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EROSION

Contents

Irrigation-Induced

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Introduction

Soil erosion is caused by wind, tillage, precipitation, or irrigation. Erosion caused by irrigation, usually termed 'irrigation-induced erosion,' can be the most damaging because it affects many of the most productive soils in the world. These are the soils of arid irrigated regions, which typically have thin A horizons, little organic matter, and weak structure, making them highly erodible. Moreover, these soils, once degraded, recover very slowly. Irrigation-induced erosion occurs as an unintended consequence of irrigation for improved crop production.

To produce food and fiber worldwide, irrigation is vital. Irrigation enables crops to be produced in many areas where they could not otherwise be grown. In other drought-prone areas, irrigation on average doubles crop yield and nearly triples crop value, while improving production reliability and commodity quality. According to the Food and Agriculture Organization (FAO) of the United Nations, irrigation is practiced on only approximately 5% of the world's food-producing land, which includes rangeland and permanent cropland. That irrigated land, however, produces approximately 30% of the world's food. Similarly in the USA, only 15% of harvested cropland is irrigated, yet that land produces 40% of the nation's total crop value.

Three basic types of irrigation are drip, surface, and sprinkler. Drip irrigation supplies water to growing plants at very small rates, wetting relatively small soil volumes either at or below the soil surface. Properly designed and operated drip systems produce neither erosion nor runoff. In contrast, surface (or gravity-flow) irrigation requires water flow across the soil surface and is often designed to produce runoff to improve irrigation uniformity. With overland flow, however, comes erosion. In surface irrigation, the soil surface is the conduit used to deliver and distribute water. Surface irrigation that occurs (1) on sloping areas includes graded furrows (small ditches parallel to crop rows) and border strips, and (2) on relatively flat areas includes level or contour basins, terraces, and wild flooding. Sprinkler irrigation practices, too, can produce both runoff and erosion if not designed and managed properly. In sprinkler irrigation, water droplets are distributed through the air to the soil. Sprinkler irrigation includes: (1) moving lateral systems, including center-pivot, lateral-move, and big-gun systems; and (2) stationary systems, including solid-set and side-roll systems.

Irrigation-induced erosion from sprinkler irrigation resembles that from rainfall in many ways. In both cases, water droplet impact can deteriorate surface soil structure by fracturing soil aggregates, thereby producing aggregate fragments, primary particles, or both that can obstruct surface pores leading to surface sealing and increased runoff. Water that does not infiltrate into the profile accumulates on the surface and, once surface depression storage is satisfied, runs off, often transporting detached soil downslope or off-site. Water droplet impact not only detaches soil but also increases turbulence in shallow flow, increasing the amount of sediment the flow can transport.

There are, however, notable differences between erosion from rainfall and from sprinkler irrigation. For sprinkler irrigation: (1) only a portion of the field receives water at any given time, (2) water droplet characteristics vary from system to system, and (3) irrigation is controlled and managed to apply water only when the growing crop needs more soil water or in preparation for planting, tillage, or harvest. An area's rainfall is usually very low in total dissolved solids (TDS) and its chemical composition changes little. In contrast, irrigation water contains TDS and can vary chemically as a function of water source.

The differences between erosion from surface irrigation and from rainfall are even more distinct. The key difference is surface irrigation's lack of water droplet kinetic energy, which affects surface soil structure and thus infiltration, runoff, and erosion. Also absent is the additional turbulence in overland and rill flow caused by droplet impact. In furrow irrigation, water is applied to only a small portion of the soil surface. Erosion from surface irrigation most often occurs during a number of small events rather than one or two large events, characteristic of erosion from precipitation. Water temperature, affecting water viscosity, is more likely to change during a 12- or 24-h irrigation under cloudless skies than during a rainstorm. The hydraulics of rill flow from rain also differ from those from surface irrigation. In rainfall rills, flow volume increases as water accumulates downslope. In furrow irrigation, the flow rate and volume decrease with distance down the furrow but increase with time as the soil's infiltration rate decreases. These processes gradually change the furrow stream's sediment detachment and transport capacities with both time and distance from the furrow inlet. As the irrigation proceeds, upper furrow ends often become deeper and narrower owing to detachment and transport from relatively large inflows, while the lower furrow reaches become shallower and wider owing to deposition from reduced flow. The duration of inflow, often 12 h or more, is much longer than the runoff from most rainfall events.

Sediment concentration in runoff tends to decrease with time during a furrow irrigation, but not necessarily during a rainstorm. In a furrow during irrigation, many factors change, which, in combination, may explain this phenomenon. Loose soil, frequently positioned in the furrow by recent tillage or cultivation, is often flushed from the furrow early in the irrigation. At the furrow head, coarser, more erosion-resistant fragments may armor the furrow bottom. As soil in the furrow becomes wetter, there is less tendency for the rapid aggregate disintegration that is common during the initial wetting of hot, dry soil. In the lower furrow reaches, deposition can cause the furrow to widen, thereby decreasing its flow depth and reducing shear.

The chemical composition of irrigation water affects irrigation-induced erosion, whether from sprinkler or surface irrigation. High sodium concentrations or sodium adsorption ratios (SAR) and low electrical conductivity (EC) in irrigation water allow the diffuse double layers of 2:1 clay domains to thicken, dispersing clays and weakening or fracturing aggregates. Primary particles, released from aggregates as clay disperses, and aggregate subunits obstruct surface pores, increasing both runoff and soil loss. In addition, small aggregates or fragments, rather than large ones, are more easily transported in overland flow, once they are detached. Moreover, irrigation-water chemistry can change markedly with water sources and sometimes through the irrigation season, as water sources change or as upstream return flow is mixed in changing proportions with surface water.

Significance

Furrow irrigation is an inherently erosive process. It is exacerbated by the need for long fields to increase farming efficiency and for clean tillage to ensure uniform and steady flow of water down the furrow. Soil erosion from irrigation occurs across entire fields as a consequence of overland flow and, from sprinkler irrigation, droplet impact. Soil or sediment loss, in contrast, is a measure of the sediment entrained in runoff that leaves a furrow or field at its outlet. Measured soil loss is often much less than the field total of eroded soil, predominantly from upper furrow reaches, because much sediment is redistributed and, as flow rates decrease, often deposited on to lower furrow reaches before it can leave the field in runoff. Annual soil loss from surface-irrigated fields can vary from less than 1 Mg ha^{-1} to more than 100 Mg ha^{-1}, depending on crop type, field slope, soil properties, and water management, particularly flow rate. A single 24-h furrow irrigation of erodible soil on slopes of more than 2% has caused more than 50 Mg ha^{-1} of soil loss in runoff. Little erosion occurs from level fields, surface-irrigated pastures, or fields producing forage. In contrast, much erosion occurs from row crops grown on fields with steeper slopes, generally those exceeding 2%.

The magnitude of sprinkler irrigation-induced erosion is not well documented for at least two reasons. First, it is difficult to measure, particularly so because it varies widely across time and space. Second, it tends to be an on-field problem occurring only in the area being irrigated at that time. Although sprinkler irrigation is normally regarded as a less-erosive alternative to surface irrigation, problems sometimes occur, particularly where systems are improperly designed or poorly operated. Farmers may irrigate excessively steep slopes with sprinklers, creating erosion problems because they have exceeded their irrigation system's design limits. Where center pivots with high-volume end guns are placed on rolling topography, the combination of high application rates, variable sloping land, and tower-wheel tracks can produce severe erosion in a single irrigation or in one season.

Erosion, whether occurring from sprinkler or surface irrigation, is caused by humans. Consequently, with an understanding of the processes involved, properly designed irrigation systems, and enlightened, skillfull management, irrigation-induced erosion can be nearly eliminated in many cases or at least adequately controlled.

Erosion Under Sprinkler Irrigation

Processes Causing Soil Loss

Soil erosion from water, whether caused by precipitation or irrigation, can be described in terms of three components or processes: detachment, transport, and deposition. Detachment is the release of soil aggregates, aggregate fragments, or primary particles from the soil surface as a consequence of energy input, usually from droplet impact or shear from runoff flow. Transport occurs as detached soil, that is, sediment or bedload, is splashed about and carried downslope in overland flow. Deposition occurs as sediment settles out of the flow as the water's carrying capacity for sediment is exceeded. Depending upon flow hydraulics, deposition may occur within a few meters of the detachment point or may not occur until the sediment is transported off-site.

When properly designed and carefully operated, stationary sprinkler systems, especially solid-set systems with a grid of simultaneously operating sprinklers, apply water for lengthy periods at a relatively low rate (e.g., $3\,mm\,h^{-1}$). The soil's infiltration rate is seldom exceeded, so little (if any) runoff or erosion occurs. In contrast, center-pivot systems, with a moving lateral that pivots around a fixed point, apply water at higher rates (e.g., $80\,mm\,h^{-1}$) to smaller areas (e.g., 5 to 20-m-wide strips) than solid-set systems. With center-pivot irrigation, the irrigated area per unit length of lateral must increase with distance from the pivot point. Consequently, the outer spans of pivots have relatively high discharge rates per unit lateral length (e.g., $15\,l\,min^{-1}\,m^{-1}$) and high instantaneous application rates per unit wetted area. This greatly increases the potential to exceed a soil's infiltration rate, causing runoff and erosion.

Soil erosion from sprinkler irrigation is directly proportional to the application rate in the wetted area which, in turn, is affected by sprinkler type. Low-pressure-type spray heads, which are relatively economical to operate and thus have become popular, have reduced pattern widths and increased application rates relative to other sprinkler types. Again, high application rates can lead to erosion, runoff, and soil loss.

Water-drop impact, or more specifically droplet kinetic energy, detaches surface soil particles and splashes the detached soil in all directions. Some of the soil entrained in the infiltrating water obstructs surface pores. Droplet energy also compacts surface soil. The increased bulk density and obstructed pores reduce infiltration. Droplet kinetic energy also causes turbulence in shallow surface flow, increasing the flow's carrying capacity for sediment. An irrigation's total kinetic energy is a function of its droplet size distribution; the larger the droplet, the greater the kinetic energy. Droplet size distributions can be altered within limits by modifying nozzle pressure, nozzle size, and spray-head deflector plate. Sprinkler irrigation system designers must often balance desired design parameters with environmental and economic constraints.

Slope and topography also affect erosion processes from moving lateral sprinkler systems, particularly center-pivot systems. Depending upon the slope and the pivot's direction of travel, runoff can move on to dry soil, with relatively large infiltration rates, or previously wetted soil, with much smaller infiltration rates. In the first case, runoff rates decrease rapidly, fortunately because the dry soil is easily eroded. In the second, runoff accumulates and concentrates in rills or larger, ephemeral gullies, increasing in rate, erosivity, and sediment-carrying capacity. In the special case where the pivot lateral is parallel to the slope direction, the effective wetted slope length is long and erosion can be particularly severe. Under both center-pivot and lateral-move systems, the tower-wheel tracks are relatively large flow paths 40–50 m apart, with smeared and sealed surfaces underlain by compacted soil. Runoff is common in wheel tracks where they are parallel to the slope direction. Even where the tower-wheel tracks cross the slope, the tracks cause problems, because they collect and concentrate overland flow.

Practices Controlling Soil Loss

Irrigation practices New irrigation systems must be properly designed. Central to the design is an accurate estimate, preferably based upon measurements, of the soil's infiltration characteristics, particularly the infiltration decrease with time. Both new and existing systems must be operated in accordance with (1) design parameters such as nozzle diameter and pressure, and (2) operational guidelines such as set times and travel speed.

To control irrigation-induced erosion, one must minimize runoff. Without runoff, there will be no sediment transport apart from splash at the point of detachment. To minimize runoff, irrigators should schedule irrigations using scientific techniques and apply no more water than is needed for maximum economic yield. From an erosion-control standpoint, no runoff should be the goal.

Modifying the sprinkler type, nozzle pressure, and nozzle diameter alters both the application rate and wetted area. Changes that decrease the sprinkler flow rate, decrease the application rate, or increase the wetted area minimize erosion, runoff, and soil loss. For spray heads, changing the nozzle and deflector plate changes the drop size distribution. Shifting the distribution to smaller and fewer large droplets reduces total droplet kinetic energy striking the soil, thus reducing detachment. Disadvantages of such a size distribution change are that smaller droplets evaporate more readily and are more susceptible to wind drift, which distorts the spray pattern, decreasing both irrigation uniformity and efficiency. Another disadvantage of small droplets is that they travel relatively short distances, giving the spray head a small wetted diameter and high application rate.

A goal of irrigation system design and operation is to match the system's application rate to the soil's infiltration rate (to minimize runoff), both spatially and temporally. This goal is difficult to achieve, however. One relatively new technique with promise for moving lateral systems is to use variable-rate sprinklers that can be programmed to operate on a site-specific basis. Appropriately programmed, the sprinklers could change their discharge rate, depending upon field slope, soil-infiltration differences, presence of rock outcrops, or other factors.

Soil and crop management practices One effective way to help reduce erosion caused by early-season irrigations is to eliminate unneeded seedbed-preparing tillage. In the spring, surface soil aggregates of many soils are structurally weak and susceptible to breakdown from tillage or droplet impact. Unnecessary springtime tillage weakens or breaks particle-to-particle bonds within aggregates, often fracturing them. Aggregate fragments and primary particles are more easily transported than are larger, intact aggregates. Moreover, such tillage buries crop residue and indirectly destroys soil organic matter, further weakening aggregates.

Some tillage practices, on the other hand, instead of contributing to soil erosion can help control it. One such practice, paratilling, uses broad, angled subsoiling shanks to partially lift and laterally shatter soil, increasing the tilled soil's infiltration rate, often substantially, thereby decreasing runoff and soil loss. Another tillage practice that decreases runoff is reservoir tillage. In this postplant operation, small water-storage basins or pits are formed at intervals across a field's surface. Those basins increase surface-depression storage by collecting and temporarily holding water, allowing the water to infiltrate rather than run off. Reservoir tillage reduces runoff, even when an irrigation system's application rate somewhat exceeds the soil's infiltration rate. This practice is particularly effective where performed under the outer spans of center pivots, where application rates often exceed soil infiltration rates.

No-till and conservation tillage are other tillage practices that reduce irrigation-induced erosion. These practices leave crop residues on the soil surface as mulch. Surface mulch absorbs droplet kinetic energy, protects soil structure, and maintains surface roughness, thereby minimizing the decrease in the soil's infiltration rate with time. No-till or conservation tillage also keep soil surfaces rougher, increasing both depression storage and the tilled soil's initial infiltration rate. Within limits, crops in a rotation can be sequenced to produce crop residue regularly throughout a multiyear rotation. A canopy of growing vegetation also absorbs droplet energy, reducing energy input directly to surface soil. Production practices that hasten canopy coverage can reduce erosion from droplet impact, and may reduce erosion from overland flow by shading surface aggregates and keeping them moist and less susceptible to slaking. Vegetation on the soil surface also slows runoff and absorbs overland flow shear.

Another management practice that helps to control runoff, thus soil loss, on slightly sloping surfaces is to till or plant so that the final tillage or planting marks are perpendicular, rather than parallel, to the slope direction. On rolling topography, one should practice contour tillage, in which both tillage and planting operations are performed on the contour, as much as possible. These practices slow runoff, allowing more time for water to infiltrate into the soil.

Erosion with Surface Irrigation

Processes Causing Soil Loss

In surface irrigation, as water flows across a soil's surface or advances down a furrow, it quickly wets relatively dry aggregates or clods in its path. As a consequence of the small matric potential in the dry soil, water will quickly enter the aggregate from all directions, causing 2:1 clay domains to swell, displacing O_2 and N_2 from particle surfaces, and often compressing those gases and air within the aggregate. As the compressed air finally escapes, the force it exerts often fractures interparticle bonds within the aggregate, or the aggregate itself, liberating aggregate fragments and primary particles. This process, in which an air-dry aggregate breaks into subunits or fragments when quickly wetted or immersed in low-electrolyte water, is termed 'slaking.' It contributes substantial amounts of soil for transport in the furrow stream, accounting in large part for the relatively great sediment concentrations often observed early in an irrigation.

Water must flow across the soil during surface irrigation. This flowing water exerts shear along the wetted perimeter, detaching soil once the imposed shear exceeds a threshold, termed the 'critical shear stress.' In a furrow, this critical shear varies both spatially and temporally. In addition to detaching soil, the flowing water transports detached soil downslope, further contributing to the erosion process. Level-basin irrigation systems may have no runoff, thus no soil loss from the basin. Other surface systems on sloping fields, in contrast, have runoff. To ensure adequate wetting of the soil near their field or furrow outlet, those surface irrigation systems are designed and operated so that 20–40% of the added water runs off. Thus, without proper precautions and management, soil loss will occur from many surface-irrigated areas.

Competing processes affect the erosivity and hydraulics of the flowing irrigation water. Infiltration through the wetted perimeter reduces the furrow flow rate with distance from the furrow inlet. This decrease in flow rate with distance reduces the furrow stream's shear and carrying capacity, at times leading to sediment deposition. As time passes, however, the soil's infiltration rate decreases and, with no change in the inflow rate, the furrow flow rate increases. Increasing the flow rate increases the shear and carrying capacity. Also, as much of the slaked and easily eroded soil is flushed from the furrow early in the irrigation, the sediment concentration in the furrow stream often decreases. This decreasing sediment concentration with time (and with increasing flow rate) increases the furrow stream's transport capacity.

Practices Controlling Soil Loss

Irrigation practices One of the best ways to control erosion of surface-irrigated land is to convert to a well-designed sprinkler irrigation system, with its higher efficiency, better application uniformity, minimal runoff, and often reduced labor needs. Sprinkler irrigation does require, however, more energy, a larger capital investment, and a greater level of management than surface irrigation. Sprinkler irrigation can also encourage disease and may not meet peak crop water demand. Thus, such conversion is not possible or practical in every situation, and other practices must be used to control erosion under surface irrigation.

As mentioned above, one must minimize runoff to minimize soil loss from irrigated fields. With surface irrigation, this goal is more difficult to achieve, because runoff is usually necessary to assure adequate application uniformity. None the less, irrigation should still be performed to produce no more runoff than is needed. Scientific irrigation scheduling, good water control, and close monitoring of ongoing irrigations help to minimize both runoff and soil loss.

In some areas, irrigators may be able to shorten furrow lengths. This reduces erosion, because the inflow rate can be reduced yet still allow the furrow stream to advance to the outlet in a reasonable length of time, termed 'advance time,' usually 25–40% of the total set time. Reducing inflow rates is desirable because much detachment and transport occurs near furrow inlets, where furrow flow rates are highest. On some fields, furrow length can be halved by adding a midfield gated pipe to supply the needed inflow. Shortening furrow lengths, however, may increase runoff and soil loss from the entire field (because twice as many furrows are producing runoff) and always requires more labor. For example, adding a midfield pipe doubles the number of furrows that need to be set and the pipe itself must be moved when performing field operations. If field size is reduced to shorten furrow lengths, then more time will be required to plant, till, and harvest those smaller fields. In many areas, furrow lengths cannot be shortened due to existing return-flow channels.

In some situations, furrows may be oriented to cross the slope slightly, rather than run parallel to the slope direction. This repositioning reduces the furrow's slope, reducing the flowing water's shear on the soil along the wetted perimeter, thus reducing both sediment detachment and transport capacity. Repositioning furrows may lead, however, to increased erosion of the now-steeper tailwater collection ditch.

Another means of reducing erosion is to manage furrow inflow rates and advance times appropriately. Inflow rates must be large enough for the furrow stream to reach the outlet, but, once runoff begins, the inflow rate can be reduced ('cut back') to minimize erosion near the furrow inlet as well as runoff at the furrow outlet. Monitoring is required, however, because if a furrow's inflow is reduced too much, its outflow may cease, greatly reducing the uniformity of water application in that furrow. Also, to minimize differences in intake opportunity time from furrow inlet to outlet, irrigators would like advance times to be relatively small. However, a tradeoff must be made, since smaller advance times require greater inflow rates, yet those greater rates increase erosion near furrow inlets.

Some producers use surge irrigation to improve application uniformity. Surge irrigation is a technique wherein flow is applied intermittently ('surged') during a single irrigation set to overcome initially high infiltration rates near furrow inlets. While surge irrigation helps infiltration to be more uniform from furrow inlet to outlet, it must be used carefully or erosion near furrow inlets can be greater with its intermittent inflow than with continuous inflow if inflow rates are higher when surging than when not.

Irrigation water quality can be changed to reduce soil loss. In some areas, one may be able to mix water sources or otherwise add electrolytes to alter inflow water chemistry, principally by increasing the water's Ca^{2+} concentration. Increasing the concentration of divalent cations in the irrigation water reduces the thickness of 2:1 clay domains' diffuse double layer. This minimizes clay dispersion and enables aggregates to remain intact, less susceptible to transport downslope in the furrow stream. Since the divalent cations stabilize soil structure along furrow-wetted perimeters, they also lessen infiltration decreases with time that make furrow-irrigation management difficult. Gypsum is commonly added to water with very low EC or high SAR to improve its suitability for irrigation.

Runoff management practices Runoff can also be managed to minimize, or at least control, soil loss under surface irrigation. One technique is to use pump-back runoff reuse systems, in which all runoff and sediment are collected in a reservoir at the field end, then pumped back to the inlet, where the runoff is reintroduced during the same irrigation as inflow to the field. While incurring energy and equipment costs for pumping, pump-back return systems offer many benefits. Reintroduced inflow that contains some sediment reduces furrow-stream sediment-carrying capacity. Depending upon flow hydraulics, sediment eroded from the field may be redeposited on to the field near its origin. Where irrigation return-flow water-quality regulations are stringent, irrigators with pump-back systems will have no off-farm (or off-site) discharge of sediment, fertilizer, pesticides, weed seeds, or microbes.

To collect or retain soil eroded from irrigated fields, settling basins varying in size and shape may be constructed along runoff collection channels, often at field ends. These basins collect much of the runoff and, under quiescent conditions, allow soil particles from the runoff to settle. Some basins are large (for collecting runoff from 20 ha or more); some are small (for runoff from only a few furrows). After draining the basins at the season's end, the collected sediment can be returned to the field. While offering this advantage, settling basins suffer from many disadvantages. Erosion still occurs in the field. Clay-sized soil, containing most of the P, other plant nutrients, and agricultural chemicals, does not fully settle out but is largely lost in the basin's outflow during the irrigation season. A settling basin's sediment collection efficiency declines as it fills with sediment, reducing residence time in the basin. Land area is taken out of production. Settling basins also require weed control, can be safety hazards, and can be the source of flying insect pests. Energy, time, and, for bigger basins, heavy equipment not common on farms are required to remove sediment from the basins and redistribute the sediment on to the field or another area. In spite of these disadvantages, settling basins have their place, particularly when used in combination with other erosion-control practices.

Buried drains with standpipes are a special type of settling basin. In a field's tail ditch, plastic, corrugated pipe is placed in a trench as a drain. Standpipes that extend vertically from the drain to just above the soil surface are installed every 5–10 furrows along the drain's length, then the trench is backfilled. Earthen dams are then constructed across the tail ditch, just downstream of each standpipe's inlet, thus forming a small basin at each standpipe. In operation, each dam forces runoff to pond, allowing some sediment to settle, before the runoff enters the standpipe's inlet and drains from the field. With appropriate management, this special drainage system can eliminate excessive erosion that often occurs at field ends where furrow slope increases sharply as runoff drains into a deep tail ditch. These drainage systems: (1) increase yields from field ends, (2) bring additional land into production, (3) ease farm equipment's ingress and egress across the lower field boundary, and (4) reduce weed problems common in and near wet tail ditches. Unfortunately, buried drains do not control erosion from the bulk of the field, and still allow some sediment to enter the drain and be transported from the field in the drainage water.

Soil and crop-management practices Placing mulch or maintaining crop residues in irrigation furrows effectively reduces both erosion and soil loss. Mulch in the furrow absorbs shear and slows furrow-stream velocity, thus reducing both sediment detachment and transport. By reducing flow velocity, the mulch can reduce overland flow by allowing the added water more time to infiltrate. If available, previous crop residues should be used as mulch, but in some rotations and areas, straw from off-site works well. While effective at controlling furrow erosion and often increasing crop yields, if not properly managed, the mulch tends to float downstream and obstruct the channel, damming the water which breaks over into adjacent furrows, increasing their flow while reducing the flow in the obstructed furrow. By increasing infiltration, mulch can increase erosion from upper furrow reaches if the mulched furrows require greater inflows. Mulch placed in level basins can hinder the even spreading of water, at times channeling it to erode some areas and underirrigate others. Instead of placing mulch in an irrigation furrow, one can establish semipermanent vegetation, such as turf, along the furrow's wetted perimeter, much like a grassed waterway. Turf, once established, nearly eliminates furrow erosion but complicates field management and can reduce crop yield. Turf-covered furrows are a viable practice only for rare cropping patterns and on very steep slopes.

Narrow or twin-row plantings also reduce erosion. By positioning crop rows on bed shoulders, close to an intervening irrigated furrow, the plant root systems stabilize soil along the furrow's wetted perimeter, while overhanging vegetation drooping into the furrow and plant debris reduces furrow-stream velocity, minimizing both detachment and transport.

Filter strips, often seeded to small grain or forage, can also be placed perpendicular to the furrow direction at the downstream end of row-crop fields to trap sediment that would otherwise leave the field in the furrow outflow. By slowing and spreading the flow as it progresses through the 3- to 6-m-wide strip, the furrow stream's carrying capacity is greatly decreased, with much sediment being deposited within the strip. Filter strips do not, however, prevent erosion from occurring upslope, nor do they produce much marketable yield from the crop seeded in the strip.

A recently developed, highly effective erosion-control practice is the adding of certain types of synthetic organic polymers to surface irrigation water. These polymers, high-molecular-weight, moderately anionic polyacrylamides (PAM), are added to inflow water to be present at dilute concentrations of approximately $10\,\mathrm{mg\,l^{-1}}$. When evenly distributed throughout the inflow early in an irrigation, PAM stabilizes soil along furrow-wetted perimeters and flocculates sediment that may be present in the flow. PAM-treated water also reduces seal formation in the furrow, thus slowing the decrease in the soil's infiltration rate with time. All told, their use reduces furrow soil loss by approximately 95%, economically (e.g., less than US$40 $\mathrm{ha^{-1}}$) and with minimal additional management. PAM also reduces erosion and increases infiltration under sprinkler irrigation, but its use there requires specialized equipment and is not yet user-friendly.

Effective furrow-erosion control is also possible using whey, a natural organic by-product of cheese manufacture, at times viewed as a food-processing waste. When added without running off to newly formed furrows early in an irrigation season, it too stabilizes soil along wetted perimeters, in part owing to greatly enhanced microbial activity that leads to aggregate formation and stabilization at and below the wetted perimeter. Soil loss from subsequent irrigations of whey-treated furrows is reduced by 50–98% and infiltration increased by 50–60%.

A combination of practices can be particularly effective. PAM and/or conservation tillage can be used to reduce on-field erosion, while filter strips and small settling basins remove additional sediment before the runoff leaves the field. Larger settling basins and wetlands in return-flow streams can further reduce the runoff's sediment load before the runoff reaches receiving waters.

Summary

Controlling erosion on and soil loss from irrigated lands is critical to sustain agricultural production. Protecting and stabilizing the soil surface will minimize sediment detachment; slowing or reducing overland flow will minimize sediment transport. Reducing or managing runoff is the key to controlling soil loss wherever sprinkler irrigation or surface irrigation is practiced. Erosion caused by sprinkler irrigation is similar to that caused by rainfall, with many erosion-control practices effective for both. Techniques that protect the soil surface from raindrop or sprinkler-drop impact are effective in maintaining infiltration rates, reducing overland flow, and controlling both detachment and transport. Erosion processes with surface irrigation are quite different from those with rainfall, due to the absence of droplet kinetic energy input to the soil surface, and thus require different control strategies. Controlling erosion from surface irrigation is a challenge, due to the requirement for overland flow and runoff, and to varying flow regimes and soil infiltration rates.

For both sprinkler and surface irrigation, off-site soil loss is often least where combinations of control practices are employed. For surface irrigation, PAM use is not only economical but probably offers the most promise for effective erosion control for most furrow-irrigated production systems.

Prospects for Future Control

In the USA, surface irrigation is practiced on about 50% of the irrigated land; worldwide, however, more than 95% is surface-irrigated. Wherever surface irrigation is practiced, improved irrigation scheduling and better water control can reduce erosion and soil loss while minimizing off-site environmental damage. In furrow-irrigated areas where labor is available and relatively inexpensive, changing management practices to reduce runoff by shortening furrow lengths, reorienting furrows to reduce furrow slopes, and/or managing inflows will help reduce on-field erosion and off-site soil loss. In more industrialized areas, with established surface water quality standards, pump-back return systems offer the most comprehensive control of both runoff and soil loss. Filter strips and buried drains with standpipes can minimize future off-site soil loss. Without doubt, though, the use of PAM in surface irrigation holds the greatest potential for cost-effective erosion control.

Effective sprinkler erosion-control techniques already exist and more are on the horizon. Variable-rate sprinklers on center pivots will probably prove cost-effective for site-specific soil and water management to increase yields, improve water-use efficiency, and decrease water requirements while simultaneously reducing runoff and attendant soil loss. Engineering hindrances to PAM use in center pivots will probably be overcome, enabling PAM's erosion-controlling and infiltration-enhancing benefits to be extended to sprinkler-irrigated lands also. PAM's other environmental benefits, such as minimizing off-site discharge of sediment, weed seeds, plant disease agents, and microbes (including possible human pathogens), will become more important with stricter environmental regulations, spurring ever greater PAM use under irrigated conditions.

See also: **Erosion:** Water-Induced; **Irrigation:** Environmental Effects; **Overland Flow**

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Water-Induced

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Introduction

Water erosion is caused by the detachment and transport of soil by rainfall, runoff, melting snow or ice, and irrigation. Excessive erosion can threaten the production of agricultural and forest products. Erosion may also impact water conveyance and storage structures, and contribute to pollution from land surfaces. Water erosion may occur within rills, interrill areas (the regions between rills), gullies, ephemeral gullies, stream channels, forest areas, and construction sites. Rainfall characteristics, soil factors, topography, climate, and land use are important elements affecting soil erosion. Conservation measures that have been effectively used to reduce soil erosion on agricultural areas include contouring, strip cropping, conservation tillage, terraces, buffer strips, and use of polyacrylamide on irrigated areas. Specialized