall erosion process (Foster, 1982; Neibling, 1984).

As overland flow moves downslope it concentrates in tillage marks, previous erosion channels, or, as a result of the natural microtopography, it forms new rills. The detachment and transport processes in these rills are similar to those in irrigation furrows. One difference is that the flow rate in rills increases downslope as a result of increasing collection areas, whereas the flow rate in irrigation furrows decreases downslope. Thus, the transport capacity in rills increases until the water flows out of the area receiving water.

Water may flow downslope in rills to an area just previously irrigated, into a dry area not yet irrigated, or along the operating sprinkler line where water is being applied. These three situations can all produce different erosion and sediment transport results. Flows from rills tend to concentrate into fewer, larger channels in natural drainage ways called *ephemeral channels or gullies*. Sediment detachment and transport processes in ephemeral gullies are similar to those for rills. Typically, an ephemeral gully will erode downward to a tillage pan or a less erodible layer and then 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.

Usually the amount of erosion during each center pivot sprinkler irrigation is relatively small because only 30 to 40 mm of water is applied. This amount of water normally will not cause extensive erosion. Most of that water will infiltrate and not run off the field. The amount of runoff depends on how much the application rate exceeds the infiltration rate. Large amounts of water are applied with wheel line and hand-moved sprinklers, and erosion can be severe.

1. Cohesion Factors

The relationships between soil cohesion factors and erosion are the same under both furrow and sprinkler irrigation. The erosion difference between the two situations involves the forces acting against the soil-bonding forces. The bombardment of water drops on the soil under sprinkler irrigation is a different type of force than the shear force of a flowing stream in an irrigation furrow.

2. Tillage

Extensive tillage that breaks soils into small aggregates also breaks many particle-to-particle bonds and makes the soil more susceptible to erosion under sprinkler irrigation, just as it does under furrow irrigation. Fewer tillage operations generally result in less erosion under sprinkler irrigation. The direction of the final tillage or planting marks can have an important impact on rill and subsequent gully formation under sprinkler irrigation. Such marks up and down the slope should be avoided. This, of course, is not always possible, particularly on rolling topography where much of the sprinkler irrigation is practiced. Tillage and planting marks should follow level contours to the extent possible. No-tillage and reduced-tillage practices can be applied more easily to sprinkler-irrigated land than to furrow-irrigated land because rougher surfaces can be tolerated better under sprinkler irrigation.

3. Surface Condition Effects

The condition of the soil surface can have a major effect on erosion under sprinkler irrigation. Rough, cloddy surfaces have higher infiltration rates. As a result, runoff is decreased or eliminated and erosion is decreased. Overtilled, smooth surfaces are more erodible and generally have lower infiltration rates, greater runoff, and more erosion than rougher surfaces. To be effective as an erosion control measure, soil clods must be large and stable enough to keep infiltration at a high level until the crop canopy covers the soil surface. Such cloddy surfaces can be attained by tilling at selected soil water contents. Also, tilling compacted soils generally results in greater cloddiness than does tilling noncompacted soils (Johnson et al., 1979; Römkens & Wang, 1986).

Residue on the soil surface decreases the amount of water drop impact erosion, increases infiltration, and decreases runoff. As a result, overland flow erosion is also decreased by residue on and in the soil surface. Conservation tillage practices increase quantities of surface residues and decrease erosion under sprinkler irrigation.

B. Controlling Sprinkler Irrigation Erosion

Any practice that will reduce the impact energy of water drops striking the soil surface, maintain infiltration, reduce overland flow, and protect against rill and gully formation will decrease soil erosion under sprinkler irrigation. There are several approaches that can be used towards accomplishing these goals. Usually a combination of practices leads to the best results.

1. Irrigation Management

The most important aspect of sprinkler irrigation management is the proper design of the system. Infiltration characteristics of the soil should be evaluated and the results used to select a sprinkler system that will apply water at a rate less than the infiltration capacity of the soil (Bruce et al., 1980; 1985). This is usually easier with wheel line, lateral move systems than with center pivot systems. If the application rate is less than the infiltration capacity and adequate to supply sufficient water to meet crop needs, the only erosion that will occur is that from water drop impact.

The area covered per segment of line increases with distance from the pivot point of a center pivot system. Therefore, to apply the water needed by the crop, the application rate increases with distance from the pivot point. The most serious erosion usually occurs at the outer end of a center pivot system, because the application rate often exceeds that of infiltration.

Once a properly designed sprinkler irrigation system has been installed, it is important to operate it correctly. Operating at pressures different from those designed, improper set times, or operating center pivots at improper travel speeds can also lead to erosion problems.

Another important factor in the design and operation of sprinkler systems is that nozzles or heads should be designed to distribute water drops of the lowest possible kinetic energy to the soil. Water drops with the lowest kinetic energy will cause the least water drop splash erosion and soil surface compaction.

2. Conservation Tillage

Conservation tillage has been practiced for erosion control on rainfed soils for over 20 yr, but only recently have conservation tillage systems been developed for sprinkler-irrigated lands. The same basic systems used for erosion control on rainfed soils will also control erosion on sprinkler-irrigated soils. Such systems are easier to apply under sprinkler irrigation because water can be applied when needed instead of depending upon nature to provide rainwater. For example, deep-furrow drills used to place seed into moist soil on rainfed lands are not required on sprinkler-irrigated land where water can be applied to wet the soils to germinate the seed if necessary.

Conservation tillage systems for sprinkler-irrigated land should leave crop residues on and in the soil surface, provide a rough cloddy surface, and leave drill or tillage marks on level contours to the extent possible. Crop residues are the most important consideration and tend to mask the effects of the other two parameters.

Crop rotations impact the application of conservation tillage on irrigated land. Usually more crop rotating is required to minimize crop disease on irrigated land than on rainfed land. The cropping sequence should be adjusted if necessary to assure the production of crop residues throughout the rotation. Conservation tillage is then required to maintain these residues on or near the soil surface.

3. Reservoir Tillage

Aarstad and Miller (1973) first demonstrated that making small water storage basins in the soil surface to catch and temporarily store water until it infiltrates was a useful technique to prevent runoff and increase irrigation uniformity. This also almost eliminates erosion under sprinkler irrigation (Longley, 1984). In recent years, tillage equipment has been developed and used effectively for that purpose, and the process of forming the basins has become known as *reservoir tillage*. These small reservoirs function best when they are depressions formed by scooping or pressing rather than being formed by earthen dams in furrows. The latter are not as stable when nearly filled as the former.

Reservoir tillage is generally done after planting the crop but can be done in the same operation for cereals. The tiny reservoirs are placed between rows of row crops, but can be randomly placed in solid cover crops, such as cereals. In either case, once installed, 1 h of land will have thousands of these small reservoirs on the surface (Fig. 37-6). When water is applied by a sprinkler

Fig. 37-6. Reservoir tillage on a potato field.

system, water not immediately infiltrated accumulates in the tiny reservoirs where it gradually infiltrates. Runoff can be prevented or reduced even when the water application rate far exceeds the infiltration rate. Since runoff is eliminated, so are erosion and sediment transport that would have occurred with overland flow. Therefore, erosion is confined to that caused by water drop impact. The use of reservoir tillage has had a major impact on both irrigation uniformity and erosion control under sprinkler irrigation. It compensates for design and operation errors and is of particular importance in areas covered by the outer sections of center pivot systems and on steep slopes. Crop yields have been dramatically increased and soil erosion almost eliminated by reservoir tillage of sprinkler-irrigated land.

IV. SUMMARY AND CONCLUSION

Irrigation-induced erosion began with irrigation and has continued largely unabated until the past 10 yr. The problem was recognized as serious by scientists in the late 1930s and 1940s, but work done then was given little attention by irrigated land farmers. During the late 1960s and early 1970s, sufficient attention was given to water quality that legislation was set forth to control irrigation return flow quality. This stimulated research on polluting sediment sources because sediment was defined as the most serious water pollutant from the standpoint of quantity. This continuing research has provided much-needed information about erosion on irrigated lands. It has now progressed to the point that effective erosion control practices have been developed for irrigated lands.

Although significant erosion can occur under improperly designed and operated sprinkler irrigation systems, the most serious erosion occurs under furrow irrigation.

Soil erosion results when shear forces are sufficient to overcome cohesive bonds between soil particles, allowing soil particles to be broken off the soil mass and transported by flowing water. Both the erosive shear and sediment transporting forces increase exponentially with stream size and flow velocity. Therefore, the furrow stream size, furrow roughness, and the slope in the direction of irrigation are important factors affecting the energy of the stream to exert shear forces. Controlling these factors, is of primary importance in furrow irrigation erosion. Of these factors, humans can control the furrow stream size to a limited extent. However, the furrow stream size must be large enough to provide water to infiltrate along the entire furrow length in a reasonable time to accomplish the purposes of irrigation. Usually, best results can be attained by starting the irrigation with a furrow stream that will reach the lower end of the furrow in 2 to 4 h, and then decreasing it to about one-half the original.

Crop residues in irrigation furrows and rough furrows both decrease erosion because they reduce the kinetic energy of the stream. In contrast, excessive tillage, leaving a fine soil and resulting in smooth furrows without residue, increases furrow erosion.

Cropping sequences affect irrigation furrow erosion by influencing the amount of residue remaining in the soil while producing the subsequent crop. Tillage plays the most important role in the presence or absence of residue. Moldboard plowing, which buries crop residues, is the worst tillage practice commonly used on irrigated land from the erosion standpoint.

Furrow erosion redistributes topsoil by removing soil from the upper reaches of furrows and depositing it downslope. This reduces topsoil depth on the upper 25 to 40% of each furrow-irrigated field, causing serious decreases in crop production.

During the past 15 yr, erosion and sediment loss control technology has been developed and evaluated for furrow-irrigated land. The first practices developed and evaluated were aimed primarily at sediment loss control. These included sediment retention basins ranging in size from 1.0 ha to minibasins receiving runoff water from only a few irrigation furrows. These sediment retention basins remove 65 to 95% of the inflowing sediment from the water. Vegetative filters comprised of cereal, grass, or alfalfa crops planted along the lower ends of fields can filter out about 40 to 60% of the sediment if properly managed.

One important discovery made in the mid-1970s was that large amounts of erosion and sediment loss from furrow-irrigated fields were resulting from mismanagement of the tailwater ditch, thereby creating convex field ends. A buried pipe erosion and sediment loss control system was developed to completely eliminate this problem, as well as remove the tailwater ditch and field access problems associated with it. This system increases the productive area of the field where installed. Increased crop production from that area will generally pay installation costs in 4 to 8 yr.

Placing crop residues in irrigation furrows increases infiltration and reduces furrow erosion. Equipment has been developed to accomplish this straw placement. However, a far more logical approach is to use tillage practices that will leave crop residues on and in the soil surface. Moldboard plowing must be eliminated to avoid burying crop residue.

Reduced-tillage and no-tillage systems introduced to furrow-irrigated land for erosion control in 1978 and 1984, respectively, have great potential for erosion control on irrigated land. A series of studies, beginning in the fall of 1984, have demonstrated that no-tillage and reduced tillage can be used effectively on furrow-irrigated land without causing irrigation problems. These conservation tillage systems reduce soil erosion and sediment loss from 60 to 100%, with the best results coming from no-tillage systems. Direct cropping input costs are decreased 10 to 30% when compared to conventional tillage systems. These savings translate into net profits because crop yields are generally the same as for conventional tillage. Widespread application of conservation tillage on furrow-irrigated lands has the potential to reduce erosion and sediment loss about 85 to 90%. This would also eliminate the need for sediment retention basins, vegetative filters, and placing straw in furrows. The buried pipe erosion and sediment loss control system may still be used in combination with conservation tillage, but the need for such a system would be decreased.

Soil erosion processes under sprinkler irrigation are similar to those under rainfall, with some differences. The amount of water applied by a single irrigation is controlled and it is applied only when needed. Generally, only a small part of the field is receiving water at any given time. Therefore, water flow resulting from runoff is confined. Rill and gully erosion are therefore limited when compared to erosion under rainfall.

The most important erosion control practice for sprinkler-irrigated land is the proper design and operation of sprinkler irrigation systems, which means using reliable soil water transmission and retention data. The use of conservation tillage and the application of recently developed reservoir tillage will also greatly reduce the erosion potential.

REFERENCES

Aarstad, J.S., and D.E. Miller. 1973. Soil management to reduce runoff under center-pivot sprinkler systems. J. Soil Water Conserv. 28:171–173.

Aarstad, J.S., and D.E. Miller. 1979. Corn residue management to reduce erosion in irrigation furrows. J. Soil Water Conserv. 33:289–391.

Aarstad, J.S., and D.E. Miller. 1981. Effects of small amounts of residue on furrow erosion. Soil Sci. Soc. Am. J. 45:116–118.

Allen, R.R., J.T. Musick, and A.F. Wiese. 1976. Limited tillage of furrow irrigated winter wheat. Trans. ASAE 19:234–236, 241.

Berg, R.D. 1984. Straw residue to control furrow erosion on sloping irrigated cropland. J. Soil Water Conserv. 39:58–60.

Berg, R.D., and D.L. Carter. 1980. Furrow erosion and sediment losses on irrigated cropland. J. Soil Water Conserv. 35:267–270.

Brown, M.J. 1985a. Effect of grain straw and furrow irrigation stream size on soil erosion and infiltration. J. Soil Water Conserv. 40:389–391.

Brown, M.J. 1985b. Within furrow erosion and deposition of sediment and phosphorous. p. 113–118. *In* S.A. El-Swaity et al. (ed.) Soil erosion and conservation. Soil Conserv. Soc. Am., Ankeny, IA.

Brown, M.J., J.A. Bondurant, and C.E. Brockway. 1981. Ponding surface drainage water for sediment and phosphorus removal. Trans. ASAE 24:1479–1481.

Brown, M.J., D.L. Carter, and J.A. Bondurant. 1974. Sediment in irrigation and drainage waters and sediment inputs and outputs for two large tracts in southern Idaho. J. Environ. Qual. 3:347–351.

Brown, M.J., and W.D. Kemper. 1987. Using straw in steep furrows to reduce soil erosion and increase dry bean yields. J. Soil Water Conserv. 42:187–191.

Bruce, R.R., J.L. Chesness, T.C. Keisling, J.E. Pallas, Jr., D.A. Smittle, J.R. Stansell, and A.W. Thomas. 1980. Irrigation of crops in the southeastern United States. Principles and practice. Agric. Rev. Man. (USDA-SEA) ARM-S-9.

Bruce, R.R., A.W. Thomas, V.L. Quisenberry, H.D. Scott, and W.M. Snyder. 1985. Irrigation practice for crop culture in the southeastern United States. p. 51–106. *In* D. Hillel (ed.) Advances in irrigation. Academic Press, Orlando, FL.

Bruce, R.R., S.R. Wilkinson, and G.W. Langdale. 1987. Legume effects on soil erosion and productivity. p. 127–138. *In* The role of legumes in conservation tillage systems. Soil Conserv. Soc. Am., Ankeny, IA.

Bubenzern, G.D., and B.A. Jones, Jr. 1971. Drop size and impact velocity effects on the detachment of soils under simulated rainfall. Trans. ASAE 14:625–628.

Bullock, M.S., W.D. Kemper, and S.D. Nelson. 1988. Soil cohesion as affected by freezing, water content, time and tillage. Soil Sci. Soc. Am. J. 52:770–776.

Carter, D.L. 1976. Guidelines for sediment control in irrigationreturn flows. J. Environ. Qual. 5:119–124.

Carter, D.L. 1985a. Controlling erosion and sediment loss on furrow-irrigated land. p. 355–364. *In* S.A. El-Swaity et al. (ed.) Soil erosion and conservation. Soil Conserv. Soc. Am., Ankeny, IA.

Carter, D.L. 1985b. Furrow irrigation erosion effects on crop production. p. 39–47. *In* Proc. natl. symp. on erosion and soil productivity, New Orleans. 10–11 Dec. 1984. ASAE, St. Joseph, MI.

Carter, D.L. 1989. Furrow irrigation erosion lowers soil productivity. J. Irrig. Drain. Div. Am. Soc. Civ. Eng. (In press.)

Carter, D.L., and R.D. Berg. 1983. A buried pipe system for controlling erosion and sediment loss on irrigated land. Soil Sci. Soc. Am. J. 47:749–752.

Carter, D.L., R.D. Berg, and B.J. Sanders. 1985. The effect of furrow irrigation erosion on crop productivity. Soil Sci. Soc. Am. J. 49:207–211.

Carter, D.L., R.D. Berg, and B.J. Sanders. 1989a. Crop sequences and conservation tillage to control irrigation furrow erosion and increase farmer income. J. Soil Water Conserv. (In press.)

Carter, D.L., C.E. Brockway, and K.K. Tanji. 1989b. Controlling erosion and sediment loss in irrigated agriculture. J. Irrig. Drain. Div. Am. Soc. Civ. Eng. (In press.)

Dadio, C., and W.W. Wallender. 1985. Droplet size distribution and water application with low pressure sprinklers. Trans. ASAE 28:511–516.

Daniels, R.B., J.W. Gilliam, D.K. Cassel, and L.A. Wilson. 1987. Quantifying the effects of past soil erosion on present soil productivity. J. Soil Water Conserv. 42:183–187.

Evans, R.G., J.S. Aarstad, D.E. Miller, and M.W. Kroeger. 1987. Crop residue effects on surge furrow irrigation hydraulics. Trans. ASAE 30:424–429.

Evans, N.A., and M.E. Jensen. 1952. Erosion under furrow irrigation. North Dakota Agric. Exp. Stn. Bimon. Bull. 15:7–13.

Farnstorm, K.J., J. Borrelli, and J. Long. 1985. Sediment losses from furrow irrigated croplands in Wyoming. Univ. Wyoming, Laramie.

Foster, G.R. 1982. Modeling the erosion process. p. 297–380. *In* C.T. Haan et al. (ed.) Hydrologic modeling of small watersheds. ASAE Monogr. 5. ASAE, St. Joseph, MI.

Foster, G.R., and L.J. Lane. 1983. Erosion by concentrated flow in farm fields. p. 9.65–9.82. *In* R.-M. Li and P. LaGasse (ed.) Proc. D.B. Simons symp. erosion and sedimentation, Simons and Li Assoc. Inc., Fort Collins, CO.

Frye, W.W., O.L. Bennett, and G.J. Buntley. 1985. Restoration of crop productivity on eroded or degraded soils. p. 335–356. *In* R.F. Follett and B.A. Stewart (ed.) Soil erosion and crop productivity. ASA, CSSA, and SSSA, Madison, WI.

Gardner, W., J.H. Gardner, and C.W. Lauritzen. 1946. Rainfall and irrigation in relation to soil erosion. Utah Agric. Exp. Stn. Bull. 326.

Gardner, W., and C.W. Lauritzen. 1946. Erosion as a function of the size of the irrigating stream and the slope of the eroding surface. Soil Sci. 62:233–242.

Humpherys, A.S. 1971. Automatic furrow irrigation systems. Trans. ASAE 14:466–481.

Isrealson, O.W., G.D. Clyde, and C.W. Lauritzen. 1946. Soil erosion in small furrows. Utah Agric. Exp. Stn. Bull. 320.

Johnson, C.B., J.V. Mannering, and W.C. Moldenhauer. 1979. Influence of surface roughness and clod size and stability on soil and water losses. Soil Sci. Soc. Am. J. 43:772–777.

Kemper, W.D., and R.C. Rosenau. 1984. Soil cohesion as affected by time and water content. Soil Sci. Soc. Am. J. 48:1001–1006.

Kemper, W.D., R.C. Rosenau, and S. Nelson. 1985a. Gas displacement and aggregate stability of soils. Soil Sci. Soc. Am. J. 49:25–28.

Kemper, W.D., B.J. Ruffing, and J.A. Bondurant. 1982. Furrow intake rates and water management. Trans. ASAE 25:333–339, 343.

Kemper, W.D., T.J. Trout, M.J. Brown, and R.C. Rosenau. 1985b. Furrow erosion and water and soil management. Trans. ASAE 28:1564–1572.

Kemper, W.D., T.J. Trout, A.S. Humpherys, and M.S. Bullock. 1988. Mechanisms by which surge irrigation reduces furrow infiltration rates in a silty loam soil. Trans. ASAE 31:821–829.

Kemper, W.D., T.J. Trout, and D.C. Kincaid. 1987. Cablegation: Automated supply for surface irrigation. Adv. Irrig. 4:1–66.

Kohl, R.A., and D.W. DeBoer. 1984. Drop size distributions for a low pressure spray type agricultural sprinkler. Trans. ASAE 27:1836–1840.

Kohl, R.A., D.W. DeBoer, and P.D. Evanson. 1985. Kinetic energy of low pressure spray sprinklers. Trans. ASAE 18:1526–1529.

Krauss, H.A., and R.R. Allmaras. 1982. Technology masks the effects of soil erosion on wheat yields—a case study in Whitman County, Washington. p. 75–86. *In* B.L. Schmidt et al. (ed.) Determinates of soil loss tolerance. ASA Spec. Publ. 45. ASA and SSSA, Madison, WI.

Longley, T.S. 1984. Basin tillage for irrigated small grain production p. 338–345. *In* Water today and tomorrow. Proc. Irrig. Drain. Div. Am. Soc. Civ. Eng. Flagstaff, AZ. 24–26 July. Am. Soc. Civ. Eng., New York.

McDaniel, T.A., and B.F. Hajek. 1985. Soil erosion effects on crop productivity and soil properties in Alabama. p. 48–57. *In* Proc. nat. symp. erosion and soil productivity. New Orelans. 10–11 Dec. 1984. ASAE, St. Joseph, MI.

Mech, S.J. 1949. Effect of slope and length of run on erosion under irrigation. Agric. Eng. 30:379–383, 389.

Meyer, L.D. 1981. How rainfall affects interrill erosion. Trans. ASAE 24:1472–1475.

Meyer, L.D. and W.H. Wischmeier. 1969. Mathematical simulation of the process of soil erosion by water. Trans. ASAE 12:754–762.

Miller, D.E., and J.S. Aarstad. 1983. Residue management to reduce furrow erosion. J. Soil Water Conserv. 38:366–370.

Musick, J.T., A.F. Wiese, and R.R. Allen. 1977. Management of bed-furrow irrigated soil with limited- and no-tillage systems. Trans. ASAE 20:666–672.

Neibling, W.H. 1984. Transport and deposition of soil particles by shallow flow on concave slopes. Ph.D. diss. Purdue Univ., West Lafayette, IN.

Papendick, R.I., D.L. Young, D.K. McCool, and H.A. Krauss. 1985. Regional effects of soil erosion on crop productivity—the Palouse area of the Pacific Northwest. p. 305–320. *In* R.F. Follett and B.A. Stewart (ed.) Soil erosion and crop productivity. ASA, CSSA, and SSSA, Madison, WI.

Park, S.W., J.K. Mitchell, and G.D. Bubenzer. 1983. Rainfall characteristics and their relation to splash erosion. Trans ASAE 26:795–804.

Robinson, A.R. 1971. Sediment. J. Soil Water Conserv. 26:61–62.

Römkens, M.J.M, and J.Y. Wang. 1986. Effect of tillage on surface roughness. Trans. ASAE 29:429–433.

Stillmunkes, R.T., and L.G. James. 1982. Impact energy of water droplets from irrigation sprinklers. Trans. ASAE 25:130–133.

Taylor, C.A. 1940. Transportation of soil in irrigation furrows. Agric. Eng. 21:307–309.

Trout, T.J., and W.D. Kemper. 1983. Factors which influence furrow intake rates p. 302–312. *In* Advances in infiltration. Proc. nat. conf. advances in infiltration, Chicago, IL. 12–13 Dec. ASAE, St. Joseph, MI.

Trout, T.J., and B.E. Mackey. 1988. Furrow inflow and infiltration variability. Trans. ASAE. 31:531–537.

Trout, T.J., and W.H. Neibling. 1989. Erosion and sedimentation processes in irrigation. J. Irrig. Drain. Div. Am. Soc. Civ. Eng. (In press.)

Wadleigh, C.H. 1968. Wastes in relation to agriculture and forestry. U.S. Dep. Agric. Misc. Publ. 1065.

White, A.W., Jr., R.R. Bruce, A.W. Thomas, G.W. Langdale, and H.F. Perkins. 1985. Characterizing productivity of eroded soils in the southern Piedmont. p. 83–95. *In* Proc. nat. symp. erosion and crop productivity. New Orleans. 10–11 Dec. 1984. ASAE, St. Joseph, MI.

Wolman, M.G. 1985. Soil erosion and crop productivity: A worldwide perspective. p. 9–21. *In* R.F. Follett and B.A. Stewart (ed.) Soil erosion and crop productivity. ASA, CSSA, SSSA, Madison, WI.