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Chapter 4 Surface Irrigation

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Chapter 4 Surface Irrigation

Contents

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623.0400 The Practice of Surface Irrigation

(a) Introduction

Surface irrigation is the oldest and most common method of applying water to croplands. Also referred to as flood irrigation, the essential feature of this irrigation system is that water is applied at a specific location and allowed to flow freely over the field surface, and thereby apply and distribute the necessary water to refill the crop root zone. This can be contrasted to sprinkle or drip irrigation where water is distributed over the field in pressurized pipes and then applied through sprinklers or drippers to the surface.

Surface irrigation has evolved into an extensive array of configurations that can broadly be classified as:

- basin irrigation
- border irrigation
- furrow irrigation
- wild flooding

The distinction between the various classifications is often subjective. For example, a basin or border system may be furrowed. Wild flooding is a catch-all category for the situations where water is simply allowed to flow onto an area without any attempt to regulate the application or its uniformity. Since no effort is made to regulate the application or uniformity, this type of surface irrigation does not need attention in this handbook. If control of the wild flooding event is introduced, it then evolves into a border, basin, or furrow system.

An irrigated field is only one component of an irrigation system (fig. 4–1). Water must be diverted from a stream, captured and released from a reservoir, or pumped from the ground water, and then conveyed to the field. Excess water needs to be drained from the field. Each of these components requires design, operation, and maintenance of regulating and control structures. For the system to be efficient and effective, the flow not only must be regulated and managed, but most importantly, it must also be measured. Thus, the on-field component (surface, sprinkle, or drip), is the heart of the irrigation system. While it is necessary to limit the scope of this chapter to a guide for the evaluation and design of the surface irrigation system itself, it should be appreciated that the surface irrigation system is entirely dependent on the other components for its performance.

(1) Surface irrigation processes

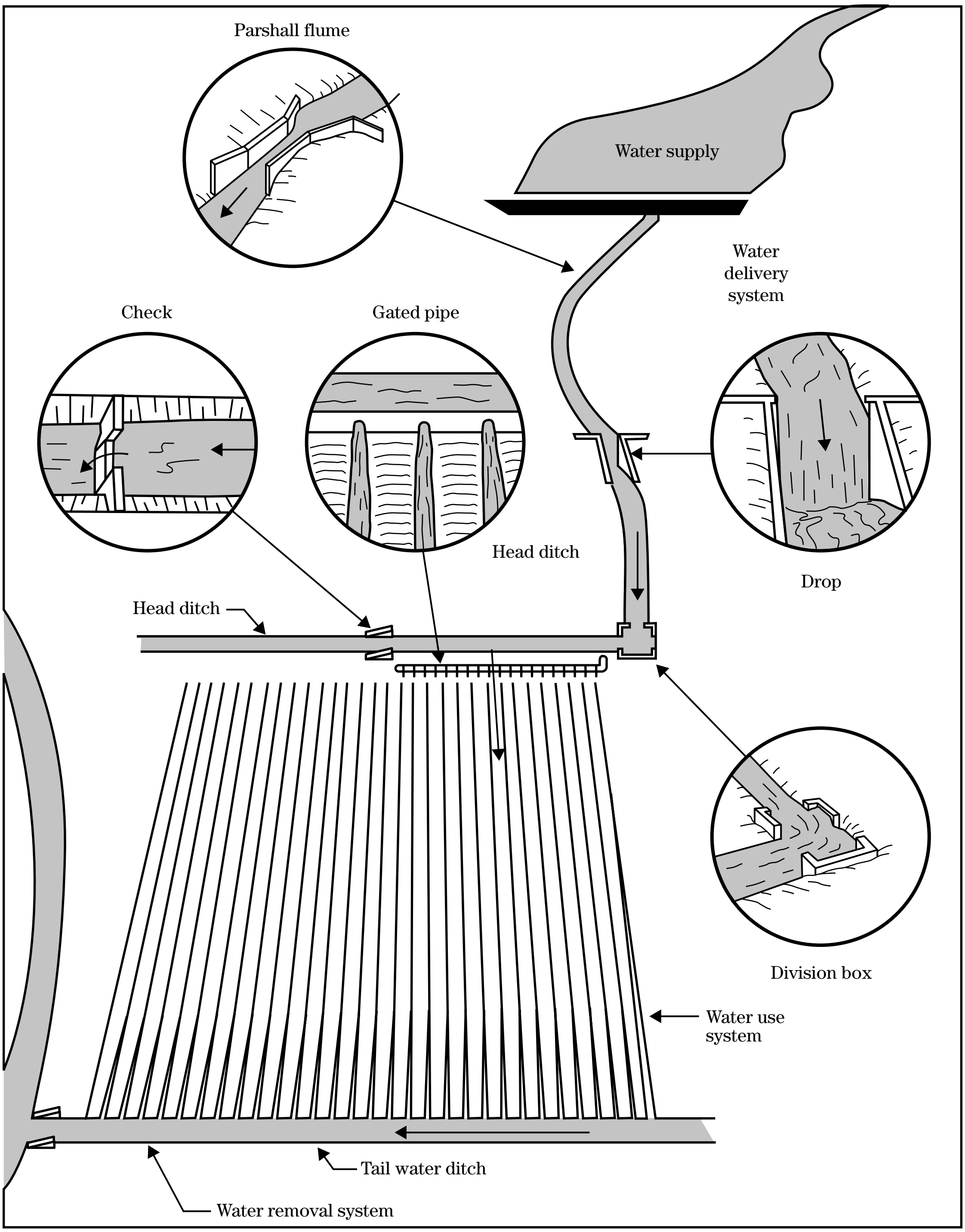
There are three general phases in a surface irrigation event (fig. 4–2):

- advance
- wetting or ponding
- recession

The advance phase occurs between when water is first introduced to the field and when it has advanced to the end. Between the time of advance completion, or simply advance time and the time when water is shutoff or cutoff, is the period designated as the wetting or ponding phase. The wetting or ponding phase will not be present if the inflow is terminated before the advance phase is completed, a typical situation in borders and basins, but a rarity in furrows.

The wetting phase is accompanied by tailwater runoff from free-draining systems or by ponding on blocked-end systems. After the inflow is terminated, water recedes from the field by draining from the field and/or into the field via infiltration. This is the recession phase. All numerical models of surface irrigation attempt to simulate these processes.

Figure 4–1 Layout and function of irrigation system components



(b) Surface irrigation configurations

Choosing a particular surface irrigation system for the specific needs of the individual irrigator depends on the proper evaluation and consideration of the following factors:

- costs of the system and its appurtenances
- field sizes and shapes
- soil intake and water holding characteristics
- the quality and availability (timing of deliveries, amount and duration of delivery) of the water supply
- climate
- cropping patterns
- historical practices and preferences
- accessibility to precision land leveling services

(1) Basin irrigation

Basin irrigation is distinguished by a completely level field with perimeter dikes to control and/or prevent runoff. Figure 4–3 illustrates the most common basin irrigation concept.

Development costs—Basin irrigation is generally the most expensive surface irrigation configuration to develop and maintain, but often the least expensive to operate and manage. Land leveling is the most costly development and maintenance requirement, although the perimeter diking can also be expensive to form and maintain. In areas where turnouts from the delivery system have relatively small discharges, development costs may also be increased by necessary changes in the irrigation system upstream of the basin.

Since basins are typically designed to pond the water on their surfaces and prevent tailwater, they are usually the most efficient surface irrigation configurations. In addition, management is almost always simpler.

Field geometry—In the absence of field slope to aid the movement of water on the field surface, the run length, or distance the water has to advance over the field, tends to be minimized. Many basins take on a square rather than a rectangular shape, but this depends entirely on the availability of sufficient flow rates and the intake characteristics of the soil. One of the major advantages of basins is their utility in irrigating fields with irregular shapes and small fields.

Soil characteristics—Basin irrigation systems usually operate at less frequent intervals than furrows or borders by applying a larger depth during irrigation. Consequently, medium to heavy soils with their high moisture holding capacity are better suited to basins than lighter soils. The efficiency and uniformity of basin irrigation depend on the relative magnitude of the field inflow and the soil intake. A soil with a relatively

Figure 4–2 Basic phases of a surface irrigation event

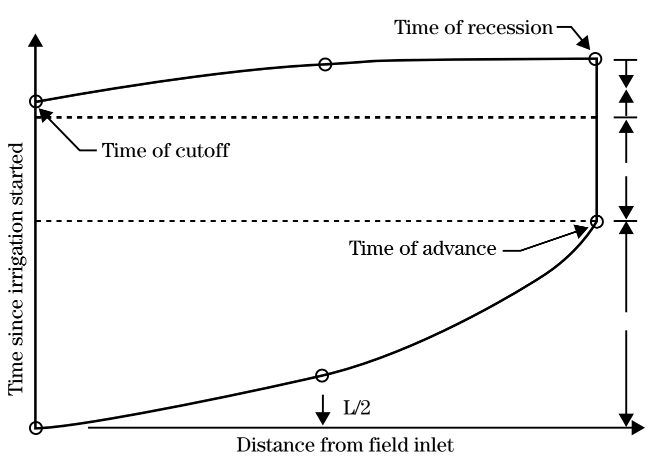


Figure 4–3 Typical basin irrigation system in the western U.S.

high intake characteristic will require a substantially higher flow rate to achieve the same uniformity and efficiency as for a heavier soil.

Since the water may cover the entire basin surface, a soil that forms dense crusts upon drying may have detrimental impacts on seed germination and emergence. It is common practice to furrow soils of this nature to reduce crusting problems. On the other hand, basin irrigation is an effective means for reclamation and salt leaching.

Many of the heavier soils will form cracks between irrigations which may be responsible for much of the water that infiltrates during irrigation. These soils are also susceptible to forming compacted layers (hard pans or plow pans) at the cultivation depth. The impact of cracking in basin irrigation is an increased applied depth. The impact of a plow pan is to restrict it.

Water supply—The water supply to an irrigated field has four important characteristics:

- quality
- flow rate
- duration
- frequency of delivery

The quality of the water added to the field will be reflected in the quality of the water throughout the root zone. Salinity is usually the most important quality parameter in surface irrigation, and the higher the salinity in the irrigation water, the higher the concentration of salts in the lower regions of the root zone. However, since basins do not apply water to the crop canopy as does sprinkle irrigation, water supplies with relatively high salinities can be used. Some water supplies also have poor quality due to toxic elements like Boron.

The most important factor in achieving high basin irrigation uniformity and efficiency while minimizing operational costs is the discharge applied to the field. In basin irrigation, the higher the available discharge the better, constrained only by having such a high flow that erosion occurs near the outlet.

The duration of irrigation is dependent on the depth to be applied, the flow rate onto the field, and the efficiency of the irrigation. Basin irrigation's typically high discharges and high efficiencies mean that basin irrigations may require less total time than borders and furrows. This, coupled with the fact that basins usually irrigate heavier soils and apply larger depths, means that the irrigation of basin is typically less frequent than borders or furrows. The duration and frequency of basin irrigation impose different requirements on the water supply system than systems operated to service border and furrow systems.

Climate—Whenever water ponds on a cropped surface for an extended period of time, the oxygen-carbon dioxide exchange between the atmosphere and the roots is disrupted. If the disruption is long enough, the crops will die. This process is sometimes called scalding. Scalding is perceived as a serious risk in basin irrigation by irrigators in hot dry climates. Of course, rice farming depends on this process for weed control.

Another climate related impact of basin irrigation is the effect of water temperature on the crop at different stages of growth. Irrigation with cold water early in the spring can delay growth, whereas in the hot periods of the summer, it can cool the environment—both of which can be beneficial or detrimental in some cases.

One important advantage of basins in many areas of high rainfall is that they can more effectively capture it than can borders or furrows. Thus, basins enjoy the benefits of higher levels of effective precipitation and may actually require less irrigation delivery during rainy periods as long as the crops are not damaged by subsequent scalding or flooding.

Cropping patterns—With its full wetting and large applied depths, basin irrigation is most conducive to the irrigation of full-stand crops like alfalfa, grains, grass, and rice. Row crops can be and often are grown in basins, as well. Widely spaced crops like fruit trees do not require as much of the total field soil volume to be wetted and thus, basin irrigation in these instances is less useful. Although, it should be noted that mini-basins formed around each tree and then irrigated in pass-through or cascade fashion are found in many orchard systems. Cascading systems are usually less efficient and have low uniformity due to poor water control.

Basin irrigation is also more effective with deep-rooted crops like alfalfa than with shallow-rooted crops like vegetables. Crops that react adversely to crown wetting do not favor basins.

Cultural factors—Because surface irrigation depends on the movement of water over the field surface whose properties change from year to year and crop to crop, as well as from irrigation to irrigation, surface irrigation management is a difficult task to do well and consistently. Basin irrigation reduces this burden by eliminating tailwater from the management process. However, where basin irrigation has not been practiced previously, the added costs and the uncertainty associated with a lack of experience are often substantial barriers to its adoption.

Basin irrigation is less common in the United States than either border or furrow systems but has been shown to have significant advantages. Nevertheless, most irrigators will stay with practices that have been used previously in their area rather than take the risk associated with a new technology. Consequently, demonstrations are often necessary to introduce basin irrigation.

One of the criticisms of basin irrigation when used with square fields is the increased equipment turns during cultivating, planting, and harvesting operations.

Land leveling—Before the advent of the laser guided land grading equipment, it was common to find surface elevations as much as one or two inches lower or higher than the design elevations of the field. Land leveling operators varied in skill and experience. Today, the precision of land grading equipment is much greater and does not depend nearly as much on operator skill and experience.

Since the field surface must convey and distribute water, any undulations will impact the flow and, therefore, the efficiency and uniformity. Basin irrigation is somewhat less dependent on precision field topography than either furrow or border systems because of high flows or the ponding. Many users of basin irrigation insist that the most important water management practice is lasering. Precision land leveling is an absolute prerequisite to high performance surface irrigation systems, including basins. This includes regular precision maintenance during field preparations (land smoothing).

(2) Furrow irrigation

Furrow irrigation is at the opposite extreme of the array of surface irrigation configurations from basins. Rather than flooding the entire field, small channels called furrows and sometimes creases, rills, or corrugations are formed and irrigated (fig. 4–4). The amount of water per unit width on a furrow irrigated field may only be 20 percent of the water flowing over a similar width in a basin. Infiltration is two-dimensional through the wetted perimeter rather than a vertical one-dimensional intake. Furrows can be blocked at the end to prevent runoff, but this is not a common practice unless they are used in basins or borders to compensate for topographical variation or provide a raised seed bed to minimize crusting problems. The distinction between a furrowed basin or a furrowed border and furrow irrigation lies in the semantic preference of the user. For purposes of evaluation and design, both of these situations would fall under the term furrow irrigation.

Development costs—Furrow irrigation systems are the least expensive surface irrigation systems to develop and maintain primarily because minimal land leveling is required to implement a furrow system and less precise land smoothing is necessary for maintenance. The furrow themselves can be formed with cultivation equipment at the time of planting.

Figure 4–4 Furrow irrigation using siphon tubes from a field bay

While less expensive to implement, furrow systems are substantially more labor intensive than basins. Variations in individual flows, slopes, roughness, and intake alter the advance rate of each furrow, and there are often substantial differences in how long it takes the water to reach the end of the furrow. In addition, some furrows are compacted by the wheel traffic of planting and cultivation equipment and have substantially different characteristics than non-traffic furrows. Irrigators compensate by adjusting the furrow flows and, thereby, need to be at the field longer. Further, they also have to assess how long to allow the water to run off the field before shutting it off, as opposed to shutting the flow off in a basin when the correct total volume has been added to the field.

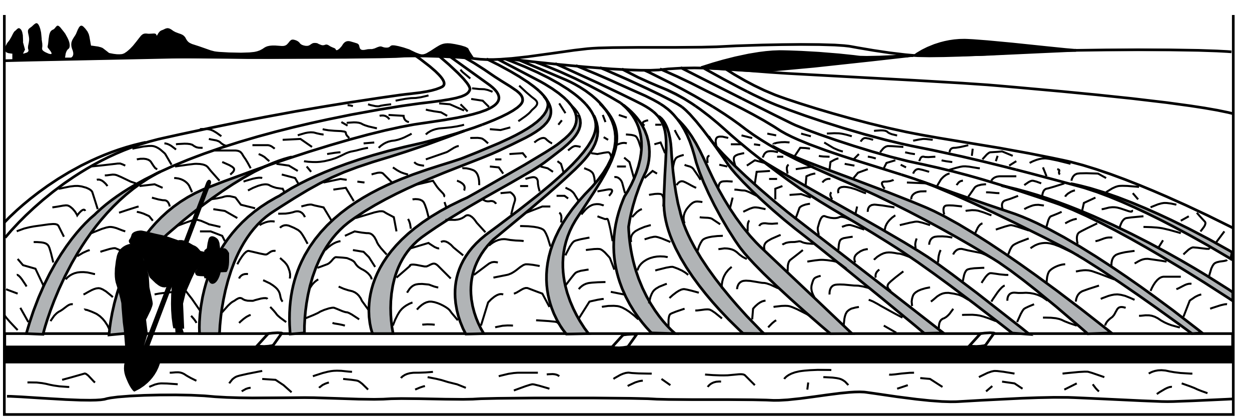
Because most furrow systems allow field tailwater, they are seldom as efficient as basin systems and, thereby, require more water per unit area. Measures such as the capture and reuse of tailwater can be employed to increase efficiency. Another alternative is a concept called ***cutback*** that involves reducing the furrow inflow after the flow has reached the end of the furrow. Surge flow and cablegation systems are examples of automated cutback systems.

Field geometry—Furrow irrigated fields generally have slopes in both the direction of the flow and the lateral direction. These slopes can vary within a field; although, the slope in the direction of flow should not vary significantly unless it is flattened at the end of the field to improve uniformity. Figure 4–5 illustrates the use of contour furrows to irrigate irregularly sloped fields. One of the major advantages of furrow irrigation is that undulations in topography have less impact on efficiency and uniformity than they do in either basin or border irrigation.

Soil characteristics—Furrow irrigation can be practiced on nearly all soils, but there are two important limitations. First, the risk of erosion is higher in furrow irrigation than in either basin or border irrigation because the flow is channeled and the flow velocities are greater. Secondly, since the furrow actually wets as little as 20 percent of the field surface (depending on furrow spacing), applying relatively large depths of irrigation water in the heavy soils can require extended periods of time and will result in low efficiencies. A 4- or 6-inch irrigation application is common in basin and border irrigation but would not be feasible with a furrow system on a particularly heavy soil.

Furrow irrigation is more impacted by soil cracks than borders and basins since the cracks often convey flow across furrows. Furrows are probably less impacted by restrictive layers due to their inherent two-dimensional wetting patterns.

Figure 4–5 Contour furrow irrigation



Water supply—Since the flow on the field is substantially less than in a basin or border system, a major advantage of furrow irrigation is that it can accommodate relatively small delivery discharges per unit area. As furrows typically apply smaller depths per irrigation, the availability of the delivery must be more frequent and for longer durations. More water on a volumetric basis is required for furrow irrigation because of its lower application efficiency in most cases.

Salts can accumulate between furrows; therefore, the quality of irrigation water is more important in furrow systems than in basins or borders.

Climate—The climate over a surface-irrigated field does not have significant impacts on the furrow irrigation. Scalding is seldom a problem even when the furrow ends are blocked. High winds can retard the furrow advance, but this is rarely a problem. The effect of water temperature is less in furrows than in borders or basins because the wetted area is less.

Cropping patterns—Furrows are ideally suited for row crops of all kinds but are also used in solid plantings like alfalfa and grains. When the seed bed is between furrows and must be wetted, it is necessary to apply water to the furrows for extended periods and efficiencies of these emergent irrigations can be very low. The lateral movement of water or subbing, wetting-across, is a relatively slow process, so many irrigators of higher value crops like vegetables use portable sprinkle systems for the emergent irrigations. Special crops, like rice, are generally not irrigated with furrows because of the need for a uniform submergence to control weeds.

Cultural factors—Most of the cultural factors affecting furrow irrigation are the same as those noted previously for basin irrigation. The higher labor requirements require a resource in United States agriculture that is becoming critically short. The lower efficiencies are problematic in an era of diminishing supplies, competition by urban needs, and the detrimental impact of salts and sediments on the quality of receiving waters when efficiencies are low. When polypipe is used to distribute water to the furrows, an environmental concern with its disposal is raised. On the other hand, furrow irrigation is more flexible than either borders or basin as the configuration is easily changed by simply increasing or decreasing the number of furrows being irrigated simultaneously or by irrigating alternate furrows.

Land leveling—While precision land leveling is not as critical to furrow irrigation as it is to basin and border irrigation, an irrigator cannot expect to achieve high uniformities and efficiencies without it. Precision land leveling will reduce the furrow to furrow variations in advance times and will improve both uniformity and efficiency. Land leveling for furrow systems is also much less intrusive since field slopes can run in both field directions, thereby, reducing the volume of soil that has to be moved. Land smoothing, while not as important, is nevertheless a good practice on a regular basis.

(3) Border irrigation

Border irrigation looks like basin irrigation and operates like furrow irrigation. Figure 4–6 illustrates a typical border irrigation system in operation. Fields may have a slope along the traditionally long rectangular fields but cannot have a cross-slope. The flow covers the entire surface and may be blocked at the down-

Figure 4–6 Border irrigation in progress

stream end to prevent runoff. Borders can also follow the contour lines in terraced fields (fig. 4–7).

Development costs—The two major development costs for borders are land leveling and border construction. Land leveling is more extensive for furrows and less extensive for basins, particularly if the field is leveled along the existing slope in the direction of flow. The border dikes do not have to be as high as for basins, but do need to be maintained to prevent crossflow into adjacent borders, and care should be taken to intercept the flow that can occur in the dead furrow created by the diking equipment.

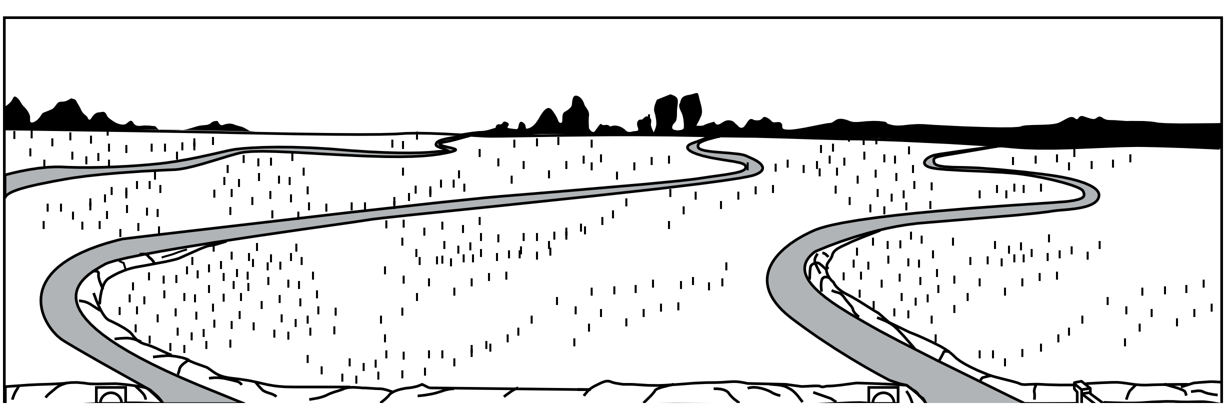
Borders do not generally require as much labor as furrow irrigation, but do require more for basins, since the time of cutoff has to be judged properly. In fact, furrow system cutoff times are usually after the completion of advance. For borders, cutoff times are typically shorter and before the completion of the advance phase. Consequently, achieving high efficiencies is more difficult in border irrigation than in furrow irrigation. Traditionally, free-draining borders have about the same efficiency and uniformity as furrows, thereby, reducing the economic feasibility of borders that allow tailwater. However, borders can also be blocked to prevent runoff and achieve efficiencies as high as those for basins, becoming slightly more economical than basins.

Field geometry—Borders are usually long and rectangular in shape. Often referred to as border strips, borders contain the flow within side dikes to direct the flow over the field. Borders can be furrowed where necessary for elevating a seed bed or compensating for micro-topography within the border. Borders can also be level or nearly level, making them effectively the same as basins. Distinguishing borders from basins is often based on the rectangular shape rather than slope and in any event the differences are only semantic.

Soil characteristics—Borders do not generally have erosion problems except near outlets and tailwater drains, so they are somewhat more flexible irrigation systems than furrows. The slope aids advance and recession so border irrigation can be applied to the full range of soils as long as the flow per unit width is selected properly. However, as with basins, borders are better suited to the heavier soils, and crusting soils may require special care such as furrowing.

Water supply—Typical water applications under border irrigation are similar to basin systems and usually larger than furrows. In general, border systems require three to five times as much flow per unit width as furrow systems and somewhat less than basins. For example, it would not be unusual to irrigate furrows on a spacing of 2.5 feet with a 15 grams per minute (gpm) flow (6 gpm/ft) and to irrigate a border with the same

Figure 4–7 Illustration of contour border irrigation



soil with a flow of 20 gpm/ft. The same water quality constraints noted for basins apply to borders, as well. Consequently, water supplies for borders should be relatively high discharges for relatively short durations on relatively long intervals.

Climate—Scalding is a more serious problem in blocked-end borders than in basins because the end depths are greater and require longer to drain from the field. It is common practice to provide blocked-end borders with surface drainage capability in case an error is made in the time of cutoff and too much water ponds at the end of the field. Figure 4–8 shows one of these end drains in a border irrigated alfalfa field.

In areas of high rainfall, ponding and subsequent scalding may be a problem without a surface drainage capability. And, the timing of irrigations in these areas is a critical issue. If irrigation is completed immediately prior to a large rainfall event, water may pond at the lower end; therefore, the scalding potential might be substantial.

Cropping patterns—Borders are used to irrigate most solid planting crops, and if furrowed, many row crops, as well. Widely spaced trees usually are not irrigated with borders unless the borders enclose the tree line, leave an empty space between tree rows, and rice is not grown in borders. Since the water ponds the entire surface, crops with sensitivity to scalding may not be well irrigated with borders. Likewise, borders are better suited to deeply rooted crops like alfalfa than shallow rooted crops like vegetables.

Figure 4–8 Tailwater outlet for a blocked-end border system

Cultural factors—Many growers like two things about borders: the long travel lengths for their machinery operations and the slope to facilitate the application of water during the initial wetting. These advantages are offset by more labor and management than for basins. Properly designed and managed, blocked-end borders will have the same high efficiencies and uniformities as basins. Leaching is better in borders than in furrows, but not as good as in basins.

Land leveling—Precision land leveling is just as important to high performance in border irrigation as it is for either basins. The ponding can compensate for some micro-topography, or furrows, where the channeled flow will keep the water from concentrating in one location of the field. With precision land grading, a border flow will advance uniformly to the end of the field and apply a uniform and efficient irrigation. Land smoothing to maintain the surface profile is also important.

One of the interesting features of borders, as with furrows, is that the field slope does not need to be the same. In some heavy soils, the slope can be flattened over the lower 25 percent of the border to increase uniformity at the end of the field.

(4) Summary of surface irrigation methods

Choosing one type of surface irrigation over another is very subjective because of the number of criteria to consider and the complicated interactions among the criteria. Table 4–1 gives a general summary of the discussion and some typical comparisons.

(c) Water management in surface irrigation systems

Surface irrigation is difficult to manage at consistently high levels of performance (efficiency and uniformity) because the basic field characteristics change from irrigation to irrigation, crop to crop, and year to year. For example, the soil intake changes dramatically between the first irrigation following cultivation and the next. The field is also smoother, as long as the crops do not grow in the flow path, but will become rougher as the season progresses. These variations cause the water to not only infiltrate at different rates, but also change how fast the water advances over the field and recedes from it after the flow is turned off. If an irrigator misjudges the behavior of the system, the performance will decline. It is not surprising that surface irrigation efficiencies worldwide are low.

At the appraisal, design, or rehabilitation stage, the essential questions to be asked about the surface irrigation system are:

- what kind of surface system should be selected
- what unit flows to choose
- when to turn the inflow off
- what the field slope should be, as well as its length
- what structures and facilities are needed
- what should be done about tailwater if the field is to allow it

At the operational stage, the questions are: what the unit flow should be and when it should be shut off? In other words, water management in surface irrigation systems involves both design and operational questions that involve the same set of parameters. The following are some general guidelines. More specific tools will be presented in subsequent sections.

(1) Choosing a surface irrigation system

The eight factors described under basin, furrow, and border irrigation generally will dictate the type of surface system that should be employed in a particular situation, but the cultural factor is the deciding factor. The crops to be irrigated may determine the system immediately. For instance, if paddy rice is the major crop, basins will nearly always be the logical choice. Some rice areas in the southern United States prefer low-gradient, blocked-end borders to facilitate drainage and to better accommodate second crops like soybeans.

Table 4–1 General comparison of surface irrigation surface methods

Selection criteria	Furrow irrigation	Border irrigation	Basin irrigation
Necessary development costs	Low	Moderate to high	High
Most appropriate field geometry	Rectangular	Rectangular	Variable
Amount and skill of labor inputs required	High labor and high skill required	Moderate labor and high skill required	Low labor and moder-ate skill required
Land leveling and smoothing	Minimal required but needed for high efficiency. Smoothing needed regularly	Moderate initial in vestment and regular smoothing is critical	Extensive land leveling required initially but smoothing is less critical if done periodically
Soils	Light to moderate texture soils	Moderate to heavy textured soils	Moderate to heavy textured soils
Crops	Row crops	Solid-stand crops	Solid-stand crops
Water supply	Low discharge, long duration, frequent supply	Moderately high discharge, short duration, infrequent supply	High discharge, short duration, infrequent supply
Climate	All, but better in low rainfall	All, but better in low to moderate rainfall	All
Principal risk	Erosion	Scalding	Scalding
Efficiency and uniformity	Relatively low to moderate	High with blocked-ends	High

Future water quality goals for watersheds may be such that the surface irrigation systems must have a higher efficiency than can be achieved with furrows and, therefore, dictate basins, blocked-end borders, or furrow systems with tailwater reuse. In many cases, there may not be a definite advantage associated with any form of surface irrigation. The system selected must be based on farmer preference, cropping pattern, or environmental constraints.

Land leveling is nearly always the most expensive operation on the field. In choosing a border or basin system over a furrow system, consider these capital costs in lieu of the savings in operational costs like water, labor, and maintenance. Consequently, leveling costs are probably the first indicator. Consider, for example, a field that would require $300 per acre to level it for basins. If the water cost is $15 per acre-foot, it would require many years to recapture the investment costs of the leveling with water savings alone. On the other hand, if labor is critically expensive and short, perhaps the basins would be a more feasible choice. If a change in surface irrigation system is contemplated, examining the leveling costs after considering cultural factors will prove useful.

(2) Inlet discharge control practices

There is an interesting trade-off between the inflow rate and the time of cutoff which influences uniformity and efficiency differently. If the discharge per unit width is too small, the water will advance very slowly over the field resulting in poor uniformity and low efficiency. The problems with uniformity will be due to the large differences in the time water is allowed to infiltrate along the field (intake opportunity time). Low efficiency is caused by intake exceeding the soil's ability to store it in the root zone of the crop (deep percolation). If the unit flow is incrementally increased, both uniformity and efficiency will increase, and will continue in a positive manner for basin irrigation, but not for border and furrow irrigation.

In free-draining furrow and most border systems, the incremental increase in unit discharge (with a corresponding decrease in cutoff time so the volume required is approximated) will reach a point where the efficiency reaches a maximum and begins to decline even as uniformity continues to increase. The cause of this peaking of efficiency is the gradual increase in field tailwater that will more than offset the decreases in deep percolation as uniformity improves.

One of the problems in surface irrigation is that the first irrigation of the season following planting or cultivation often requires two or three times the flow rate that subsequent irrigations need to achieve acceptable uniformity. The infiltration rates are higher during these initial irrigations and thus, the need for higher inlet flows. As the soil intake diminishes during the season, the inlet flows can be reduced. The design and operation of surface irrigation systems requires adjusting the inlet flow and its duration to achieve maximum efficiencies.

(3) Changing the field geometry and topography

Cultivation, planting, and harvesting with modern United States agriculture and its advanced mechanization are more efficient for large fields with long lengths of run. As the soil texture in a large field may range from clay and clay loam to silt loam and sandy loam, the length of the field may be too long for efficient surface irrigation. Dividing the field in half, thirds, or quarters is often an effective way to achieve better uniformities and efficiencies. However, because a field subdivision costs the farmer in mechanization efficiency, land area, and money for the changes, surface irrigation should be evaluated first using the field dimensions that correspond to property lines, organization of supply pipes or ditches, or what the farmer is currently doing.

Good design practice avoids slope changes unless necessary to change type of surface irrigation system. Surface irrigation can be configured to work well within a range of slopes between 0 and 0.5 percent. If a flatter slope is needed to control erosion at the end of a sloping field, flattening the last quarter of a field's slope is easily accomplished with modern laser guided land leveling equipment and need not be prohibitively expensive.

Surface irrigation performance can always be improved by accurate leveling and smoothing of the field surface. As noted previously, most irrigators consider precision land grading as the best water management practice. Figure 4–9 shows a land plane in the process of smoothing a field.

Furrowing borders or basins also reduces the effect of topographical variations. Some soils are too coarse textured for efficient surface irrigation, but practices aimed at incorporating crop residues and animal manures not only change intake rates, but also improve soil moisture-holding capacity. When water advance over a freshly cultivated field is a problem because of high intake, a limited discharge, or an erosion problem, the surface is often smoothed and compacted by attachments to the planting machinery.

(4) Tailwater recovery and reuse

To convey water over the field surface rapidly enough to achieve a high degree of application uniformity and efficiency, the discharge at the field inlet must be much larger than the cumulative intake along the direction of advance. A significant fraction of the inlet flow remains at the end of the field that will run off unless the field is diked or the tailwater is captured and reused. In many locations, the reason to capture tailwater is not so much for the value of the water, but for the soil that has eroded from the field surface. Other conditions exist where erosion is not a problem and the water supply is abundant, so the major emphasis is merely to remove the tailwater before waterlogging and salinity problems emerge. Finally, it may be cost-effective to impound the tailwater and pump it back to the field inlet for reuse or store it for use on lower-lying fields. Figure 4–10 shows a typical tailwater recovery and reuse system.

(5) Automation and equipment

High labor requirements are a disadvantage of surface irrigation that many irrigators cite as reasons for converting to sprinkle or drip irrigation. Automation, which can regulate the supply flow to various parts of the field and properly adjust unit flows and cutoff times, is a critical need in surface irrigation. Unfortunately, experience to date has been mixed because a standard technology has not been developed for widespread use.

Border and basin facilities and automation— Some of the common facilities for border and basin irrigation are shown in figure 4–11. They include single-gate offtakes, ditch gates, siphons, alfalfa valves, and simple check-dividers, to show a few options. The automation for basin and border involves mechanizing and controlling individual outlets. This is comparatively straight forward for the single-gate offtakes but can be substantially more complicated for multiple-gate outlets. For instance, the jack gate shown in figure 4–11 readily can be equipped with a remotely controlled actuator such as a pneumatic piston. Where water control involves siphons or ditch gates, automation is generally impractical.

Figure 4–9 Field smoothing can be done by a land plane

Figure 4–10 Typical tailwater recovery and reuse system

As a rule, automation of border and basin offtakes involves retrofitting mechanization to the gate and then connecting it via wire, telephone, or radio to a controller where the irrigator can make remote changes, or where regulation can be made of the system at specified time intervals. The wheel-actuated gate shown in figure 4–12 can be equipped with a small electric motor and gear assembly to automate the offtake. In any event, whenever automation can be reduced to single gate as for many borders and basins, it is much more feasible and reliable than for furrow systems.

Furrow irrigation facilities and automation— Furrows are often supplied water by some of the same facilities used in borders and basins. For example, figure 4–13 shows two furrow systems supplied by ditch gates and siphon tubes.

Perhaps the most common furrow irrigation system is one using gated pipe. Figure 4–14 shows two examples that illustrate both the rigid and flexible options. Rigid-gated pipe is generally found in aluminum or PVC and range in size from 6 to 12 inches with gate spacings ranging from 20 to 48 inches. The flexible-gated pipe, or polypipe, can be purchased in sizes from 12 to 18 inches with wall thicknesses of 7 to 10 mil. An advantage of

Figure 4–11 Typical border and basin field outlets

(a) Jack slide gate

(b) Ditch gates

(c) Alfalfa valve

(d) Large diameter siphon tubes

flexible gated pipe is being able to place gates at any spacing desired. Typically gates are not used at all, just holes punched in the pipe.

Furrow systems can also be served by field bays or narrow shallow channels at the head of the field that create a small reservoir from which individual furrows are supplied water. In figure 4–4, water is diverted from a head ditch into the field bay and then diverted into the furrows with siphons.

(6) Cutback

To achieve the most uniform surface irrigation, the advance phase has to occur fairly quickly, and requires a relatively large unit flow. In border or basin irrigation, the inflow is terminated in most cases before the advancing front reaches the end of the field. In furrow irrigation, however, it is nearly always necessary to maintain inflow well beyond the completion of advance to refill the root zone. Consequently, the runoff

Figure 4–12 A wheel lift slide gate before and after automation

(a) Typical gate structure

(b) Gate with automation

Figure 4–13 Two methods of supplying water to furrows

(a) Furrow ditch gates

(b) Siphon tubes

Figure 4–14 Gate pipe options for furrow irrigation

or tailwater volume can be high and the efficiency low. One way to overcome this problem is to allow a high flow during the advance phase, and then reduce it to a smaller value during the wetting phase, thereby, minimizing tailwater. This is called cutback. A simple example is the use of two siphons per furrow during the advance phase and then reducing the flow by eliminating one of the siphons during the wetting phase.

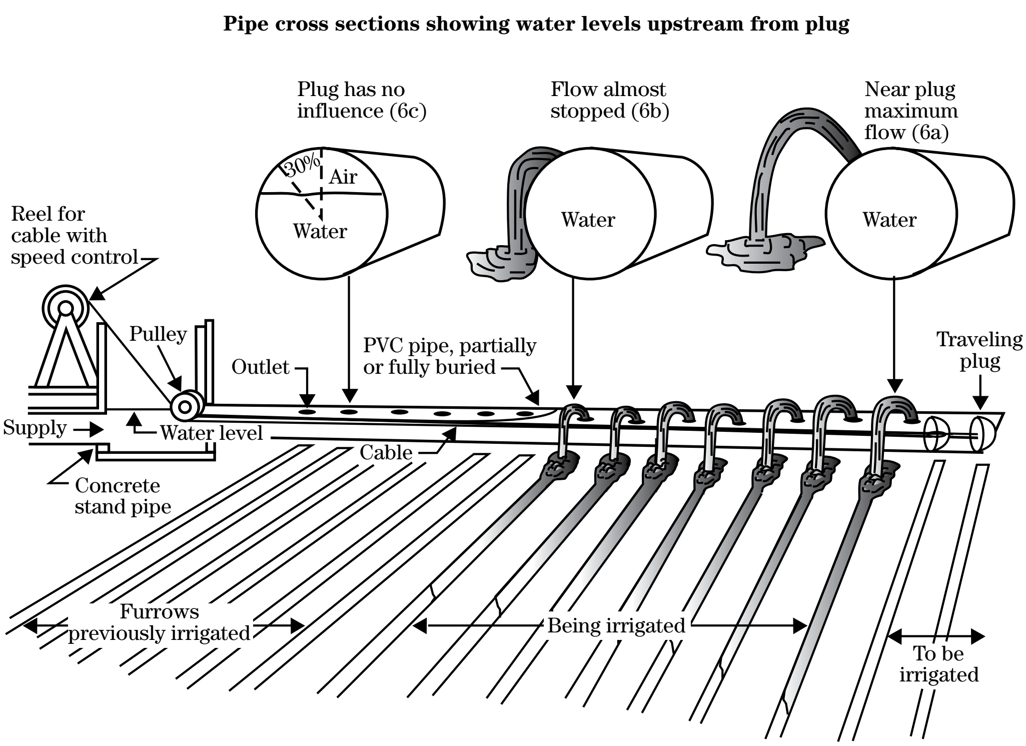
Furrow irrigation automation was not very successful until the advent of the surge flow concept; although, systems like the cablegation system developed in Idaho have proven to work well during field research and demonstration studies (fig. 4–15). Cablegation involves a mechanized plug attached to a cable that is extended at a fixed rate from the upper end of the system. The flows from gated openings near the plug have higher rates than those away from the plug and thus, as the plug moves along the pipe, the flow in the upstream furrows decrease. Cablegation is an interesting form of a more general concept called cutback irrigation. Cablegation has not found widespread use due to its complex hardware, difficult management requirements, and lack of standardized and commercial equipment.

As a concept, cutback is an attractive way to improve furrow irrigation performance. In practice, it is almost impossible to implement in the field and is inflexible. When the flow is reduced, the flow characteristics of the system are changed, and the gate openings would not be adjusted. With simple furrow irrigation system using siphons, it can be done with substantial labor. Since the advance time and wetting time need to be about equal, the savings in tailwater may be nearly offset by increases in deep percolation. In terms of automation, the practicable ways of implementing cutback are the cablegation system or surge flow.

(7) Surge irrigation

Under the surge flow regime, irrigation is accomplished through a series of short duration pulses of

Figure 4–15 Schematic cablegation system

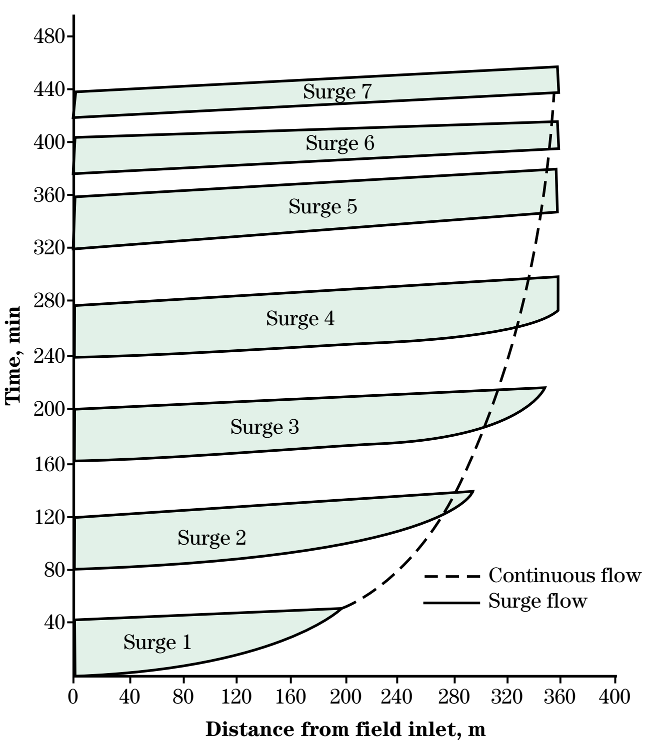


water onto the field. A typical advance/recession plot for a surged system is illustrated in figure 4–16. Instead of providing a continuous flow onto the field, a surge flow regime would replace a 6-hour continuous flow set with something like six 40-minute surges. Each surge is characterized by a cycle time and a cycle ratio.

The cycle time is the sum of an on-time and an off-time that do not need to be equal. The ratio of on-time to the cycle time is the cycle ratio. Cycle times can range from as little as 1 minute during a cutback phase to as much as several hours in low gradient borders and basins. Cycle ratios typically range from 0.25 to 0.75. By regulating these two parameters, a wide range of surge flow regimes can be produced to improve irrigation efficiency and uniformity.

Effects of surging on infiltration—Since its introduction in 1979, surge flow has been tested on nearly every type of surface irrigation system and over the full range of soil types. Results vary depending on the selection of cycle time, cycle ratio, and discharge. Generally, the intermittent application significantly reduces infiltration rates, and the time necessary for the infiltration rates to approach the final or basic rate. To achieve this effect on infiltration rates, the flow must completely drain from the field between surges. If the period between surges is too short, the individual surges overlap or coalesce, and the infiltration effects are generally not created. The advance time for surge irrigation may not be an improvement on soils that initially have low intake rates and on fields with relatively large slopes. Soils that crack when dry also are less likely to produce a favorable response to surge irrigation. Even though advance time may not be improved, the benefits of reduced runoff and reduced labor may still prove surge irrigation to be worthwhile.

Figure 4–16 Advance and recession trajectories for a surge flow system



The effect of having reduced the infiltration rates over at least a portion of the field is that advance rates are increased. Generally, less water is required to complete the advance phase by surge flow than with continuous flow. Surging is often the only way to complete the advance phase in high intake conditions like those following planting or cultivation. As a result, intake opportunity times over the field are more uniform. However, since results will vary among soils, types of surface irrigation, and the surge flow configurations, tests should be conducted in areas where experience is lacking to establish the feasibility and format for using surge flow.

Surge flow systems—The original surge flow system involved automating individual valves for each furrow using pneumatic controls. Figure 4–17 shows one of the early systems. The complexity and cost of these systems proved to be infeasible, and a simpler system involving an automated butterfly valve like the ones in figures 4–18 and 4–19 was developed to implement surge flow by sequentially diverting the flow from one bank of furrows to another on either side of the value.

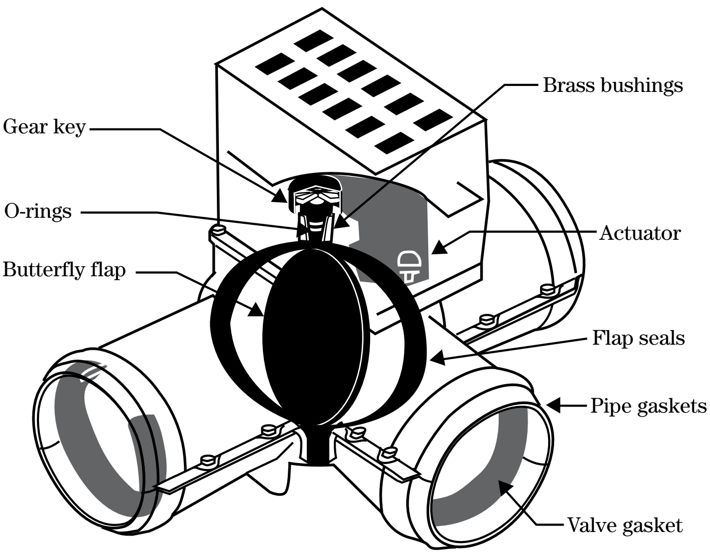
The automated butterfly valves have two main components: a butterfly valve and a controller. The valve body is an aluminum tee with a diverter plate that directs water to each side of the valve. The controller uses a small electric motor to switch the diverter plate, and its type varies with its manufacturer. Most controllers can be adjusted to accomplish a wide variety of surge flow regimes, and have both an advance stage and a cutback stage. During the advance stage, water is applied in surges that do not coalesce and can be sequentially lengthened. Specifically, it is possible to expand each surge cycle so surges that wet the downstream ends of the field are longer than those at the beginning of irrigation. During the cutback stage, the cycles are shortened so the individual surges coalesce.

The positioning of the surge valve will largely be determined by preexisting field properties. An ideal situation would be when the water supply, or irrigation well, is located near the middle of the pipeline. In this case, the valve is located with equal land area on each side of the valve. However, most situations require the water to be brought to the proper location using mainline pipe. An alternative to locating the valve in the middle of the pipeline would be to place the valve at the water source. This still requires extra mainline pipe. For irregular shaped fields, there are two methods of placing the valve. The first method is to place the valve so that there is an equal amount of acres on each side of the valve. With this option, the cycle times are the same for each side of the valve, but the number of rows irrigated for each set is indirectly proportional to the furrow length for that set. For example, if the furrow length is 500 feet on the left set, and 1,000 feet on the right set, there would be half as many furrows irrigated per set on the right side. The second method is to place the valve in the middle of the pipeline and have different cycle times for each side of the valve. The goal for this method is to apply the same amount of water to each set.

Adaptation for border and basin systems can be made by automating existing control structures and perhaps by a new control structure. Generally, the surge cycle time for these systems must be two to four times as long as in furrow systems to allow complete recession between surges.

Figure 4–17 Early surge flow system

Figure 4–18 Automated butterfly surge flow valve



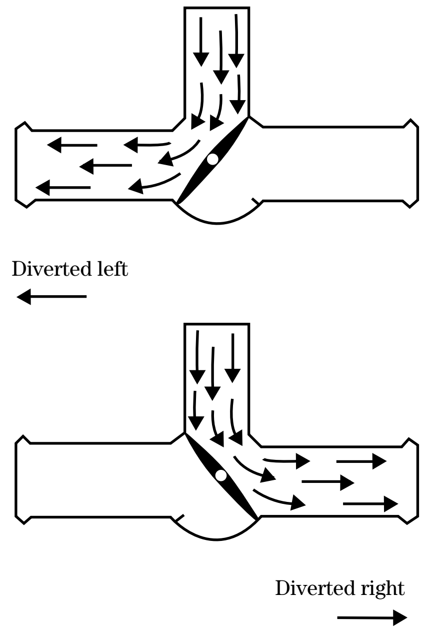


Figure 4–19 Automated butterfly surge flow valve watering one side

623.0401 Surface —NRCS Surface Irrigation Simulation, Evaluation, and Design software

(a) Overview

The practices of surface irrigation evaluation and design have changed significantly since the first publication of the Natural Resources Conservation Service (NRCS) National Engineering Handbook, Section 15 Irrigation, chapters 4 and 5 describing border and furrow irrigation. Two generations ago, engineers relied on tables, nomographs, and slide rules to choose a flow and a field length. Rules of thumb led to choices of flow, length of run, and slope. A generation ago, the slide rule was replaced by programmable handheld calculators, and computer models supplemented available tables and nomographs. Calculation of advance and recession trajectories allowed the irrigation specialist to more accurately evaluate uniformity and efficiency. Realistic assessments of the impact of changing flows, length, and slopes were possible. Today, the personal computer has replaced all of its predecessors. Information is online and real time. Rules of thumb are almost entirely unknown in current curricula, and very few graduating engineers have even seen a slide rule. Analyses now focus on hydrodynamic, zero-inertia, or kinematic wave models. Most of what is carried in a brief case today will be carried in a shirt pocket tomorrow, and perhaps, a new generation of biosensors will be available that will allow surface irrigation systems to be managed online and real time.

In recognizing the need to update section 15, the NRCS also recognized the need to provide modern tools for simulating, evaluating, and designing surface irrigation systems. The NRCS Surface Irrigation Simulation, Evaluation, and Design (**Surface**) software program was written to fulfill this need.

Surface is a comprehensive software package for simulating the hydraulics of surface irrigation systems at the field level, selecting a combination of sizing and operational parameters that maximize performance. It is a convenient way to merge field data with the simulation and design components. The programming uses a 32 bit C++ language to encapsulate the numerical procedures that describe the hydrodynamic theory in general use today. The software has been written for IBM compatible personal or microcomputer systems utilizing Microsoft Windows® 95 or later operating systems. This section provides the reader with a user's manual for the **Surface** program and some detailed data sets that demonstrate its use.

(b) Getting started

Surface and its companion files can be obtained from your state irrigation specialist or IT personnel. The local IT person can provide help installing the program. (NRCS_Surface is supplied with various files that can be simply copied to a subdirectory of the user's choice and then executed in the usual way.)

There are a number of files included in the package. These include the NRCS_SURFACE.EXE file, and several sample input data files with a cfg extension.

(c) Special controls

Figure 4–20 shows the opening or main screen of **Surface**. Program controls can be accessed via either a set of icons or a series of drop-down menus. Figure 4–21 shows a closer look at the command bar.

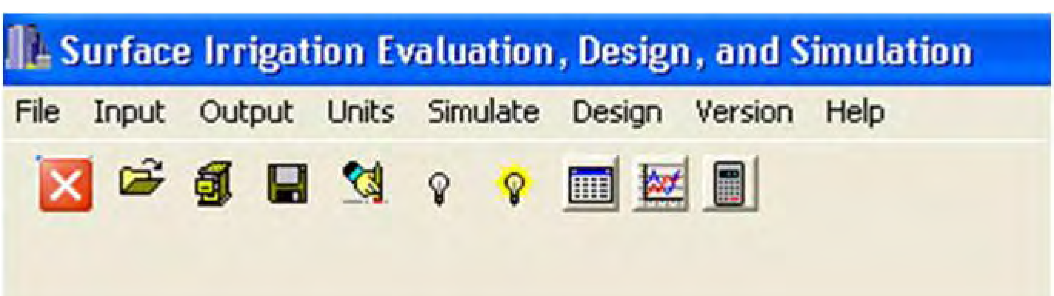
The **Surface** software can be run from the **Run** command of the Windows® Start menu by double clicking on **NRCS_SURFACE.EXE** from the Windows® Explorer or by clicking on a shortcut icon the user has created. In whatever case, the first program screen the user sees will involve four basic tasks:

- inputting or retrieving data from a file
- manipulating data and storing them
- simulating the surface irrigation system described by the input data
- viewing, storing, and printing results

In addition, there are two special cases provided in the software to manipulate data and/or simulations. The first is to derive infiltration parameter values from field measurements, and the second is to simulate alternative system configurations as part of an interactive design feature. Both of these will be described separately.

Figure 4–20 Main **Surface** screen

Figure 4–21 **Surface** command bar



(1) File operations and exiting Surface

The program and any window or screen object can be closed by clicking the **Exit** button, or by clicking **File** and selecting **Exit** from the pull-down menu.

Existing input files can be accessed by selecting **Open** from the **File** drop-down menu or by clicking the **Open** icon.

Once the user has finalized a set of input data, it should be saved to an existing or new file. Saving to an existing file is accomplished from the **File** pull-down menu using the **Save** option or by clicking on the **Save** icon. The **Save As** option from the **File** pull-down menu reveals a dialog box in which the user can save the data under a new file name.

(2) Input

Both the **Input** menu and icon are one-click actions that will cause the input tabbed notebook to appear in the main screen (fig. 4–22). Data can then be input and viewed.

(3) Output

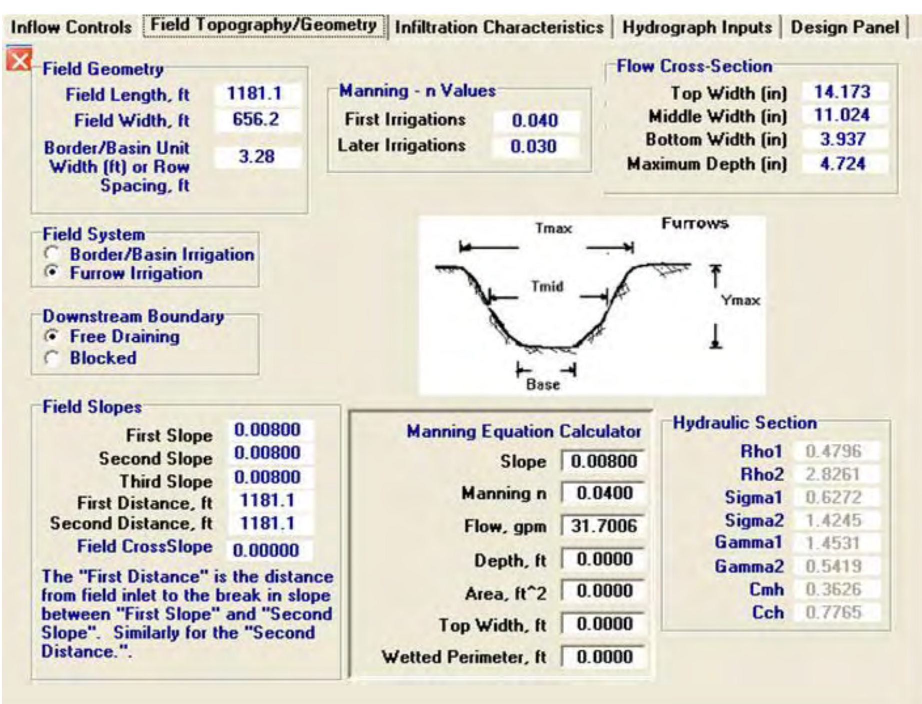
The **Surface** software includes tabular, as well as graphical presentation of simulation results. These options are accessed from the main menu by clicking on **Output** and then choosing displayed (numerical) or plotted results. Icons are also available for displayed and plotted results. Figure 4–23 illustrates the **Surface** tabular output screen.

(4) Units

The input data and results of simulation, design, and evaluation can be displayed in metric or English units via the **Units** pull-down menu. Units may also be selected from the Infiltration Characteristics panel in the input tabbed notebook.

There are three options, English-cfs, English-gpm, and Metric. The default selection is English-gpm. The selected system of units is stored with the input data file, so each time a file is loaded, those units will be displayed and used. Thus, the unit selection should be made before entering input data and/or before saving the input data file.

Figure 4–22 **Surface** input tabbed notebook



(5) Simulation

The selection of **Simulate** on the main menu bar or the **Speed** icon will cause the simulation programming to execute using whatever data are currently stored in memory. A number of safety checks are made to ensure that the appropriate characteristics of the surface irrigation system are defined. The simulate pull-down menu uses a fully hydrodynamic analysis of the system. Input data options are provided to increase or decrease the execution speed to suit the visual appearance of the graphics screen which presents the simulation results time step by time step. There is a more detailed discussion of the simulation functions along with some example problems.

(6) Design

The **Design** option on the main menu bar will open the input data tabbed notebook to the Design Panel. This can also be accessed through the input options. The **Design** option allows the user to simulate and modify various design configurations in an interactive mode.

(d) Data input

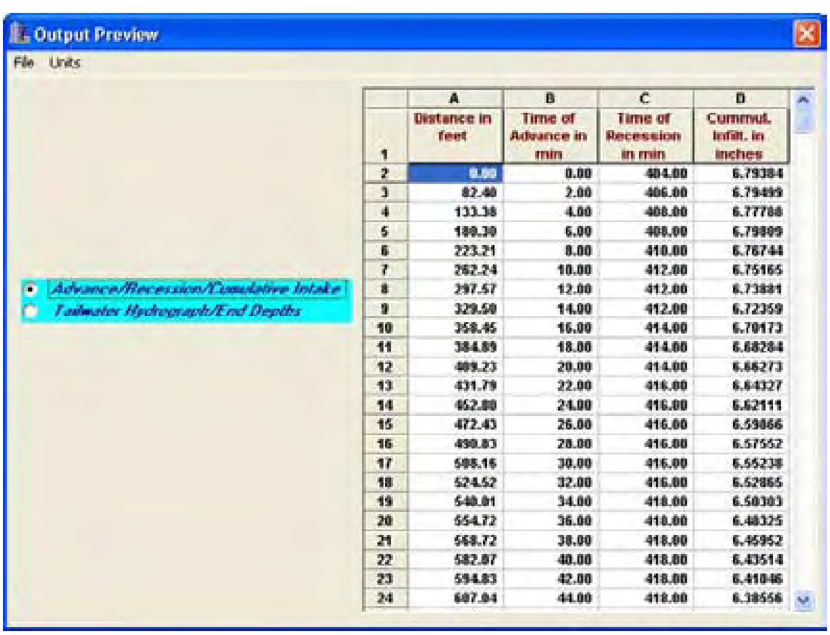
Providing input data to the **Surface** software involves two activities: defining the characteristics of the surface irrigation system and defining the model operational control parameters.

The input tabbed notebook (fig. 4–22) is accessed from either the **Input** menu command or the **speed** button. The tabs are from left to right:

- Inflow Controls
- Field Topography/Geometry
- Infiltration Characteristics
- Hydrograph Inputs
- Design Panel

Input data for the first three panels are required for all applications of the **Surface** software. The fourth, Hydrograph Inputs is an optional feature to allow field data inputs to the simulation programming. The Design Panel is only for interactive design functions and is discussed separately.

Figure 4–23 **Surface** tabular output screen



	A	B	C	D
1	Distance in feet	Time of Advance in min	Time of Recession in min	Cummul. Infilt. in inches
2	0.00	0.00	404.00	6.79384
3	82.40	2.00	406.00	6.79499
4	133.38	4.00	408.00	6.77788
5	180.30	6.00	408.00	6.79809
6	223.21	8.00	410.00	6.76744
7	262.24	10.00	412.00	6.75165
8	297.57	12.00	412.00	6.73881
9	329.50	14.00	412.00	6.72359
10	358.45	16.00	414.00	6.70173
11	384.89	18.00	414.00	6.68284
12	409.23	20.00	414.00	6.66273
13	431.79	22.00	416.00	6.64327
14	452.80	24.00	416.00	6.62111
15	472.43	26.00	416.00	6.59866
16	490.83	28.00	416.00	6.57552
17	508.16	30.00	416.00	6.55238
18	524.52	32.00	416.00	6.52865
19	540.01	34.00	418.00	6.50303
20	554.72	36.00	418.00	6.48325
21	568.72	38.00	418.00	6.45952
22	582.07	40.00	418.00	6.43514
23	594.83	42.00	418.00	6.41046
24	607.04	44.00	418.00	6.38556

(1) Entering field characteristics

The first data the user may wish to define are those associated with the field topography and geometry (fig. 4–24).

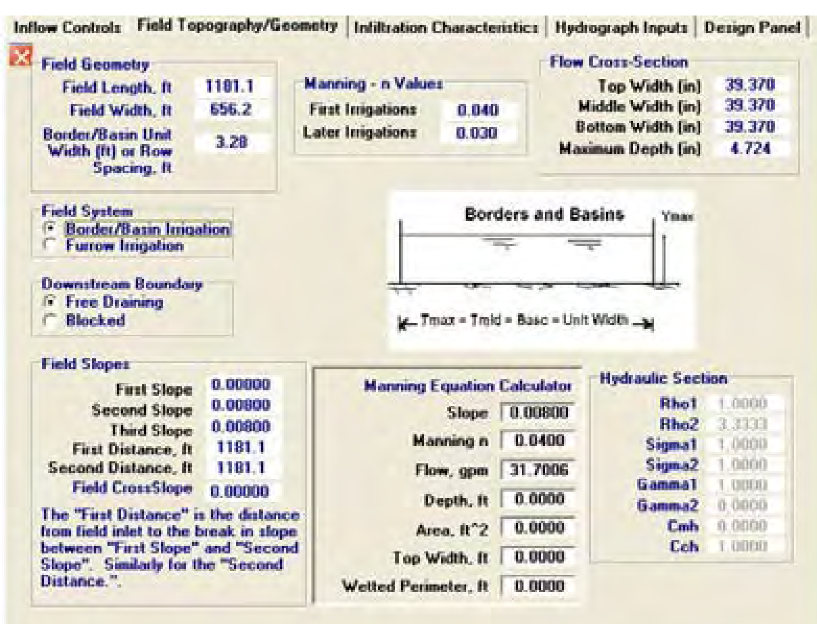
The geometry and topography of the surface irrigated field is described by inputting the following parameters:

- Field Length and Width
- Field CrossSlope
- Field System—Border/Basin or Furrow Irrigation (Furrow spacing refers to the spacing between adjacent irrigated furrows. When alternate furrows are irrigated, an unused furrow lies between the irrigated furrows and is not considered in the definition of furrow spacing.)
- Downstream Boundary—Free Draining or Blocked
- Manning roughness - *n* Values—First and Later Irrigations
- Field Slopes—Three slope values in the direction of flow
- Two distance parameters associated with the three slopes
- Four measurements of flow cross section

Basic field geometry—The basic geometry of the field includes its length or the distance water will run its width and cross-slope, the type of surface irrigation system, a unit width or furrow spacing, and the nature of the downstream field boundary. The field's cross slope is not used in the software, but is needed to design the headland pipes or ditches used to irrigate the field. These parameters are constant within each field and may not represent the entire area being irrigated.

The simulation program evaluates the hydraulics of the irrigation over a unit width. Typically, the unit width for border and basin simulation is 1 foot, but can be other dimensions if desired. Whatever value that is selected must be consistent with the simulated unit flow. In other words, if the unit width is 2.5 feet, the simulated unit flow must be the discharge onto the border or basin that flows within this width.

Figure 4–24 Field characteristics panel of the input tabbed notebook



If the system is configured for furrows, the simulation evaluates the flow in a single average furrow.

Manning *n*—One of the most important considerations in surface irrigation evaluation and design is the changes that occur on the field surface as it is irrigated. Newly tilled soil is usually hydraulically rougher than soil surfaces that have been smoothed by the flow of water during irrigation. On the other hand, surfaces such as borders and basins may become hydraulically rougher as crop density and size increase.

The **Surface** software includes the feature necessary to examine two field conditions which are noted as first irrigation and later irrigation conditions. To perform the various simulations, the software requires input of two estimates of the Manning *n* coefficient for these two conditions.

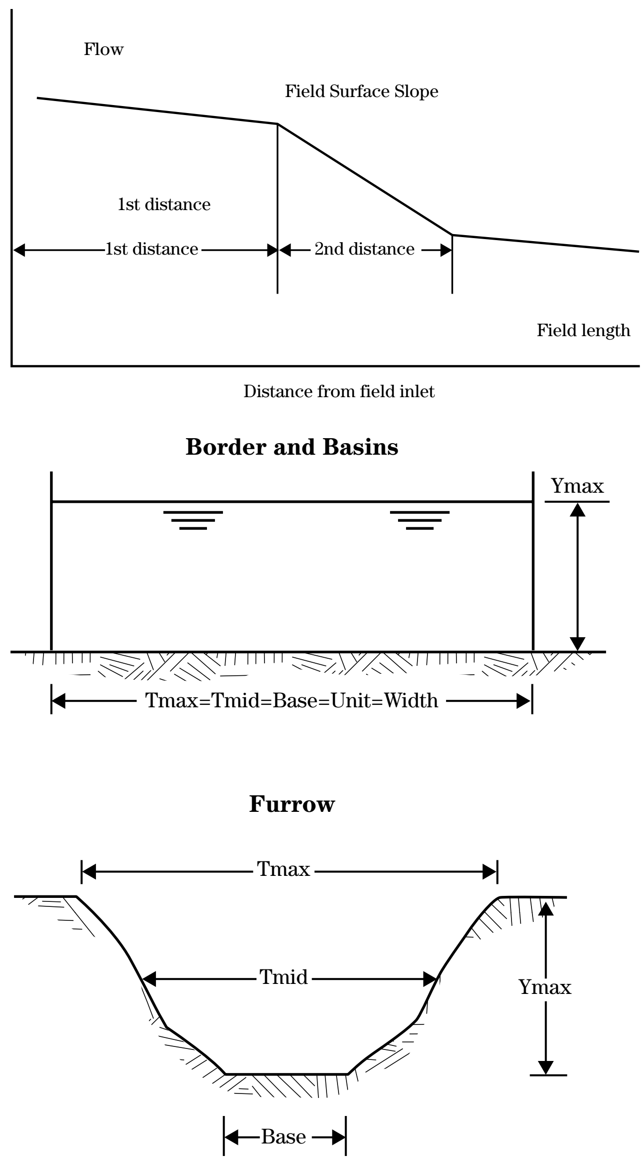
Freshly constructed furrows typically have *n* values of about 0.03 to 0.05, depending on the soil aggregation. Previously irrigated furrows without crops growing in the furrow itself will have substantially lower *n* values. Measurements have been reported where these *n* values have been as low as 0.015. In the absence of more detailed information, it is probably sufficient to use an *n* value of 0.04 for first irrigations and 0.02 for later irrigations, but the user has an opportunity to apply judgment where necessary.

The Manning *n* values for borders and basins vary over a much wider range than they do for furrows, primarily because they are affected by the crop and the geometry of its crown. A freshly tilled and prepared border or basin with a bare soil surface probably has an *n* value about the same as for furrows, 0.03 to 0.05. After initial irrigations and before substantial crop growth, the *n* value may be as low as 0.15 to 0.20, but later as the water is impeded by the crop, the ***n*** values can be as high as 0.80 for a crop like an alfalfa-grass mix. The **Surface** software can be used in conjunction with field measurements of advance and recession to estimate the *n* values, and this will be described later.

Field slope—The **Surface** software is capable of simulating fields with a compound slope (fig. 4–25). Up to three slopes can be located in the field by two distance values. When the field has only one slope, the same value needs to be entered for all three slopes and both distance values should be set to the field length.

A field with two slopes can be defined by setting the second and thirds slopes to the same value and the second distance to be the difference between the field length and the first distance.

Figure 4–25 Illustration of multiple sloped surface irrigated field



Flow cross section—The flow cross section is defined and computed with four parameters: top width, middle width, base, and maximum depth. As these are entered, eight parameters labeled *Rho1*, *Rho2*, *Sigma1*, *Sigma2*, *Gamma1*, *Gamma2*, *Cch*, and *Cmh* are automatically computed. It is important that the four dimensions required in the input screen are those that are associated with the unit discharge for border and basins or per furrow for those systems. If the field system selected is a border or basin, the values of top width, middle width, and bottom width are the same and equal to the unit width.

The values of *Rho1* (ρ_1), *Rho2* (ρ_2), *Sigma1* (σ_1), *Sigma2* (σ_2), *Gamma1* (γ_1), *Gamma2* (γ_2), *Cch*, and *Cmh* are based on the following relationships:

$$WP = \gamma_1 y^{\gamma_2} \tag{4–1}$$

$$A = \sigma_1 y^{\sigma_2} \tag{4–2}$$

$$A^2 R^{\frac{4}{3}} = \rho_1 A^{\rho_2} \tag{4–3}$$

$$\rho_2 = \frac{10}{3} - \frac{4\gamma_2}{3\sigma_2} \tag{4–4}$$

$$\rho_1 = \frac{\sigma_1^{\frac{10}{3}-\rho_2}}{\gamma_1^{\frac{4}{3}}} \tag{4–5}$$

$$T = (Cch)\, y^{Cmh} \tag{4–6}$$

The parameters *WP*, *A*, *y*, *R*, and *T* are the flow cross-sectional wetted perimeter, cross-sectional area, depth, hydraulic radius, and surface top width, respectively. For borders and basins in which the unit width is b feet, the values of the respective parameters are: γ_1=b; γ_2=0; σ_1=b; σ_2=1; ρ_1=b^2; ρ_2=10/3, *Cch* =b; and *Cmh*=0. For furrows, these parameters take on many values and need to be computed from the cross-sectional measurements of T_{max}, T_{mid}, *Base*, and Y_{max}. The **Surface** program does this by numerically integrating the furrow shape. The values of *Cch*, γ_1, σ_1, and ρ_1 also depend on the units used. The **Surface** software only displays the metric values even when the English units are used for input.

On the lower center of the Field Topography/Geometry notebook is a Manning flow calculator (fig. 4–24). Once the basic shape has been defined by the unit width for borders or T_{max}, T_{mid}, Base, and Y_{max} for furrows, the user can enter a slope, a Manning *n*, and a flow. The Manning calculator will then compute the depth of flow, the cross-sectional area, depth and wetted perimeter. The user can also enter the slope and Manning *n* along with any one of the other variables such as area, and the remaining others will be determined. The Manning calculator will assist the user in evaluating border and dike heights, checking whether the furrow has overflowed due to the flow or blocked end, or to determine what the maximum flow could be without breaching the border dikes or furrow perimeters.

The Manning calculator can also be used to approximate the conditions in open channel field ditches. Note that the procedures were written for irregular shapes like typical furrows and are only approximate for the regular trapezoidal shapes. To use the calculator or field ditch evaluation and design, set the Field System to furrows by checking the appropriate box. Then enter the channel shape in the Flow Cross Section boxes. Finally, move the cursor to the Manning calculator and enter the respective parameters.

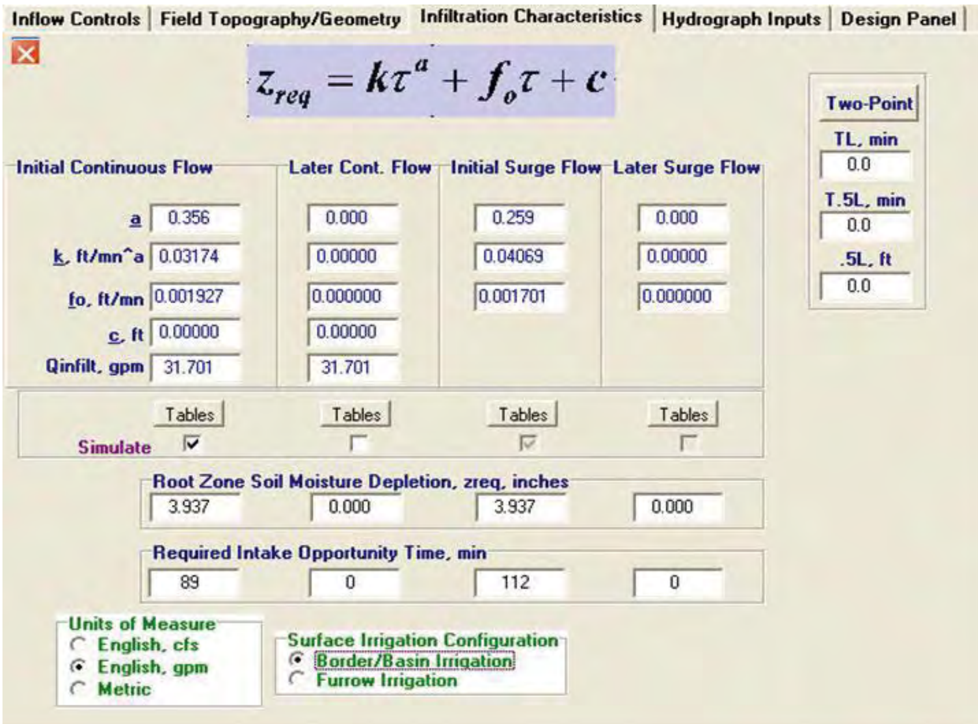
(2) Infiltration characteristics

Figure 4–26 shows the tabbed notebook where infiltration functions are defined. These data comprise the most critical component of the **Surface** software. Four individual infiltration functions can be defined as a function for:

- first conditions under continuous flow
- later irrigations under continuous flow
- first irrigations under surge flow
- later irrigations under surge flow

The user is referred to section 650.0300 for a detailed description of how these parameters are defined and measured, but they are important enough to be given further attention here. Note that the model does not allow a cracking term for surge flow since it is assumed the cracks will close during the first surge on the dry soil portion of the field.

Figure 4–26 Infiltration characteristics panel of the input tabbed notebook



Just below the four intake parameters are two boxes labeled Q_{infilt}, gpm which are used to enter the flow at which the intake parameters are defined. Furrow intake parameters are always defined for a unique flow, whereas, border and basin parameters are not. The **Surface** software uses the values of Q_{infilt} to adjust furrow intake parameters for changes in flow. Note that Q_{infilt} boxes are not provided for the surge flow conditions as they must be the same as the respective continuous flow value. In other words, the Q_{infilt} value for the initial surge flow condition is assumed to be the same as that for the initial continuous flow condition.

It is not necessary to define infiltration for each of the four conditions. However, they must be defined for the cases the user wishes to simulate, evaluate, or design by having checked the boxes next to the Simulate label. Specifically, looking at the figure 4–26, if the user is interested in only simulating the initial continuous flow, then the values necessary are just in that column. If surge flow is to be evaluated, the intake coefficients are necessary in the first and third columns. By changing the check box selections, the user can simulate later irrigation conditions, as well. The surge flow check boxes are deactivated since it is necessary for the simulation of an initial surge flow or later surge flow condition that the associated continuous flow intake be used for the flow of water over the dry portion of the field.

The **Surface** software includes sets of values for a, k, f_o, and c (or a, K, F_o, and C) which are accessed by clicking on one of the buttons. The intake functions represented are based on the original USDA NRCS (formally SCS) intake families modified to be consistent with for the intake equations used in the **Surface** software (section 623.0405(b)(2)). Figure 4–27 shows one of these tables for a furrow system. A set of values can be selected by clicking on the associated radio button on the left of the table. The corresponding values then will be automatically entered in the boxes of figure 4–26. The c or C values are terms to adjust

Figure 4–27 NRCS reference intake family for initial continuous flow furrow irrigations

Continuous Flow Intake Curve Parameters for Initial Irrigations

ID	Soil Name	a	K (ft^3/ft/mn^a)	Fo (ft^3/ft/mn)	Qr (gpm)	Wpr (ft)
.02	Heavy Clay	0.1880	0.002420	0.0000786	7.41	0.365
.05	Clay	0.2488	0.004466	0.0001981	8.26	0.399
.10	Clay	0.3067	0.006823	0.0003369	9.65	0.452
.15	Light Clay	0.3517	0.008710	0.0004704	11.02	0.500
.20	Clay Loam	0.3878	0.010346	0.0005974	12.38	0.544
.25	Clay Loam	0.4175	0.011807	0.0007212	13.72	0.586
.30	Clay Loam	0.4427	0.013140	0.0008396	15.04	0.626
.35	Silty	0.4637	0.014396	0.0009548	16.35	0.663
.40	Silty	0.4814	0.015563	0.0010656	17.63	0.699
.45	Silty Loam	0.4970	0.016671	0.0011733	18.90	0.733
.50	Silty Loam	0.5124	0.017740	0.0012777	20.15	0.767
.60	Silty Loam	0.5359	0.019730	0.0014768	22.60	0.830
.70	Silty Loam	0.5550	0.021591	0.0016652	24.98	0.889
.80	Sandy Loam	0.5718	0.023352	0.0018417	27.28	0.945
.90	Sandy Loam	0.5854	0.025004	0.0020096	29.51	0.999
1.00	Sandy Loam	0.5978	0.026596	0.0021679	31.68	1.050
1.50	Sandy	0.6412	0.033670	0.0028384	41.42	1.282
2.00	Sandy	0.6712	0.039805	0.0033508	49.38	1.483
4.00	Sandy	0.7490	0.059571	0.0044606	63.40	2.131

for large field cracks and may be set to zero. The value of f_o and F_o are basic or long term intake rates and may be set to zero for short irrigation events that are typical for borders and basins but generally not so for furrows. The k or K and a parameters should always be defined.

The root zone soil moisture depletion, z_{req}, is entered in the input boxes below the **Tables** buttons (fig. 4–26). These values are always entered as the target depth of irrigation or the depth of the soil moisture deficit and can be converted to an equivalent volume per unit length:

$$Z_{req} = z_{req} w \tag{4–7}$$

where

w = the unit width in feet for borders and basin or the irrigated furrow spacing

For convenience, the values of root zone moisture depletion in these input are entered in units of inches and then are converted into units of feet for use in the infiltration equations where k, f_o, and c values have units of feet, ft/min^a, and feet respectively for borders and ft^3/ft/min^a, ft^3/ft/min, and ft^3/ft for K, F_o, and C in furrow infiltration.

Below the input boxes for the root zone depletion are the associated required intake opportunity time to achieve infiltration equal to the root zone deficit. For example, a 4-inch deficit will require 204 minutes of infiltration. These input boxes are updated whenever values of the intake coefficients or z_{req} are input. Values of intake opportunity time can also be input directly, and the values of z_{req} will be adjusted automatically.

At the bottom of the screen are four buttons to switch between English and metric units and between furrow and border/basin configurations. This feature is provided in the software to allow the user to compare the furrow and border/basin intake parameters for various unit widths, furrow geometries, and flow rates. The simulations can be run from this point if the user wishes to compare furrow and border irrigation performance if the field has a slope or level furrows and basin irrigation if the field is level.

Finally, at the right of the intake parameters are three input boxes and a button labeled Two-Point. The software uses what is called the two-point volume balance procedure to estimate the a and k or K intake parameters. A more detailed explanation of this procedure will be provided in section 623.0403(c)(2). Usually, field measurements of advance time to the field midpoint and end are made to adjust intake parameters, thus, this tool is part of the software's evaluation capability.

(3) Inflow controls

The **Surface** programming is controlled by the model control parameters as shown in figure 4–28. User input is required for three options:

- Simulation Shutoff Control
- Inflow Regime Control
- Run Parameters

Simulation Shutoff Control—The basic cutoff or shutoff for surface irrigation system occurs when the inflow to the furrow, border, or basin is terminated at the field inlet. Unlike drip or sprinkle systems in which this represents the end of the water applications, surface irrigation systems have a continuing or recession phase that can, depending on the type of system and its configuration, involve a significant application of water to parts of the field. The termination of field inflow for the purposes of software execution is defined by two check boxes and an input box, Time of Cutoff. Under the heading Simulation Shutoff Control, the user must select either to terminate inflow at a specific time, by elapsed time or number of surges, or when the downstream end of the field has received a depth of water approximately equal to z_{req}, by target application.

As a numerical safety measure, the Time of Cutoff will always terminate the simulated inflow even when the box By Target Application, z_{req} is checked. Thus, to let inflow control to be managed by z_{req}, the cutoff time must be entered as a large value. Likewise, the number of surges specified for surged systems dominates the applied depth control and should be set to a large number. If z_{req} controls the shutoff time, the control value is the same as z_{req} specified in the Infiltration Characteristics panel. The simulation portions of the models also require a time step which is designated as Dtm. The software always computes a default value that can be overridden with an input value, particularly if the software is encountering convergence or stability problems in the numerical procedure. As a rule, instability can be remedied by reducing the value of the time step.

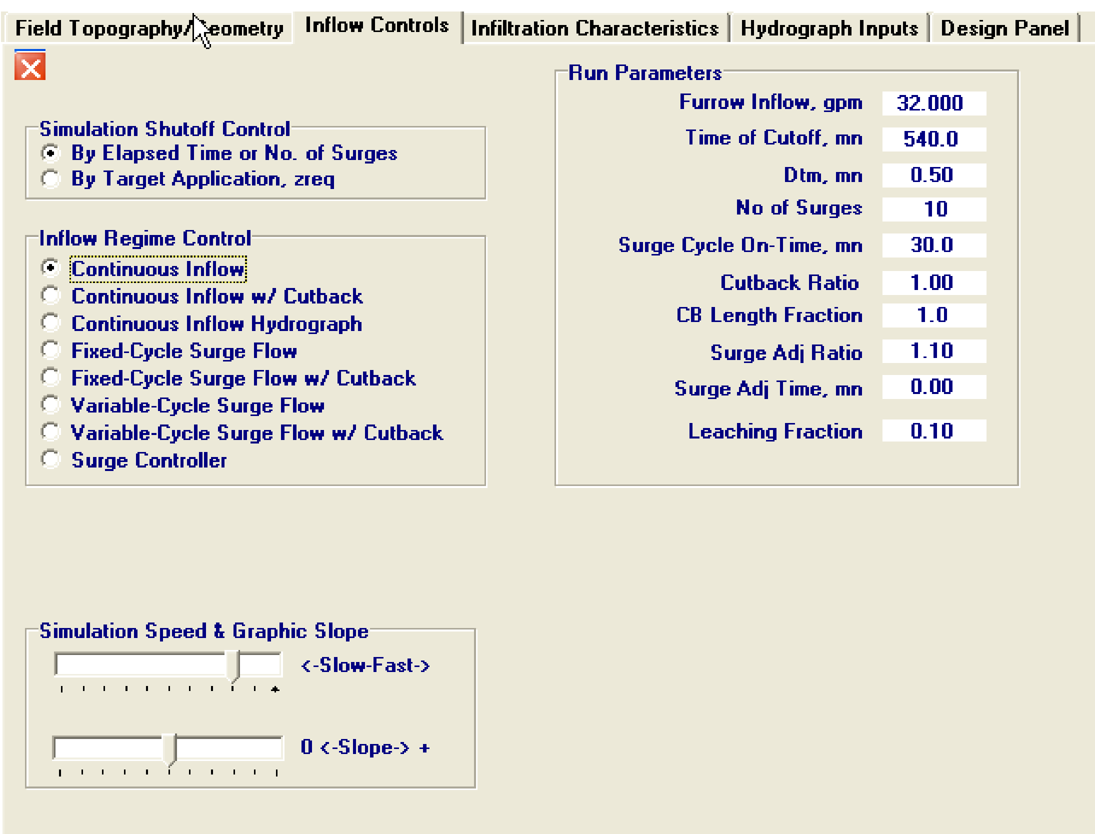
The discharge that the program will use in the simulation is specified by the user's entry into the **Simulated Unit Inflow** box.

Inflow regime—The **Surface** software will simulate both continuous and surge flow irrigation. There are three continuous and four surge flow regimes as shown in figure 4–28. The user may select one regime at a time by clicking on the respective check box.

Generally, surface irrigation systems are designed with a fixed inflow during the advance phase. This value is specified in the **Simulated Unit Inflow** box. Note that this flow is the discharge into each furrow or into each unit width of border or basin. Occasionally, during efforts to evaluate surface irrigation systems, an inflow hydrograph is measured, and the user would like to evaluate the effect of inflow variations. This option requires the **Continuous Inflow Hydrograph** check box to be selected and an input hydrograph specified in the Hydrograph Inputs panel in the tabbed notebook.

Under a surge flow regime, there are two cycle options. The first is a fixed cycle on-time surge flow system, and the second is a variable on-cycle time option. It is assumed that the off-time equals the on-time, thus, the actual cycle time is double the on-time. In other words, the cycle ratio, on-time divided by cycle time is always 0.50.

Figure 4–28 Inflow controls panel of the input tabbed notebook



Surface offers two ways to vary the surge to surge cycle on-time. The first is by multiplying the first surge on-time by a user-specified fraction (**Surge Adj. Ratio** edit box). For example, if the first surge on-time is 30 minutes, and it is desirable to expand the surges by 10 percent each cycle, then the Surge Adj. Ratio can be set to 1.1. The second way of varying the surge cycle time is by adding a fixed amount of time to each surge on-time via the Surge Adj. Time parameter. If one begins with a 60-minute cycle and wishes to expand it by 10 minutes each surge, then the Surge Adj. Time parameter is set to 10. In both cases of variable cycle surge flow, the cycle times can be compressed by specifying a value less than 1.0 for Surge Adj. Ratio or a negative number for Surge Adj. Time. The user should be careful with this input.

The concepts of continuous and surge flow are fairly standard surface irrigation terms. Cutback is a concept of having a high initial flow to complete the advance phase and a reduced flow thereafter. Both continuous and surged systems can operate with a cutback regime. If a cutback regime is selected, two additional parameters are required. The first is the definition of the Cutback Ratio, and the second is the definition of CB Length Fraction. A cutback ratio of 0.80 results in a reduction of inflow to 80 percent of the initial flow. A cutback length fraction of 0.8 initiates the cutback flow when the advance has completed 80 percent of the field length. Likewise, a cutback length fraction of 1.2 results in the cutback when the software estimates the advance would have exceeded the field length by 20 percent. In surge flow simulation, the CB Length Fraction should always be set to a value greater than 1.0.

There is one note of caution. If the advance phase has been completed and the cutback is sufficient to dewater the end of the field, the simulations will often fail. These are situations where the cutback causes a front-end recession prior to inflow shut off. In some cases, the simulations will compute the front-end recession and subsequent advance without problems, but the numerical failures are common enough that the software has been programmed to discontinue simulation for all case of front-end recession during cutback.

Leaching fraction—Although the software does not simulate or evaluate water quality parameters like salinity, the definition of irrigation efficiency includes a leaching fraction term. A more detailed discussion of efficiency is given in section 623.0402.

Simulation speed and graphical presentation— Modern computers will execute the most intensive of the **Surface** programming too fast for a clear run-time graphical presentation. To adjust computational speed, the software has built-in delays that can be adjusted by moving the Simulation Speed track bar to the right (faster) or left (slower).

The lower track bar will adjust the plotting slope of the run-time surface and subsurface profiles. This feature has been included solely for presentation purposes and has no computational or physical ramifications.

(4) Hydrograph inputs

Three of the important uses of software such as **Surface** are to:

- evaluate the operation of existing surface irrigation systems
- simulate the design of a surface irrigation system
- compare the simulated and measured conditions

The Hydrograph Inputs panel of the input tabbed notebook is included to provide a convenient way to input three important field measurements that might be useful in the three main uses of the software. These three field measurements are:

- an inflow hydrograph
- a tailwater or runoff hydrograph
- advance and recession trajectories

On the panel are three mini-spreadsheets (fig. 4–29). Data in these spreadsheets can be input from or output to Microsoft® Excel spreadsheets with simple drag and drop or copy and paste operations.

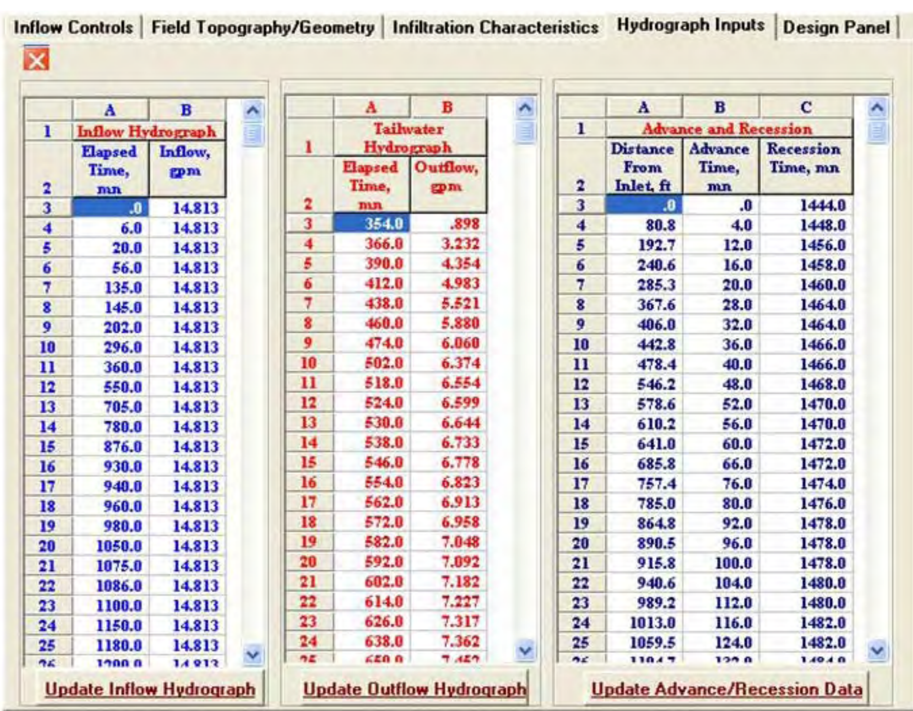
The first mini-spreadsheet describes the inflow hydrograph. These data can be measured in the field or simply input by the user to test a flow change behavior of the system. The hydrograph is defined by elapsed time (the time since the beginning of irrigation) and the discharge into a furrow or border/basin unit width. It is not necessary to develop and input these data on equal time steps since the software includes interpolation algorithms to match computational points with the input points.

The second hydrograph is for any surface runoff of tailwater that might be recorded or estimated. It is not necessary to have a tailwater hydrograph if, for example, the end of the field is blocked.

Finally, a mini-spreadsheet is available to record advance and recession trajectories. In this case, the data do not represent a hydrograph and may have points on the two trajectories where data are not available. If data are not available for both trajectories or at certain points, the user should enter a –1 as shown. The software will ignore the negative values and use what data points are available to plot the trajectories.

Below the spreadsheets are three buttons labeled Update Inflow Hydrograph. Clicking on each of these buttons is necessary to record the data in the software arrays for use and storage later. Any input data not updated with these buttons will not be available to the computational algorithms of the software nor for later storage in files. However, once updated, the hydrographs and trajectories are stored in the .cfg file and will reappear upon opening such a file. It is not necessary to update these data once recorded unless changes are made. And, it should be noted that any updated data in these spreadsheets will be plotted in the graphic output screens discussed below whenever the **Continuous Inflow Hydrograph** check box is checked.

Figure 4–29 Hydrograph input panel of the input tabbed notebook



(5) Design panel

The interactive design capabilities of the **Surface** software will be discussed in a separate section below. It has been included with the input tabbed notebook to facilitate data entry and change during the interactive design process.

(e) Output

The **Surface** software includes both tabular and graphical display output capabilities. Output is accessed from the main screen by selecting **Output** and then choosing either **Display Output Results** or **Plotted Results** from the drop-down menu. Printed output can be accessed directly by clicking once on the print icon, and likewise, plotted output can be directly accessed by the plot icon.

If the user would like a printout of the software's basic input data, then the Print Input Data option can be selected.

(1) Printed output

Figure 4–23 showed the surface tabular output screen. Selecting the **File** option from the main command bar provides various print and save options. Data can be saved in a comma delimited text file, but the mini-spreadsheets on the form are also Microsoft® Excel compatible so the user can also drag and drop or copy and paste the data from the screen directly. Tabular output can be either printed or previewed. Each selection of the print or save options allows the user to choose one of two sets of data: the advance/recession/infiltration profiles and/or the runoff hydrographs.

A Units option on the main command bar is available to change the units of previewed or printed data.

(2) Plotted output

Choosing plotted output reveals the plotting screen. The screen command bar has two drop-down menus accessed by selecting **Files** or *Current Data Plot Options*. The **Files** options are either to open an existing output file or to save the current output to a file, either of which leads to standard file open/save dialog boxes.

The Current Data Plot options selection provides plots of advance and recession, a runoff or tailwater hydrograph, depth of water at the end of the field, and the distribution of applied depths over the field.

Figure 4–30 shows a typical plot of the advance recession data, as well as data from recorded field measurements. Figure 4–31 shows a typical tailwater hydrograph and figure 4–32 shows the plot of infiltrated water.

(f) Simulation

Once the input and control data have been entered, the simulation is executed by clicking on the calculator button or the simulate menu. The simulation screen will appear, and the run-time plot of the advance and recession profiles will be shown (fig. 4–33).

Three important regions are in the simulation screen. The first occupies the upper two-thirds of the screen and plots the surface and subsurface movements of water as the advance and recession trajectories are computed. The target or required depth of application is plotted as z_{req}, so that when an infiltrated depth exceeds this value the user can see the loss of irrigation water to deep percolation (The subsurface profile color changes as the depth exceeds $\boldsymbol{z_{req}}$).

In the lower right side of the screen, a summary of the simulated irrigation event will be published after the completion of recession. The uniformity and efficiency terms are defined later in section 623.0402. The bottom four edit windows give a mass balance of the simulation, including an error term describing the computed differences between inflow, infiltration, and runoff (if the field is not diked). As a rule, an error less than 5 percent is acceptable, most simulations will have errors of about 1 percent.

In the lower left side of the screen, a runoff hydrograph will be plotted for the cases where the downstream end of the field is not diked.

Note that neither the advance recession nor the runoff hydrograph is intended to be quantitative, as no units are included in the plot. These details are presented in the plotted and printed output from the model.

Figure 4–30 Typical advance/recession plot from the **Surface** graphics output

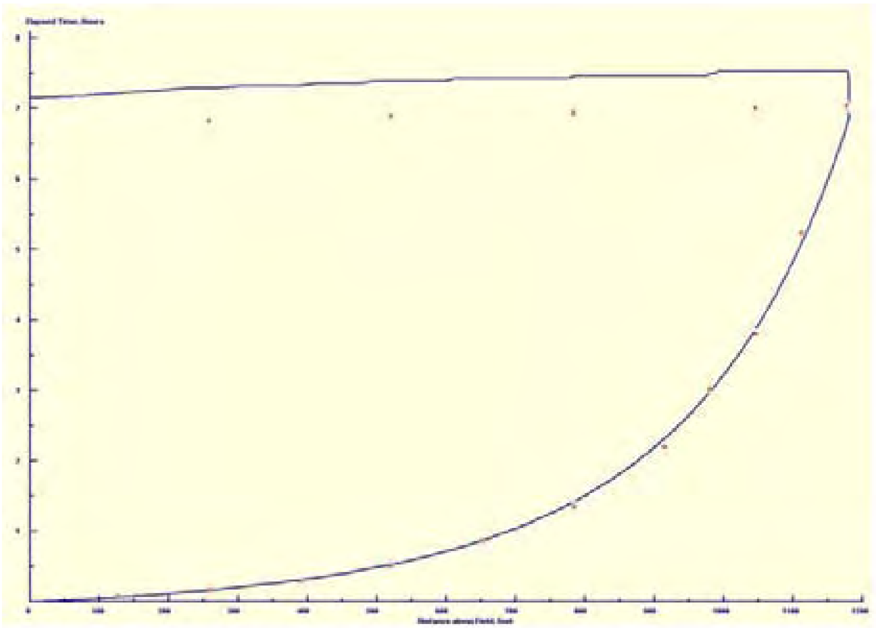


Figure 4–31 Typical runoff hydrograph from the **Surface** graphic output

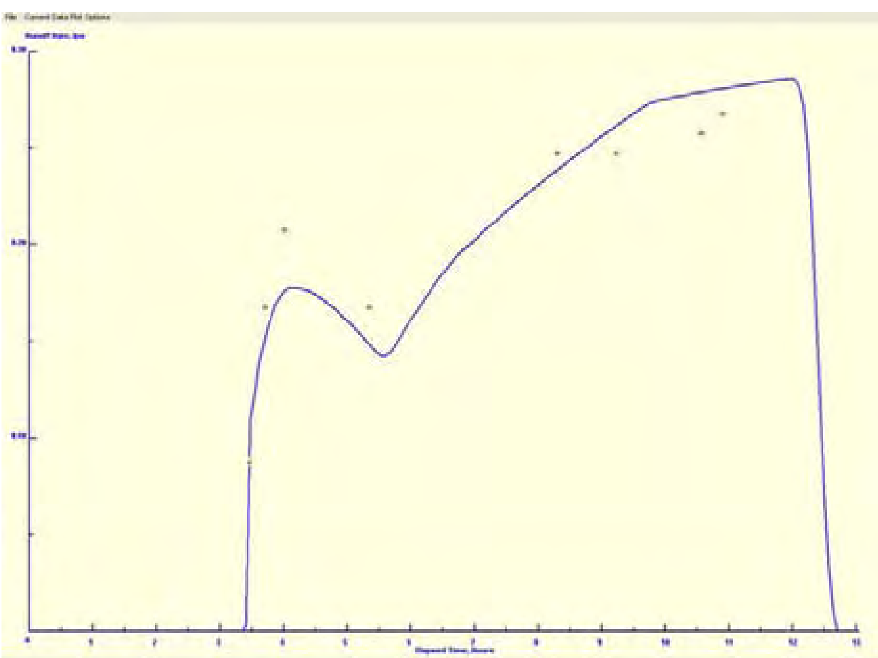


Figure 4–32 Typical plot of intake distribution for the **Surface** graphics output

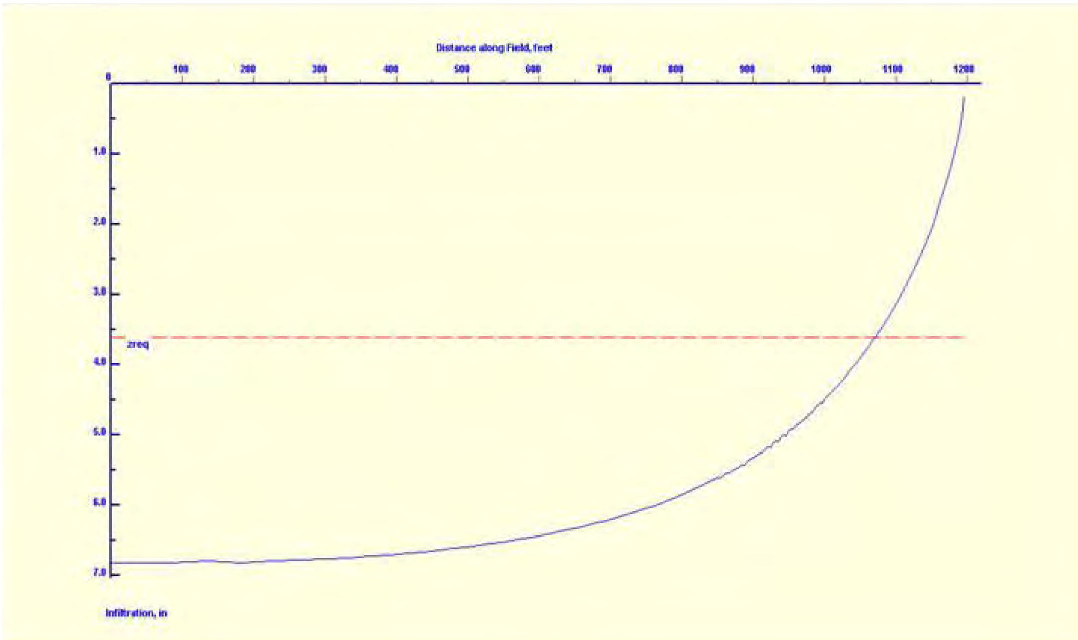
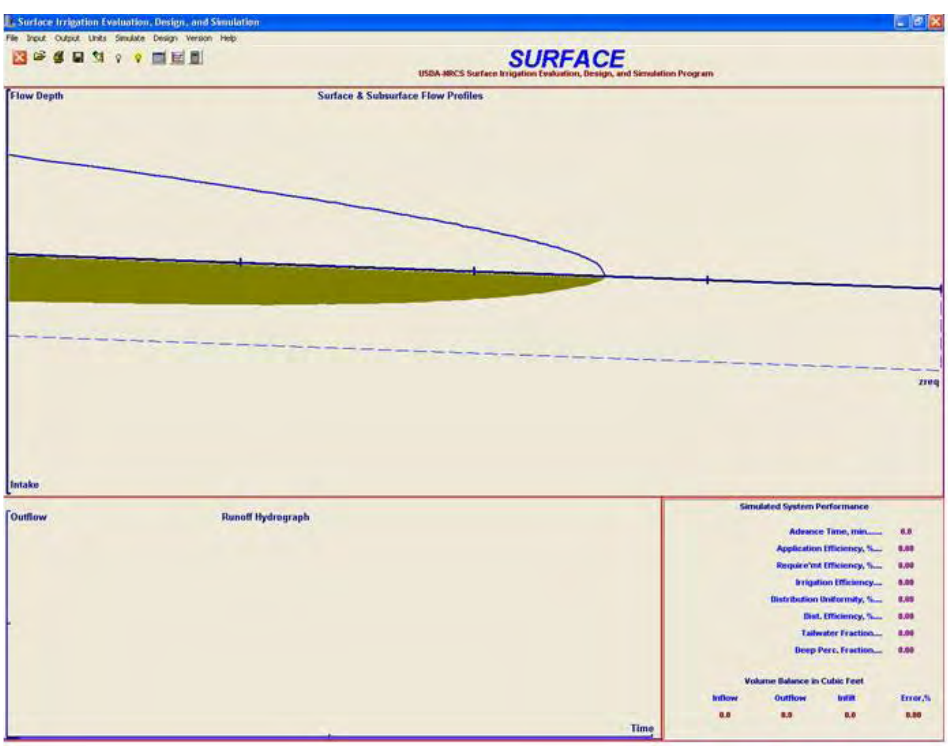


Figure 4–33 Main simulation screen



(g) Design

The **Surface** software includes an interactive field design program located within the input data tabbed notebook. This panel is shown in figure 4–34.

(1) Input data for design

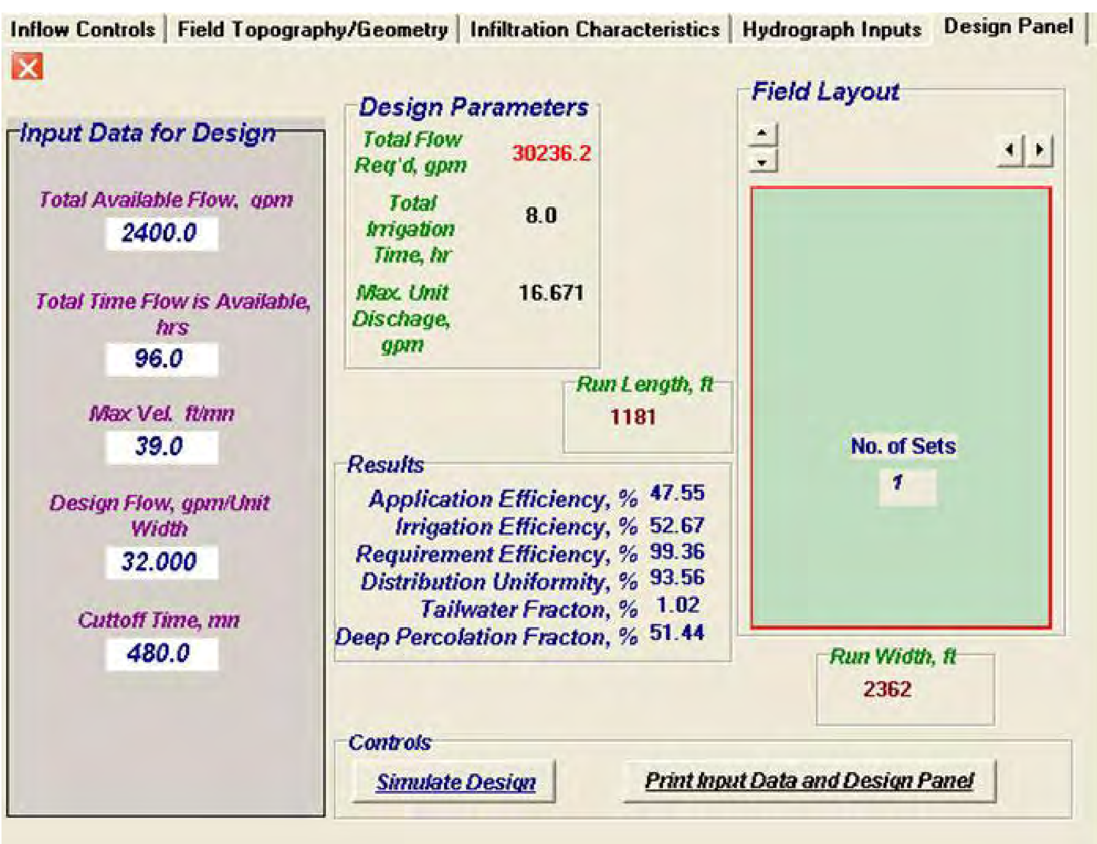
Although the interactive design process does not require all of the data needed for the respective input tables, it is prudent to enter all of the information for the input tabbed notebook table: Inflow Controls, Field Topography/Geometry, and Infiltration Characteristics. The hydrograph inputs are not required because designs are based on a fixed inflow rate. There are then five special inputs for the design process:

- total available flow
- total time flow is available
- maximum non-erosive flow velocity
- design flow per unit width
- design cutoff time

The design flow per unit width and the cutoff time may be different than the simulated unit inflow and the time of cutoff entered into the inflow controls table. If the **Calculator** button is selected on the main window command bar, the simulation will be different than if the **Simulate Design** button in the design panel is selected. The flow, time of cutoff, and run length can be different.

Total available flow—The field water supply is defined by its discharge, duration, and frequency of availability. For design purposes, the total available flow entry on the design panel should be the maximum available to the field. This should be a relatively reliable maximum since the field configuration will depend on this flow for efficient operations.

Figure 4–34 **Surface** design panel



In many cases of surface irrigation, the available flow from the delivery system will not efficiently irrigate the entire field at one time, or with one set. The field must be partitioned into sets which are irrigated sequentially. The number of sets depends on the total available flow as follows:

$$N_s = \frac{Q_o W_f}{Q_T w} \frac{L}{R_L} \tag{4–8}$$

where:

N_s = number of sets required to irrigate the field
W_f = width of the field
w = unit width in the same units as W_f
Q_T = total available flow
Q_o = design flow in the same units as Q_T
L = length of the field
R_L = run length in the same units as L

As an example, suppose the field is 2,361 feet in width and should be irrigated by furrows spaced at 3-foot intervals and with a unit flow of 24 gpm. The field is 1,180 feet long, but will be subdivided into 590-foot long furrows. If the available flow to the field is 2,376 gpm, the number of sets will be:

$$N_s = \frac{24 \text{ gpm} \times 2{,}361 \text{ ft}}{2{,}376 \text{ gpm} \times 3 \text{ ft}} \frac{1{,}180 \text{ ft}}{590 \text{ ft}} = 16 \tag{4–9}$$

Total time flow is available—Depending upon the policies of the delivery system, there may be a limit on the time the flow will be made available to the field. For instance, many systems operate on a rotational delivery scheme where the field can receive water every 7 to 21 days for a fixed number of hours. Suppose the set time or the time required by each set to completely irrigate it is 4 hours or 240 minutes. The time needed to irrigate the entire field is:

$$T_T = N_s \times t_{co} = 16 \text{ sets} \times 4 \text{ hrs/set} = 64 \text{ hrs} \tag{4–10}$$

where:

T_T = total required time
t_{co} = cutoff time for each set

The required total time to irrigate the field has to be less than the actual total time the flow is available, or else, the field must be irrigated at different times.

Maximum velocity—To prevent erosion, the designer will need to place an upper limit on flow velocity over the field. This limit may be as low as 30 ft/min for erosive soils to as high as 75 ft/min if the soil is quite stable. The actual velocity over the field will be highest at the field inlet and will depend on the unit discharge, field slope, and field roughness.

Generally, erosive velocity is more of a concern in furrow irrigation than in border irrigation. It is generally not a concern in basin irrigation except near the delivery outlets. Typical values of maximum velocity for furrow systems are shown in the following table.

Soil type	Suggested maximum non-erosive velocity (ft/min)
Fine sands	30
Sandy loams	36
Silt loams	39
Clay Loams	49
Clay	75

Design flow—The performance of surface irrigation systems is highly dependent on the unit discharge, thus, this parameter may be the most important management parameter either the designer or irrigator considers. Unit flows that are too small advance slowly and can result in poor uniformity and efficiency, as well as excessive deep percolation. Flows that are too high may result in low efficiencies due to excessive tailwater or downstream ponding; although, the uniformities will typically be high.

In an interactive design process, the designer searches for a design flow that maximizes efficiency subject to a lower limit on adequacy. For example, one may wish to find the flow that maximizes irrigation or application efficiency while ensuring that at least 95 percent of the field root zone deficit has been replaced by the irrigation.

Cutoff time—Shutting the flow off when irrigation is complete is one of the most important operational parameters in surface irrigation and one that is often most difficult to determine. Many irrigators choose convenient cutoff times, also called set times, to reduce irrigating time or move the delivery from set to set at easily scheduled times.

Designed cutoff times should be an integer fraction of a day and hourly. For instance, one could have 1, 2, 3, 4, 6, 8, and 12 hours set times in 1 day. Setting a cutoff time of 252 minutes is unworkable without automation. Under severe water supply constraints, many irrigators manage their water on intervals that are highly variable and often at intervals of much less than an hour.

(2) Field layout

On the right side of the design panel, the **Surface** software includes a field divider tool (fig. 4–33). Two up-down buttons are provided at the top of a rectangular representation of the field. Note the width and length scales are not equal so that very wide fields still assume the vertical rectangular shape.

By clicking on the vertical up-down button the field can be subdivided along its length axis. Likewise, by clicking on the horizontal up-down button, the field width can be subdivided. Each rectangular subdivision represents one set in the irrigation scheme. The easiest way to interactively design a surface irrigate field with the **Surface** software is to determine the most efficient unit discharge and then subdivide the field until the constraints on total available supply and total available time are satisfied.

In many situations, the fields that require redesign have irregular shapes. It may be necessary to partition the field into two or more separately managed units to achieve a square or rectangular layout. In other cases, it may be necessary to design for a single field dimension like the average run length or a set of average run lengths corresponding to the dimensions of the expected set layout. It is always good practice to evaluate the extreme conditions like the maximum and minimum run lengths to anticipate the management problems the irrigator will face.

(3) Simulation of design

The interactivity of the **Surface** design programming is accessed by clicking on the **Simulate Design** button at the bottom of the design panel. The run time advance, recession, tailwater hydrograph, and results will show on the main screen. The results will also be posted on the design panel. During the design simulation, the input tabbed notebook will be hidden until the simulation is completed. If the simulation is interrupted, the user will need to click on the button to make the tabbed notebook re-appear. Iteratively choosing the design flow, cutoff time, and if necessary, the run length will allow the user to develop designs that produce maximum efficiencies and uniformities.

(4) Results

Each design simulation produces an estimate of its performance with six indicators:

- Application efficiency—the percentage of the field delivery that was captured in the root zone of the crop
- Irrigation efficiency—an extension of application efficiency to include leaching water where a leaching fraction has been specified
- Requirement efficiency—the percentage of the root zone deficit that is replaced during the irrigation
- Distribution uniformity—the ratio of applied water in the least watered 25 percent of the field to the average over the entire field
- Tailwater fraction—the fraction of applied irrigation water that runs off as tailwater
- Deep percolation fraction—the fraction of applied water percolating below the root zone.

(5) Printed output

A printout of the principle input data and a graphical print of the design panel can be obtained by clicking the **Print Input Data and The Design Panel** button. The graphical printout of the design panel will be the same as illustrated in figure 4–34. When the print button is pressed, a screen pops up (fig. 4–35) that allows the user to input various project data that will be included on the printout.

(h) Sample data sets

(1) FreeDrainingFurrow_1.cfg

The FreeDrainingFurrow_1 data set describes a 64-acre, furrow-irrigated field supplied by a well with a capacity of 2,400 gpm. The furrows are irrigated on 30-inch spacings. The soil is a silt loam with an average 6-hour intake rate of 0.2585 $ft^3/ft/hr$ which, within the 2.5-ft furrow spacing, is 1.24 in/hr (curve no. 1.00–1.50). The target depth of application is 4 inches. The furrow stream is 32 gpm with a 9-hour cutoff time. The maximum non-erosive velocity of 39 ft/min was taken from the table shown earlier.

A simulation of these data reveals that substantial over irrigation occurs at the upper end of the field, and substantial under irrigation occurs at the downstream end. The application efficiency is about 42 percent, primarily because more than 55 percent of the inflow was lost in deep percolation. For a 4-inch irrigation, it would require only 160 minutes to infiltrate the desired depth. The 9-hour cutoff time allows a full irrigation at the downstream end of the field.

(2) FreeDrainingFurrow_2.cfg

The FreeDrainingFurrow_2 data describe a 113-acre field supplied by a canal. The typical canal flow that is available to the field is 10.0 ft^3/s. The field is currently irrigated by furrows on 30-inch spacings with a required depth of application of 3.5 inches. The soil is a clay loam with an average 6-hour intake rate of 0.052 $ft^3/ft/hr$ or 0.25 in/hr (curve no. 0.25) over the 2.5-foot spacing of the furrows. An inflow of 0.033 ft^3/s is being applied over a 24-hour set time. The maximum non-erosive velocity was assumed to be 49 ft/min.

The uniformity of this irrigation is excellent at nearly 97 percent, but the application efficiency is poor at only 52 percent primarily because nearly 40 percent of the applied water is lost as tailwater. There is about 7.5 percent deep percolation which is excessive given the leaching fraction of 5 percent.

(3) FreeDrainingBorder_3.cfg

This data set describes a 33-acre field supplied by a well with a capacity of 3,400 gpm. The soil is a clay but with an average 6-hour intake rate of 0.54 in/hr in part because of a cracking component.

Figure 4–35 ProjectDataForm for design printout

The field is currently irrigated as a free-draining border using 1,200-foot runs and a unit flow of 13.5 gpm/ft. The inflow is cutoff at 4 hours and before the end of the advance phase. The resulting application efficiency is 69 percent. The field requires a leaching requirement of 9 percent, but this irrigation configuration produces a 20 percent deep percolation. In addition, more than 11 percent of the inflow resulted in tailwater.

This field has a grass surface that is described by a Manning *n* value of 0.18 during both initial and later irrigations.

(4) FreeDrainingBorder_4.cfg
The FreeDrainingBorder_4 data describe a 24.7-acre field irrigated by canal water supply having a maximum flow rate of 6 ft^3/s and a maximum availability of 48 hours. The soil intake characteristics were selected on the basis of NRCS curve 0.50 which has an average 6-hour intake rate of 0.5 in/hr.

Based on the simulation of this field using the NRCS 0.50 intake curve and a unit flow of 0.036 $ft^3/s/ft$ applied for 4 hours, the application efficiency of this system would be about 39 percent due primarily to a loss of almost 44 percent of the inflow to tailwater. A 10 percent leaching requirement was more than satisfied with the nearly 17 percent of deep percolation.

(5) BlockedEndBorder.cfg
This data set describes a border irrigated field of 33 acres having 1,200 foot dimensions. It has a relatively steep slope of 0.00264, but also relatively rough surface indicated by a Manning *n* of 0.24 for initial and later irrigations due to a crop like alfalfa growing in the border.

The 6-hour intake rate for this soil is 0.55 in/hr. The target application depth is 3 inches, and with the intake coefficients given will require an intake opportunity time of about 312 minutes for initial irrigations and 441 minutes for later irrigations.

With a unit flow of 0.025 $ft^3/s/ft$, the field irrigates with an application efficiency of 66 percent. The 5 percent leaching fraction is exceeded by a deep percolation of about 33 percent.

(6) Basin_5.cfg
The Basin_5 data comes from a 19.7-acre field irrigated by a canal water supply limited to 5.3 ft^3/s over a 48-hour period. The soil has a 6-hour intake rate of 0.95 in/hr, which is typical of silt loam soil. The target depth of application is 4 inches.

A simulation of the data as given shows an application efficiency of about 57 percent due primarily to a deep percolation loss of about 43 percent. The flow barely completes the advance phase in the 7 hours of application, so there is also substantial under-irrigation near the downstream end of the basin.

(7) Basin_6.cfg
The Basin_6 data comes from a large 193-acre basin system with a clay soil (the average 6-hour intake rate is 0.47 in/hr). An irrigation district supplies water to the field with an upper limit on flow of 16 ft^3/s and availability of 96 hours per irrigation.

Under present operations, the application efficiency is about 63 percent. A 5 percent leaching requirement is exceeded by a deep percolation loss of more than 36 percent of the inflow.

(8) CutbackDesign.cfg
A furrow-irrigated field of about 21 acres is supplied by a well with a capacity of 1,200 gpm. Each furrow is initially irrigated with a flow of 14 gpm that is reduced to 8.4 gpm after the advance phase is completed. The total set time is 12 hours, and the resulting application efficiency is more than 79 percent. If the cutback is not initiated, the application efficiency would decrease to 51 percent as the tailwater losses increase from 21 percent to about 49 percent of the total inflows.

The soil of this field is a clay loam with an average 6-hour infiltration rate of 0.24 in/hr (curve no. 0.25) over the 2.5-foot spacing of the furrows. The target applied depth is 2.5 inches, which is not quite satisfied. There is also a 5 percent leaching to consider.

(9) FreeDrainingFurrow_1Surge.cfg
This is a surge flow data set for the data in 623.0401(g)(1).

623.0402 Surface Irrigation Evaluation

(a) Introduction

An evaluation of a surface irrigation system will identify various management practices and field layouts that can be implemented to improve the irrigation efficiency and/or uniformity. The evaluation may show, for example, that achieving better performance requires a reduction in the flow and duration of flow at the field inlet, or it may indicate that improvements require changes in the field size and topography. Perhaps a combination of several improvements will be necessary. Thus, the most important objective of the evaluation is to improve surface irrigation performance. The procedures for field evaluation of irrigation systems are found in the NRCS National Engineering Handbook Part 652, National Irrigation Guide, particularly chapter 9, Irrigation Water Management. This section does not repeat each of the various procedures applicable to surface irrigation but will supplement some of them in more detail or with more recent developments.

(b) Important surface irrigation concepts

(1) Soil moisture

As commonly defined, the available moisture for plant use is the soil water held in the soil matrix between a negative apparent pressure of one-tenth to one-third bar (field capacity) and a negative 15 bars (permanent wilting point). However, the soil moisture content within this pressure range will vary from 3 inches per foot for some silty loams to as low as 0.75 inches per foot for some sandy soils.

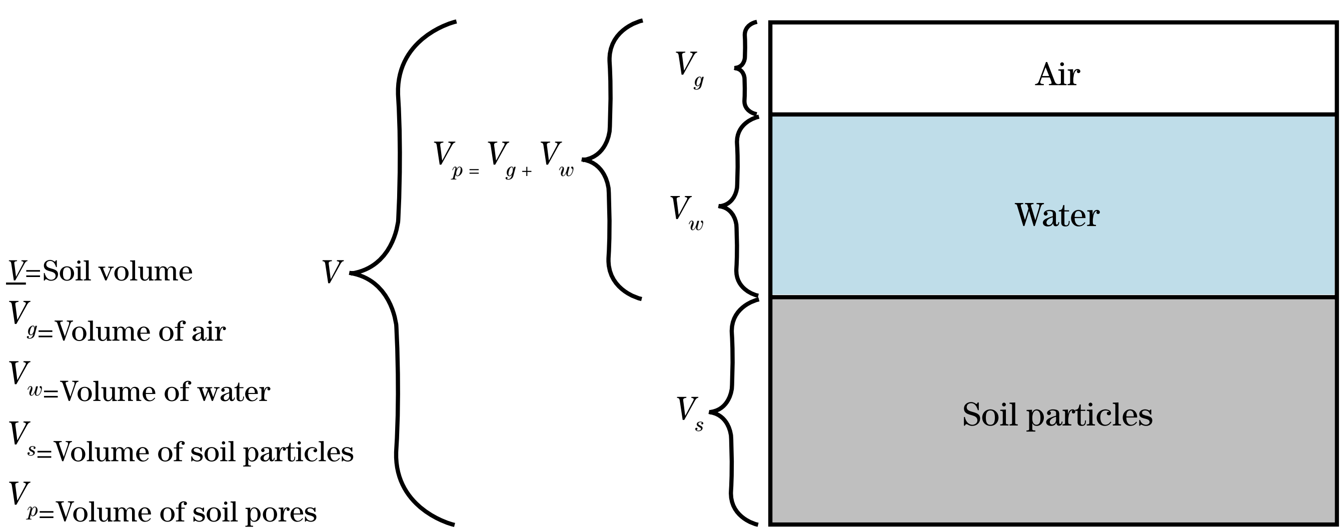
Consider the simplified unit volume of soil comprised of solids (soil particles), liquid (water), and gas (air) as shown in figure 4–36. The porosity, (ϕ), of the unit volume is:

$$\varphi = \frac{V_p}{\underline{V}} \qquad (4\text{–}11)$$

The volumetric water content, *θ*, is

$$\theta = \frac{V_w}{\underline{V}} \qquad (4\text{–}12)$$

Figure 4–36 Components of the soil-water matrix



The saturation, ***S***, which is the portion of the pore space filled with water, is

$$S = \frac{V_w}{V_p} \quad (4\text{–}13)$$

Porosity, saturation, and moisture content in a soil are related by the expression:

$$\theta = S\varphi \quad (4\text{–}14)$$

There are a number of ways to measure water in a soil. These include tensiometers, resistance blocks, wetting-front detectors, soil dielectric sensors, time domain reflectometry, frequency domain reflectometry, neutron moderation, and heat dissipation. However, one of the most common and simplest is the gravimetric method in which soil samples are extracted from the soil profile, oven-dried, and evaluated on the basis of the dry weight moisture fraction, *W*, of the soil sample:

$$W = \frac{\text{sample wet wt.} - \text{sample dry wt.}}{\text{sample dry wt.}} = \frac{W_w}{W_s} \quad (4\text{–}15)$$

The dry weight moisture fraction can be converted to volumetric water content as follows:

$$\theta = \gamma_b W \quad (4\text{–}16)$$

where γ_b is the bulk density or bulk specific weight of the dry soil. Also, γ_b is related to the specific weight of the soil particles, γ_s, by:

$$\gamma_b = \gamma_s(1-\varphi) \quad (4\text{–}17)$$

Field capacity, W_{fc}, is defined as the moisture fraction of the soil when rapid drainage has essentially ceased and any further drainage occurs at a very slow rate. For a soil that has just been fully irrigated, rapid drainage will generally cease approximately after 1 day for a light sandy soil and after approximately 3 days for a heavy soil. This corresponds to a soil moisture tension of 1/10 to 1/3 atm (bar).

The permanent wilting point, W_{pw}, is defined as the soil moisture fraction at which permanent wilting of the plant leaf has occurred and applying additional water will not relieve the wilted condition. This point is usually taken as the soil moisture content corresponding to a soil moisture tension of 15 bars.

The volumetric moisture contents at field capacity and permanent wilting point become:

$$\theta_{fc} = \gamma_b W_{fc} \quad (4\text{–}18)$$

$$\theta_{wp} = \gamma_b W_{wp} \quad (4\text{–}19)$$

The total available water, *TAW*, to the plants is approximately the difference in these volumetric moisture contents multiplied by the depth of the root zone, *RD*:

$$TAW = (\theta_{fc} - \theta_{wp})RD \quad (4\text{–}20)$$

Note that equation 4–20 is not technically exact because crop roots do not extract water uniformly from the soil profile.

Figures 4–37 and 4–38 illustrate the relation among field capacity, permanent wilting point, total available water, and soil type. Table 4–2 lists some common rooting depths for selected crops.

Figure 4–37 Components of soil water

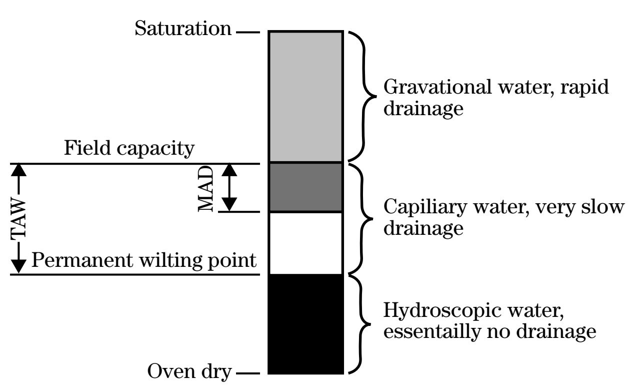


Figure 4–38 Variation of available soil moisture with soil type

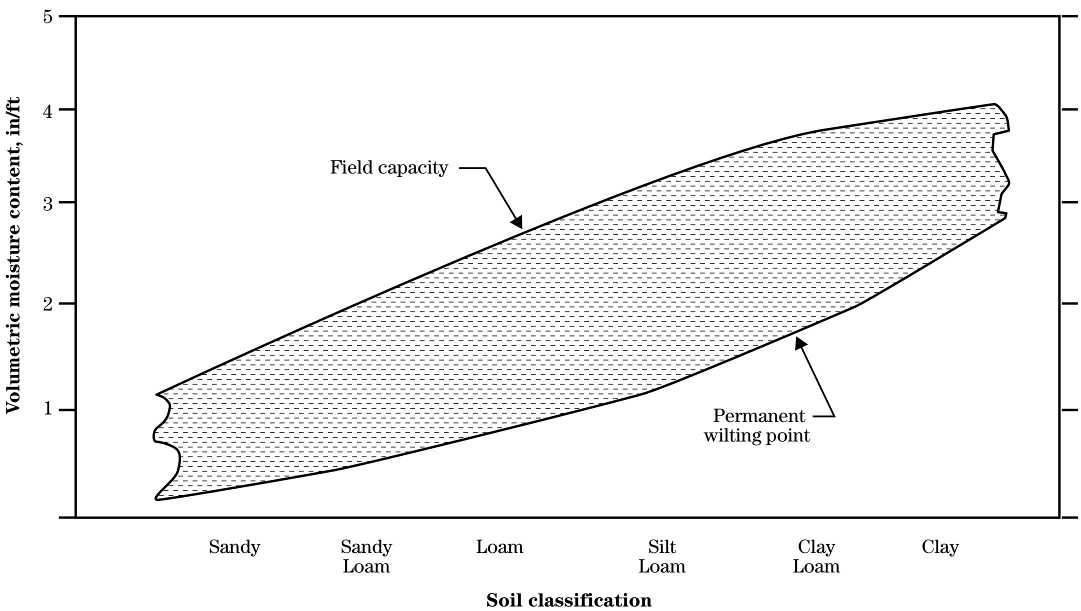


Table 4–2 Average rooting depths selected crops in deep, well-drained soils

Crop	Root depth, ft	Crop	Root depth, ft
Alfalfa	5	Grapes	3
Almonds	7	Ladino clover and grass mix	2
Apricots	7	Lettuce	1
Artichokes	4.5	Melons	5
Asparagus	3.0	Milo	4
Barley	4	Mustard	3.5
Beans (dry)	3.5	Olives	5
Beans (green)	3	Onions	1
Beans (lima)	3.5	Parsnips	3.5
Beets (sugar)	3	Peaches	7
Beets (table)	3	Pears	7
Broccoli	2	Peas	3
Cabbage	2	Peppers	3
Cantaloupes	5	Potatoes (Irish)	3
Carrots	2	Potatoes (sweet)	4.5
Cauliflower	2	Prunes	6
Celery	2	Pumpkins	6
Chard	3	Radishes	2
Cherries	4.5	Spinach	2
Citrus	4.5	Squash (summer)	3
Corn (field)	4	Strawberries	5
Corn (sweet)	3	Sudan grass	5
Cotton	4	Tomatoes	3
Cucumber	4	Turnips	3
Eggplant	3	Walnuts	7
Figs	7	Watermelon	5
Grain and Flax	4		

The management allowed deficit, *MAD*, is the soil moisture that can be used by the crop before irrigation should be scheduled. For deeply rooted and stress tolerant crops like alfalfa, the *MAD* can be as much as 60 to 65 percent of *TAW*, whereas for shallow rooted and stress sensitive crops like vegetables, the *MAD* level should not exceed 35 to 40 percent of *TAW*. Some crops, like cotton and alfalfa seed, require a stress period to produce lint or seeds, and *MAD* may need to be as much as 80 percent of *TAW* for some irrigations late in the maturation period. In the absence of crop specific information in a locality, assuming a MAD level of 50 percent of *TAW* generally can be used to schedule irrigations.

The soil moisture deficit, SMD, is the depletion of soil moisture at particular soil moisture content, θ, and can be expressed as a depth of water as follows:

$$\text{SMD} = \left(\theta_{fc} - \theta\right)\text{RD} \tag{4–21}$$

Example 1—One of the most important characteristics of soil is its bulk density or bulk specific weight. When evaluating soil moisture, particularly with the gravimetric method, this parameter is necessary to accurately estimate *TAW*, *SMD*, and *MAD*. The following example is given to demonstrate these relationships.

What is the bulk density or bulk specific weight of an undisturbed sample 12 inches long by 1 inch diameter and weighing when collected 0.573 pounds? The entire sample was oven-dried to specification and then saturated with 3.594 in^3 of water. The specific weight of the soil particles is 165.434 lb/ft^3.

The solution to this question is found in equation 4–17, which relates porosity to bulk density and the specific weight of the soil particles: recognizing that the 3.594 in^3 of water occupies the entire pore space in the sample, the porosity from equation 4–11 is:

$$\varphi = \frac{V_p}{V} = \frac{3.594}{12 \times \frac{\pi(1)^2}{4}} = 0.381 = 38.1\% \tag{4–22}$$

Then from equation 4–17 for γ_b yields:

$$\begin{aligned}\gamma_b &= \gamma_s\left(1-\varphi\right)\\ &= 165.434\frac{\text{lb}}{\text{ft}^3}\times\left(1-0.381\right)\\ &= 102.404\frac{\text{lb}}{\text{ft}^3} = 1.640\frac{\text{gm}}{\text{cm}^3}\end{aligned} \tag{4–23}$$

Example 2—The most important uses of soil moisture characterizations are those that assist the irrigator in determining when to irrigate and how much to apply. A corollary problem for the surface irrigation evaluation is determining the soil moisture prior to irrigation so an estimate of efficiency can be made. This example is a typical exercise as part of a surface irrigation evaluation.

A number of soil samples from throughout a 65-acre, border irrigated field were collected and evaluated gravimetrically. The bulk density, field capacity, and wilting point were estimated for each soil depth during earlier evaluations. All the data were averaged by depth and are presented along with the average dry weight soil moisture fraction in the table below. How much water should the surface irrigation system apply based on these data?

Soil depth, in	Soil bulk density	WB_{fcB}	WB_{wpB}	W
0–6	1.25	0.24	0.13	0.16
6–12	1.30	0.28	0.14	0.18
12–24	1.35	0.31	0.15	0.23
24–36	1.40	0.33	0.15	0.26
36–48	1.40	0.31	0.14	0.28

This data is presented on a dry weight basis, not a volumetric basis and needs to be converted as follows:

Soil depth, in	$\theta_{fc} = \gamma_b W_{fc}$	$\theta_{wp} = \gamma_b W_{wp}$	$\theta = \gamma_b W$	Soil moisture, in
0–6	0.300	0.163	0.200	1.200
6–12	0.364	0.182	0.234	1.404
12–24	0.419	0.203	0.311	3.732
24–36	0.462	0.210	0.364	4.368
36–48	0.434	0.196	0.392	4.704
Depth weighted average	0.412	0.195	0.321	

Values for two key soil moisture parameters that can be determined from the above data are:

TAW = (0.412–0.195)(48 inches) = 10.416 inches

SMD=(0.412–0.321)(48 inches) = 4.368 inches, or 41.9% of *TAW*

If the irrigation were to occur at this point, the volume the system should apply is 4.368 inches, and this will require (4.368 in/12 in/ft)(65 ac) = 23.66 ac–ft.

Working through this example, note that expressing bulk density in gm/cm^3 makes θ a dimensionless number since 1 gm of water has a volume of 1 cm^3. This allows the evaluator to express the equivalent depth in any units desired.

(2) Infiltration

Basic theory—Infiltration is perhaps the most crucial factor affecting surface irrigation. This parameter controls the amount of water entering the soil and secondarily impacts the duration of both advance and recession. In other terms, infiltration has an important impact on the duration of the irrigation itself. Unfortunately, infiltration exhibits very large variability over a field and is difficult to characterize on a field scale because of the large number of measurements generally necessary.

One of the simplest and most common expressions for infiltration is the Kostiakov Equation that can be written in general terms for furrow irrigation as:

$$Z = K\tau^a \qquad (4\text{–}24)$$

where:

Z = the cumulative volume of infiltration per unit length, ft^3/ft

The coefficient *K* has units of ft^3/ft/min^a, while a is dimensionless. The intake opportunity time, ft, τ, has units of minutes.

In a border or basin where a unit width can also be defined, infiltration is expressed as:

$$z = \kappa\tau^a \qquad (4\text{–}25)$$

where:

z = the cumulative depth of infiltration, ft

k = units of /ft/min^a

a = dimensionless as before

The units of equations 4–24 and 4–25 must be different since a unit width as used for borders and basins cannot be used for furrow systems. The wetted perimeter of the furrow does not usually equal the distance between furrows.

The duration of the water application for border and basin systems is usually short enough that the intake rate derived from equation 4–25, I=, will not significantly underestimate infiltration at the end of irrigation. However, generally, it will in furrow irrigation systems. A more generally applicable relation for furrows is Kostiakov-Lewis Equation, which adds a term for final or basic intake rate, f_o ft/min, for borders and basins, or F_o ft^3/ft/min for furrows. The Kostiakov-Lewis function for furrows is:

$$Z = K\tau^a + F_o\tau \qquad (4\text{–}26)$$

and for borders and basins is:

$$z = k\tau^a + f_o\tau \qquad (4\text{–}27)$$

Note that *k* will have different values in equations 4–25 and 4–27 due to the width implied, as will the values of *K* in equations 4–24 and 4–26. For this manual, it is assumed that the exponent, a, has the same value for both furrow and border/basin irrigation.

The cumulative intake in furrow can be expressed as an equivalent depth by:

$$z = \frac{Z}{w} \qquad (4\text{–}28)$$

where:
w = furrow spacing

However, equation 4–28 assumes complete lateral uniformity between furrows, which is generally not the case. Nevertheless, it is often convenient to express the required intake necessary to refill the root zone as a depth, z_{req}, and then determine the corresponding required furrow intake Z_{req} using equation 4–28. One note of caution is that equation 4–28 does not imply that $k=K/w$ or that $f_o=F_o/w$.

Since surface irrigation is often applied to the heavier soils and some of these tend to crack, equations 4–26 and 4–27 can be extended to include a combined term for cracking and depression storage, c, C:

$$z = k\tau^a + f_o\tau + c \qquad (4\text{–}29)$$

$$Z = K\tau^a + F_o\tau + C \qquad (4\text{–}30)$$

The units of c and C are the same as z and Z, respectively. To date, there are no general recommendations for the cracking terms.

One can observe that if f_o is set to zero, equation 4–29 has the same form as the NRCS infiltration family equations:

$$z = k\tau^a + c \qquad (4\text{–}31)$$

(3) Revised NRCS intake families

The original SCS intake families, based on equation 4–31 with a fixed c value, have provided users with a starting point in the design and evaluation of surface irrigation systems. These original intake family curves are revised in this manual to correspond to equations 4–26 and 4–27. To provide the revised families that are typical of values found in field measurements, there are several assumptions that have been made:

- The availability of data in the form of equations 4–26 and 4–27 is much greater for furrow systems than for either borders or basins. Consequently, the reference family structure is formulated for furrow irrigation and then modified for borders and basins.
- The intake families should encompass both initial and later irrigations since the intake characteristics are usually reduced after the first irrigation. The reference family of curves is for the initial irrigations. Changes due to previous irrigations have been estimated from field experience and expressed as a modification of the reference family.
- The intake families are denoted with numbers varying from 0.02 to 4.00. These family categories are the average infiltration rate over the first 6 hours of irrigation. For initial continuous flow irrigations, the average 6-hour intake rate is essentially the same as the family designation, but 6-hour intake rates for subsequent irrigations are less. Table 4–2 shows the average 6-hour intake rates for each soil and irrigation regime (app. A).
- The effect of surge flow for initial irrigations is approximately the same as the effect of previous irrigations under continuous flow. Intake under surge flow systems during subsequent irrigations is based on adjustment of the initial irrigation surge flow intake.
- It has been assumed that the exponent a in equations 4–26 and 4–27 are the same value (the a exponent is the same for furrow and border/basins) for each soil.

Figure 4–39 shows a comparison of the total 6-hour cumulative intake for the reference family and the three other furrow irrigated conditions. Tables 4–3 through 4–6 shows the intake parameters for furrows.

To determine the Kostiakov-Lewis parameters for border and basin irrigation, it has been assumed that the infiltration through the furrow perimeter is uniform and that the a exponent is the same for both situations. A reference wetted perimeter for each furrow family has been defined as shown in figure 4–39. Recognizing that one-dimensional border/basin infiltration will be different per unit width than in furrow, a reference wetted perimeter for each furrow family has been defined that is intended to compensate for these differences. Figure 4–40 shows typical values of wetted perimeter for furrow irrigation in each of the soil families. These values will change with slope, roughness, crop, and cultural practice and are only for reference purposes. To convert from furrows to borders or basins, the furrow *K* and FB_oB coefficients are divided by the reference wetted perimeter raised to the 0.4 power. Tables for initial and later border and basin irrigation under both continuous and surged flow are given in tables 4–8 to 4–11.

A reference discharge should be specified for the furrow irrigation families since furrow intake is proportional to the wetted perimeter and must be adjusted based on the actual flow in the furrow. The values of the reference wetted perimeter and flow are given in tables 4–4 through 4–7. Figure 4–41 shows the relationship of reference flow to intake family.

Figure 4–39 Average 6-hour intake rate for the revised NRCS furrow intake families

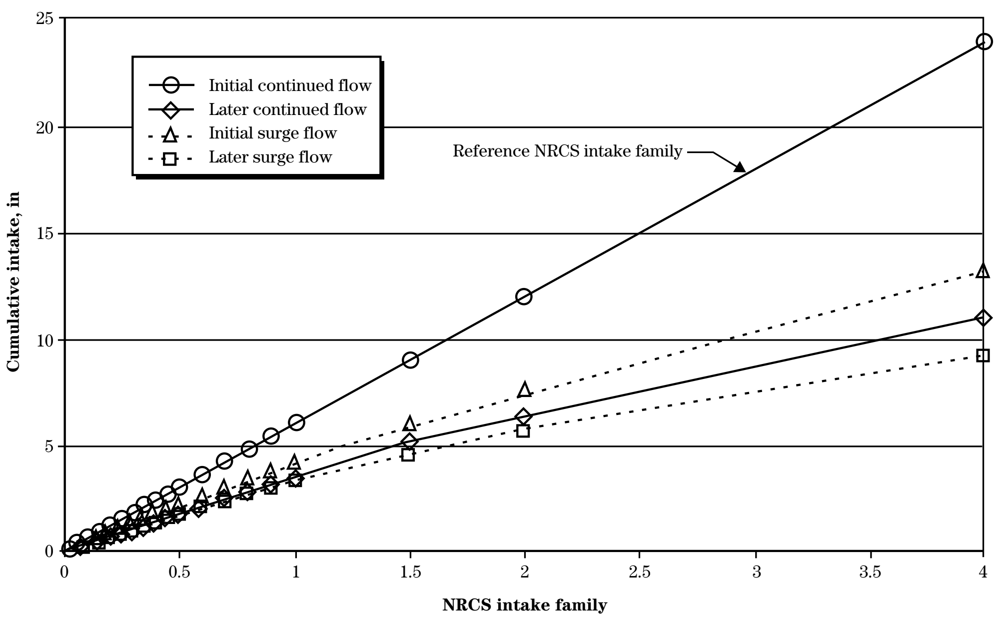


Figure 4–40 Reference furrow wetted perimeters for the revised NRCS intake families

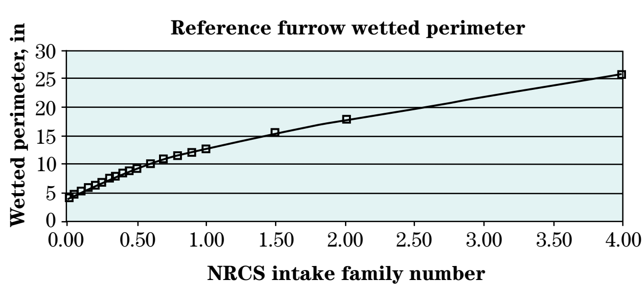


Figure 4–41 Relationship of reference flow to intake family

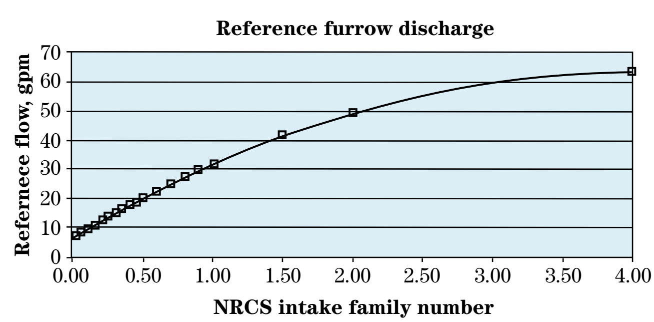


Table 4–3 Average 6-hour intake rates for the furrow-based reference intake families

NRCS curve no.	Soil type	Initial continuous flow irrig. 6-hour intake rate, in/h	Later continuous flow irrig. 6-hour intake rate, in/h	Initial surge flow irrig. 6-hour intake rate, in/h	Later surge flow irrig. 6-hour intake rate, in/h
0.02	Heavy clay	0.022	0.017	0.018	0.016
0.05	Clay	0.055	0.042	0.045	0.039
0.10	Clay	0.099	0.074	0.080	0.068
0.15	Light clay	0.145	0.106	0.115	0.097
0.20	Clay loam	0.193	0.138	0.150	0.126
0.25	Clay loam	0.242	0.170	0.185	0.155
0.30	Clay loam	0.292	0.202	0.221	0.183
0.35	Silty	0.343	0.234	0.256	0.211
0.40	Silty	0.395	0.265	0.291	0.239
0.45	Silty loam	0.447	0.296	0.326	0.266
0.50	Silty loam	0.500	0.326	0.361	0.293
0.60	Silty loam	0.605	0.386	0.429	0.345
0.70	Silty loam	0.710	0.445	0.495	0.396
0.80	Sandy loam	0.815	0.501	0.560	0.445
0.90	Sandy loam	0.918	0.556	0.624	0.492
1.00	Sandy loam	1.021	0.610	0.686	0.538
1.50	Sandy	1.517	0.855	0.973	0.745
2.00	Sandy	1.994	1.074	1.234	0.926
4.00	Sandy	3.966	1.834	2.180	1.527

Table 4–4 Continuous flow furrow intake families – initial irrigations

Continuous Flow Intake Curve Parameters for Initial Irrigations

ID	Soil Name	a	K (ft^3/ft/mn^a)	Fo (ft^3/ft/mn)	Qr (gpm)	Wpr (ft)
.02	Heavy Clay	0.192	0.002620	0.0001461	7.411	0.365
.05	Clay	0.247	0.004756	0.0002340	8.255	0.399
.10	Clay	0.303	0.006783	0.0003475	9.648	0.452
.15	Light Clay	0.348	0.008500	0.0004621	11.023	0.500
.20	Clay Loam	0.385	0.010086	0.0005797	12.381	0.544
.25	Clay Loam	0.416	0.011517	0.0006961	13.721	0.586
.30	Clay Loam	0.442	0.012870	0.0008130	15.042	0.626
.35	Silty	0.464	0.014166	0.0009285	16.347	0.663
.40	Silty	0.483	0.015383	0.0010425	17.633	0.699
.45	Silty Loam	0.499	0.016541	0.0011534	18.901	0.733
.50	Silty Loam	0.514	0.017660	0.0012628	20.152	0.767
.60	Silty Loam	0.537	0.019750	0.0014715	22.599	0.830
.70	Silty Loam	0.556	0.021701	0.0016687	24.976	0.889
.80	Sandy Loam	0.572	0.023512	0.0018535	27.281	0.945
.90	Sandy Loam	0.585	0.025224	0.0020268	29.514	0.999
1.00	Sandy Loam	0.597	0.026836	0.0021894	31.677	1.050
1.50	Sandy	0.638	0.033830	0.0028582	41.420	1.282
2.00	Sandy	0.666	0.039706	0.0033515	49.381	1.483
4.00	Sandy	0.751	0.059331	0.0044455	63.401	2.131

Table 4–5 Continuous flow furrow intake families–later irrigations

Continuous Flow Intake Curve Parameters for Later Irrigations

ID	Soil Name	a	K (ft^3/ft/mn^a)	Fo (ft^3/ft/mn)	Qr (gpm)	Wpr (ft)
.02	Heavy Clay	0.153	0.002230	0.0001169	7.411	0.365
.05	Clay	0.197	0.004036	0.0001872	8.255	0.399
.10	Clay	0.242	0.005763	0.0002780	9.648	0.452
.15	Light Clay	0.278	0.007230	0.0003697	11.023	0.500
.20	Clay Loam	0.308	0.008566	0.0004638	12.381	0.544
.25	Clay Loam	0.333	0.009797	0.0005569	13.721	0.586
.30	Clay Loam	0.354	0.010940	0.0006504	15.042	0.626
.35	Silty	0.371	0.012046	0.0007428	16.347	0.663
.40	Silty	0.386	0.013083	0.0008340	17.633	0.699
.45	Silty Loam	0.399	0.014061	0.0009227	18.901	0.733
.50	Silty Loam	0.411	0.015010	0.0010102	20.152	0.767
.60	Silty Loam	0.430	0.016790	0.0011772	22.599	0.830
.70	Silty Loam	0.445	0.018441	0.0013349	24.976	0.889
.80	Sandy Loam	0.458	0.019982	0.0014828	27.281	0.945
.90	Sandy Loam	0.468	0.021444	0.0016214	29.514	0.999
1.00	Sandy Loam	0.478	0.022816	0.0017515	31.677	1.050
1.50	Sandy	0.510	0.028760	0.0022865	41.420	1.282
2.00	Sandy	0.533	0.033746	0.0026812	49.381	1.483
4.00	Sandy	0.601	0.050431	0.0035564	63.401	2.131

Table 4–6 Surge flow furrow intake families – initial irrigations

Surge Flow Intake Curve Parameters for Initial Irrigations

ID	Soil Name	a	K (ft^3/ft/mn^a)	Fo (ft^3/ft/mn)	Qr (gpm)	Vpr (ft)
.02	Heavy Clay	0.163	0.002290	0.0001242	7.411	0.365
.05	Clay	0.210	0.004156	0.0001989	8.255	0.399
.10	Clay	0.258	0.005933	0.0002954	9.648	0.452
.15	Light Clay	0.296	0.007440	0.0003928	11.023	0.500
.20	Clay Loam	0.328	0.008826	0.0004928	12.381	0.544
.25	Clay Loam	0.354	0.010077	0.0005917	13.721	0.586
.30	Clay Loam	0.376	0.011270	0.0006911	15.042	0.626
.35	Silty	0.394	0.012396	0.0007892	16.347	0.663
.40	Silty	0.410	0.013463	0.0008862	17.633	0.699
.45	Silty Loam	0.424	0.014471	0.0009804	18.901	0.733
.50	Silty Loam	0.437	0.015450	0.0010734	20.152	0.767
.60	Silty Loam	0.457	0.017280	0.0012508	22.599	0.830
.70	Silty Loam	0.473	0.018981	0.0014184	24.976	0.889
.80	Sandy Loam	0.486	0.020572	0.0015755	27.281	0.945
.90	Sandy Loam	0.498	0.022074	0.0017228	29.514	0.999
1.00	Sandy Loam	0.507	0.023486	0.0018610	31.677	1.050
1.50	Sandy	0.542	0.029600	0.0024294	41.420	1.282
2.00	Sandy	0.566	0.034746	0.0028488	49.381	1.483
4.00	Sandy	0.638	0.051911	0.0037787	63.401	2.131

Table 4–7 Surge flow furrow intake families – later irrigations

Surge Flow Intake Curve Parameters for Later Irrigations

ID	Soil Name	a	K (ft^3/ft/mn^a)	Fo (ft^3/ft/mn)	Qr (gpm)	Vpr (ft)
.02	Heavy Clay	0.144	0.002090	0.0001169	7.411	0.365
.05	Clay	0.185	0.003806	0.0001872	8.255	0.399
.10	Clay	0.227	0.005423	0.0002780	9.648	0.452
.15	Light Clay	0.261	0.006800	0.0003697	11.023	0.500
.20	Clay Loam	0.289	0.008066	0.0004638	12.381	0.544
.25	Clay Loam	0.312	0.009217	0.0005569	13.721	0.586
.30	Clay Loam	0.332	0.010300	0.0006504	15.042	0.626
.35	Silty	0.348	0.011336	0.0007428	16.347	0.663
.40	Silty	0.362	0.012313	0.0008340	17.633	0.699
.45	Silty Loam	0.374	0.013231	0.0009227	18.901	0.733
.50	Silty Loam	0.385	0.014130	0.0010102	20.152	0.767
.60	Silty Loam	0.403	0.015800	0.0011772	22.599	0.830
.70	Silty Loam	0.417	0.017361	0.0013349	24.976	0.889
.80	Sandy Loam	0.429	0.018812	0.0014828	27.281	0.945
.90	Sandy Loam	0.439	0.020174	0.0016214	29.514	0.999
1.00	Sandy Loam	0.448	0.021476	0.0017515	31.677	1.050
1.50	Sandy	0.478	0.027070	0.0022865	41.420	1.282
2.00	Sandy	0.500	0.031766	0.0026812	49.381	1.483
4.00	Sandy	0.563	0.047461	0.0035564	63.401	2.131

Table 4–8 Continuous flow border/basin intake families–initial irrigations

Continuous Flow Intake Curve Parameters for Initial Irrigations

ID	Soil Name	a	k (ft/mn^a)	fo (ft/mn)
.02	Heavy Clay	0.192	0.001380	0.0000770
.05	Clay	0.247	0.002446	0.0001203
.10	Clay	0.303	0.003393	0.0001740
.15	Light Clay	0.348	0.004160	0.0002261
.20	Clay Loam	0.385	0.004836	0.0002778
.25	Clay Loam	0.416	0.005427	0.0003276
.30	Clay Loam	0.442	0.005960	0.0003763
.35	Silty	0.464	0.006456	0.0004233
.40	Silty	0.483	0.006923	0.0004687
.45	Silty Loam	0.499	0.007341	0.0005121
.50	Silty Loam	0.514	0.007750	0.0005541
.60	Silty Loam	0.537	0.008490	0.0006325
.70	Silty Loam	0.556	0.009161	0.0007044
.80	Sandy Loam	0.572	0.009772	0.0007701
.90	Sandy Loam	0.585	0.010334	0.0008303
1.00	Sandy Loam	0.597	0.010856	0.0008855
1.50	Sandy	0.638	0.013030	0.0011006
2.00	Sandy	0.666	0.014766	0.0012463
4.00	Sandy	0.751	0.020151	0.0015097

Table 4–9 Continuous flow border/basin intake families–later irrigations

Continuous Flow Intake Curve Parameters for Later Irrigations

ID	Soil Name	a	k (ft/mn^a)	fo (ft/mn)
.02	Heavy Clay	0.153	0.001170	0.0000616
.05	Clay	0.197	0.002076	0.0000963
.10	Clay	0.242	0.002893	0.0001392
.15	Light Clay	0.278	0.003540	0.0001809
.20	Clay Loam	0.308	0.004106	0.0002223
.25	Clay Loam	0.333	0.004617	0.0002621
.30	Clay Loam	0.354	0.005060	0.0003010
.35	Silty	0.371	0.005496	0.0003386
.40	Silty	0.386	0.005883	0.0003750
.45	Silty Loam	0.399	0.006241	0.0004097
.50	Silty Loam	0.411	0.006590	0.0004433
.60	Silty Loam	0.430	0.007220	0.0005060
.70	Silty Loam	0.445	0.007781	0.0005635
.80	Sandy Loam	0.458	0.008302	0.0006161
.90	Sandy Loam	0.468	0.008784	0.0006642
1.00	Sandy Loam	0.478	0.009236	0.0007084
1.50	Sandy	0.510	0.011070	0.0008805
2.00	Sandy	0.533	0.012556	0.0009970
4.00	Sandy	0.601	0.017131	0.0012078

Table 4–10 Surge flow border/basin intake families–initial irrigations

Surge Flow Intake Curve Parameters for Initial Irrigations

ID	Soil Name	a	k (ft/mn^a)	fo (ft/mn)
.02	Heavy Clay	0.163	0.001210	0.0000654
.05	Clay	0.210	0.002146	0.0001023
.10	Clay	0.258	0.002973	0.0001479
.15	Light Clay	0.296	0.003640	0.0001922
.20	Clay Loam	0.328	0.004236	0.0002362
.25	Clay Loam	0.354	0.004747	0.0002784
.30	Clay Loam	0.376	0.005210	0.0003198
.35	Silty	0.394	0.005656	0.0003598
.40	Silty	0.410	0.006053	0.0003984
.45	Silty Loam	0.424	0.006431	0.0004353
.50	Silty Loam	0.437	0.006780	0.0004710
.60	Silty Loam	0.457	0.007430	0.0005376
.70	Silty Loam	0.473	0.008011	0.0005987
.80	Sandy Loam	0.486	0.008552	0.0006546
.90	Sandy Loam	0.498	0.009044	0.0007057
1.00	Sandy Loam	0.507	0.009506	0.0007527
1.50	Sandy	0.542	0.011400	0.0009356
2.00	Sandy	0.566	0.012926	0.0010593
4.00	Sandy	0.638	0.017631	0.0012833

Table 4–11 Surge flow border/basin intake families–later irrigations

Surge Flow Intake Curve Parameters for Later Irrigations

ID	Soil Name	a	k (ft/mn^a)	fo (ft/mn)
.02	Heavy Clay	0.144	0.001100	0.0000616
.05	Clay	0.185	0.001956	0.0000963
.10	Clay	0.227	0.002723	0.0001392
.15	Light Clay	0.261	0.003330	0.0001809
.20	Clay Loam	0.289	0.003866	0.0002223
.25	Clay Loam	0.312	0.004337	0.0002621
.30	Clay Loam	0.332	0.004770	0.0003010
.35	Silty	0.348	0.005166	0.0003386
.40	Silty	0.362	0.005533	0.0003750
.45	Silty Loam	0.374	0.005881	0.0004097
.50	Silty Loam	0.385	0.006200	0.0004433
.60	Silty Loam	0.403	0.006790	0.0005060
.70	Silty Loam	0.417	0.007331	0.0005635
.80	Sandy Loam	0.429	0.007812	0.0006161
.90	Sandy Loam	0.439	0.008264	0.0006642
1.00	Sandy Loam	0.448	0.008686	0.0007084
1.50	Sandy	0.478	0.010420	0.0008805
2.00	Sandy	0.500	0.011816	0.0009970
4.00	Sandy	0.563	0.016121	0.0012078

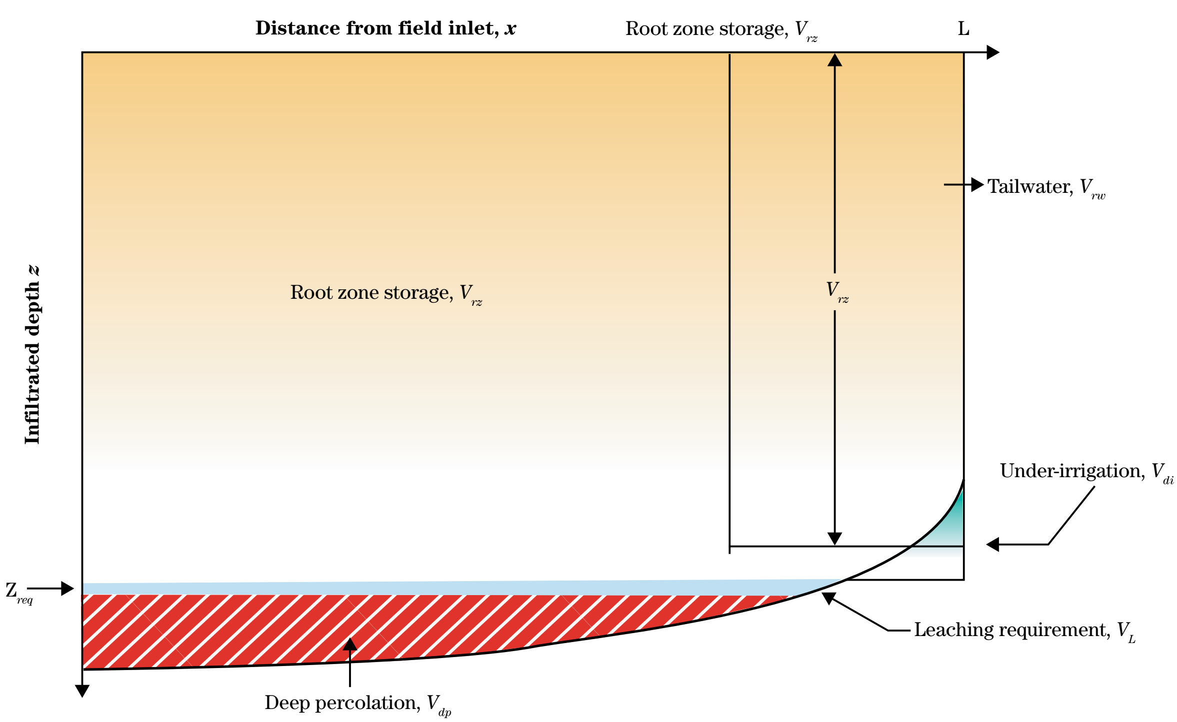
(4) Irrigation efficiency and uniformity

The effectiveness of irrigation can be described by its efficiency and uniformity. Because an irrigation system applies water for evapotranspiration and leaching needs, as well as occasionally seed bed preparation, germination, or cooling, there have emerged a number of different efficiencies and ratios to give specific measures of performance. The most important indicator of how well the irrigation served its purposes is how it impacted production and profitability on the farm.

When a field with a uniform slope, soil, and crop receives steady flow at its upper end, a water front will advance at a monotonically decreasing rate until it reaches the end of the field. If it is not diked, runoff will occur for a time before recession starts following cutoff. Figure 4–42 shows the distribution of applied water along the field length stemming from these assumptions. The differences in applied depths are non-uniformly distributed with a characteristic shape skewed toward the inlet end of the field.

The amount of water that can be stored in the root zone is $L \; x \; z_{reg}$, but as shown, some region of the root zone has not received water owing to the spatial distribution of infiltration. The depth of water that would refill the root zone is z_{req}, beyond which water percolates below the roots and is lost to the drainage or ground water system. Generally, these flows return to receiving waters where they can be used elsewhere. Thus, they are lost in terms of the local condition, but not to the regional or basin locale. The negative connotations of loss should be kept even though this water may be recovered and reused. The quality of these flows is nearly always degraded, and the timing of when they are available elsewhere may not be useful.

Figure 4–42 Distribution of applied water in surface irrigation



Computing each of these components requires a numerical integration of infiltrated depth over the field length. For the purposes of this discussion, it is convenient to define the components as follows:

V_{in} is the total depth (per unit width) or volume (per furrow spacing) of water applied to the field.

V_{RZ} is the total depth (per unit width) or volume (per furrow spacing) of water necessary to replace the soil moisture deficit.

V_{rz} is the depth of water (per unit width) or volume (per furrow spacing) of irrigation water that is actually stored in the root zone.

V_{di} is the depth of water (per unit width) or volume (per furrow spacing) that represents under-irrigation.

V_{dp} is the depth of water (per unit width) or volume (per furrow spacing) of water that percolates below the root zone.

V_{tw} is the depth of water (per unit width) or volume (per furrow spacing) of water that flows from the field as tailwater.

V_L is the depth of water (per unit width) or volume of (per furrow spacing) of water needed for leaching.

V_{lq} is the average depth (per unit width) or volume (per furrow spacing) of infiltrated water in the least-irrigated 25 percent of the field.

Irrigation efficiency—The definition of irrigation efficiency, E_i, represents the fraction of water applied to the field that could be considered beneficially used:

$$E_i = \frac{V_{rz} + V_L}{V_{in}} = \frac{V_{rz} + V_L}{V_{rz} + V_{dp} + V_{tw}} \qquad (4–32)$$

Application efficiency—Application efficiency is a subset of irrigation efficiency, which evaluates only how well the irrigation water was stored in the root zone:

$$E_a = \frac{V_{rz}}{V_{in}} = \frac{V_{rz}}{V_{rz} + V_{dp} + V_{tw}} \qquad (4–33)$$

Storage or requirement efficiency—A measure of how well the root zone was refilled is called storage or requirement efficiency and is described as:

$$E_r = \frac{V_{rz}}{V_{RZ}} = \frac{V_{rz}}{z_{req} \times w \times L} \qquad (4–34)$$

Distribution uniformity—Application or distribution uniformity concerns the distribution of water over the actual field and can be defined as the infiltrated depth or volume in the least-irrigated 25 percent of the field divided by the infiltrated depth or volume over the whole field:

$$DU = \frac{4.0 \times V_{lq}}{\left(V_{rz} + V_{dp}\right)} \qquad (4–35)$$

Deep percolation ratio—The deep percolation ratio indicates the fraction of applied irrigation water infiltrating the soil that percolates below the root zone. Precipitation during the irrigation event and perhaps within 1 to 3 days will also contribute to the total amount of water percolating below the root zone. The deep percolation ratio is intended as a quantitative measure of irrigation performance and does not include precipitation and thus may not represent all the deep percolation that occurs.

$$DPR = \frac{V_{dp}}{V_{in}} = \frac{V_{dp}}{V_{rz} + V_{dp} + V_{tw}} \qquad (4–36)$$

Tailwater ratio—The tailwater ratio is the fraction of irrigation water applied to the field that runs off as tailwater:

$$TWR = \frac{V_{tw}}{V_{in}} = \frac{V_{tw}}{V_{rz} + V_{dp} + V_{tw}} \qquad (4–37)$$

In most field evaluations, the volume of tailwater will be measured. The exception is for the case of basins or blocked-end borders where runoff is restricted. The volume of tailwater is not given and must be computed. What are the values of the various efficiencies and uniformities for this irrigation event?

The first step is to estimate the total volume of water that has infiltrated the soil from the data above. One way is to determine a best fit line through the data, integrate the function, and multiply by the furrow spacing (2.5 ft) and length. Another is simply to average the depths, multiply by the furrow spacing and then by the total field length. The result of a sophisticated numerical analysis is a total intake of 1,366 ft^3, and that of simple averaging is 1,372 ft^3.

The volume of inflow to each furrow was 13 gpm for 24 hours, which translates to 2,502 ft^3. Therefore, the total tailwater is 2,502–1,366 = 1,136 ft^3, or the *TWR* from equation 4–37 is 0.454 or 45.4 percent.

The next question is, how much deep percolation occurred? Analyses based on a numerical procedure are very helpful for this computation since a partial integration is necessary. The deep percolation graphically can be estimated, as well. Using the more elaborate analysis, the intake profile is integrated between 0 and 990 feet at which point the intake is less than the soil moisture deficit and assumed that no deep percolation occurs. This yields a total intake over the portion of field where deep percolation occurs of 1,226 ft^3, of which 886 ft^3 are captured in the root zone (990 feet x 4.3 inches x 2.5 ft /12 in/ft). The total estimated volume of deep percolation is, therefore, 340 ft^3, or

$$\text{DPR} = \frac{340}{2,501} = 13.6\%$$

The total intake in the last 330 feet of furrow can be calculated similarly and should equal about 140 ft^3 making the total water stored in the root zone 1,026 ft^3 (140 + 886). Therefore, the application efficiency, E_a, from equation 4–33 is

$$E_a = \frac{1,026}{2,501} = 41\%$$

The sum of application efficiency, E_a, the tailwater ratio, *TWR*, and the deep percolation ratio, *DPR*, should total to 100 percent.

If the root zone had been completely refilled, the volume there would have been 1,183 ft^3 (4.3 in x 1,320 ft x 2.5 ft). Since only 1,026 ft^3 was stored, the storage or requirement efficiency, E_r, from equation 4–34 is

$$E_r = \frac{1,026}{1,183} = 87.6\%$$

The distribution uniformity, *DU*, can now be solved from equation 4–35 as

$$\text{DU} = 4 \times \frac{140}{1,366} = 41.0\%$$

This is a very poor irrigation and would be a candidate for much better management and/or design. However, some improvement in the numbers at least is possible by including the leaching in the evaluation. An approximate volume of leaching can be found by assuming leaching occurs wherever deep percolation occurs, in this case, over the first 990 feet of the furrow. The volume of leaching is, therefore:

$$0.4 \times 990 \times \frac{2.5}{12} = 82.5 \text{ ft}^3$$

The irrigation efficiency from equation 4–32 is

$$\frac{(1,125 + 82.5)}{2,502} = 48.3\%$$

(5) Water measurement

One of the simplest and yet most important concepts in surface irrigation can be described mathematically as:

$$Q_T T_T = DA \qquad (4\text{–}38)$$

where:

Q_T = total flow delivered to the field
T_T = total time the flow Q_T is delivered to the field
D = depth of water applied to the field
A = area of the field

As an example, if it requires a flow of 10 ft^3/s for 48 hours to irrigate a field of 40 acres, the depth that will be applied will be about 12 inches. The flow rate delivered to a field is critically important in two respects. First, the surface irrigation system is highly sensitive to the flow because it determines how fast or slow the field will be irrigated. Secondly, the efficient surface irrigator must judge the effectiveness of the management by planning a target depth of application for each irrigation and then assessing the performance of the system as it operates. In both cases, a significant difference between the flow necessary to apply the appropriate depth in the planned period and the actual flow delivered will adversely impact the efficiency and uniformity of the surface irrigation. Flow measurement is vitally important in surface irrigation.

The NRCS uses the Water Measurement Manual of the Bureau of Reclamation, U.S. Department of the Interior as its water measurement guide (section 15, chapter 9, National Engineering Handbook). This manual is also available from your state irrigation specialist, IT personnel, or can be downloaded directly from ***http://www.usbr.gov/pmts/hydraulics_lab/ pubs/ index.html***

(c) Field evaluations

(1) Standard field evaluation procedure

The basic objective of a surface irrigation field evaluation is to establish a water balance for the field and, thereby, identify each of the components necessary to determine the efficiencies and uniformities noted in equations 4–32 through 4–37. Standard practices are developed in other NRCS manuals and are not repeated here in detail. However, based on recent experience, a number of simplifications and modifications can be suggested.

Flow shape—To estimate flow depths, it is necessary to describe the shape of the flow cross section. For borders and basins, this shape is generally assumed to be a wide rectangular sheet that can be evaluated by examining a unit width within the border or basin. In furrow irrigation, however, it is necessary to describe the actual shape so that relationships between depth and area and/or wetted perimeter can be calculated.

Furrow shapes are nearly always irregular, but can be described using a series of power functions. The following analysis uses the Manning equation as the primary relationship between depth, slope, cross section, and flow.

An expression relating wetted perimeter, WP, can be defined as a function of flow depth, y, as follows:

$$WP = \gamma_1 y^{\gamma_2} \qquad (4\text{–}39)$$

where:

γ_1 and γ_2 = numerical fitting parameters

Both wetted perimeter and depth should be expressed in feet. Similarly, a function of cross-sectional area, A, in ft^2, and depth in feet can be expressed as:

$$A = \sigma_1 y^{\sigma_2} \qquad (4\text{–}40)$$

where again σ_1 and σ_2 are numerical fitting parameters. The top width, T, can be described as:

$$T = Cch \times y^{Cmh} \qquad (4\text{–}41)$$

It has been found that for most furrows the hydraulic section can be defined as:

$$A^2 R^{\frac{4}{3}} = \rho_1 A^{\rho_2} \qquad (4\text{–}42)$$

in which:

$$\rho_2 = \frac{10}{3} - \frac{4\gamma_2}{3\sigma_2} \qquad (4\text{–}43)$$

and,

$$\rho_1 = \frac{\sigma_1^{\frac{10}{3-\rho_2}}}{\gamma^{\frac{4}{3}}} \qquad (4\text{–}44)$$

The values of γ_1, σ_1, and Cch are equal to the unit width used to describe the flow. The parameter ρ_1 equals the unit width squared. The values of γ_2, σ_2, Cmh, and ρ_2 for borders and basins are 0.0, 1.0, 0.0, and 3.33, respectively.

Using the English form of the Manning equation, the cross-sectional flow area at the field inlet, A_o in ft^2, can be determined for any flow, Q_o in ft^3/s and field slope, S_o, greater than about 0.00001:

$$A_o = \left[\frac{0.4529 \times Q_o^2 \times n^2}{S_o \times \rho_1}\right]^{1/\rho_2} \tag{4–45}$$

If the field has a slope less than 0.00001, then inlet area, A_o, will increase as the advance proceeds down the field and must be recomputed for each advance distance. For this case, the value of the field slope, S_o, is replaced in equation 4–45 by:

$$S_o = \frac{y_0}{x} \tag{4–46}$$

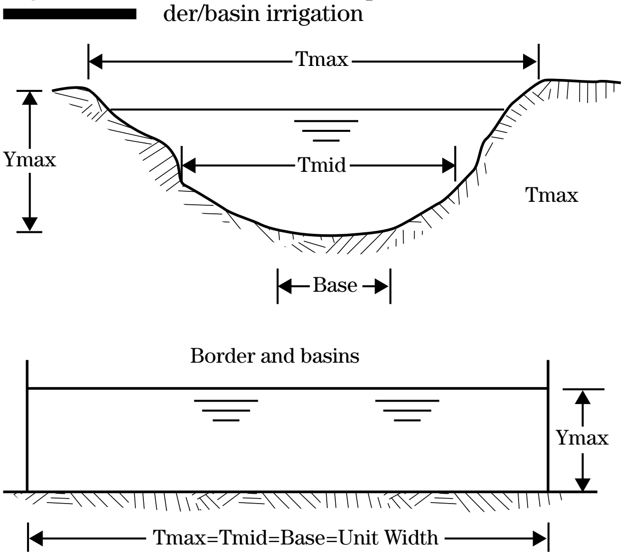
where:

y_o = depth of flow, in ft, at the field inlet

x = advance distance in feet

Figure 4–43 illustrates the basic border/basin and furrow shapes. Measuring a furrow cross section in the field involves four simple measurements: total depth of the furrow, Y_{max}; base width, *Base*; top width at the Y_{max} depth, T_{max}; and furrow width at a depth of $Y_{max}/2$, T_{mid}. The units of Y_{max}, T_{max}, and T_{mid} are feet.

Figure 4–43 Cross-sectional shapes for furrow and border/basin irrigation



The units used in the input boxes of the **Surface** software are inches. The values of γ_1, γ_2, σ_1, σ_2, ρ_1, and ρ_2 depend on the units used. In **Surface** software, only the metric values are displayed.

The values of the furrow geometry, γ_1, γ_2, σ_1, and σ_2 can then be calculated:

$$\gamma_2 = \frac{\log\left[\frac{\left[Base + \sqrt{Y_{max}^2 + (T_{mid} - Base)^2} + \sqrt{Y_{max}^2 + (T_{max} - T_{mid})^2}\right]}{\left[Base + \sqrt{Y_{max}^2 + (T_{mid} - Base)^2}\right]}\right]}{\log 2} \tag{4–47}$$

$$\gamma_1 = \frac{\left[Base + \sqrt{Y_{max}^2 + (T_{mid} - Base)^2} + \sqrt{Y_{max}^2 + (T_{max} - T_{mid})^2}\right]}{Y_{max}^{\gamma_2}} \tag{4–48}$$

$$\sigma_2 = \frac{\log\left[\frac{\frac{Y_{max}}{2}\left(\frac{Base}{2} + T_{mid} + \frac{T_{max}}{2}\right)}{\frac{Y_{max}}{2}\left(\frac{Base}{2} + \frac{T_{mid}}{2}\right)}\right]}{\log 2} \tag{4–49}$$

$$\sigma_1 = \frac{\frac{Y_{max}}{2}\left(\frac{Base}{2} + T_{mid} + \frac{T_{max}}{2}\right)}{Y_{max}^{\sigma_2}} \tag{4–50}$$

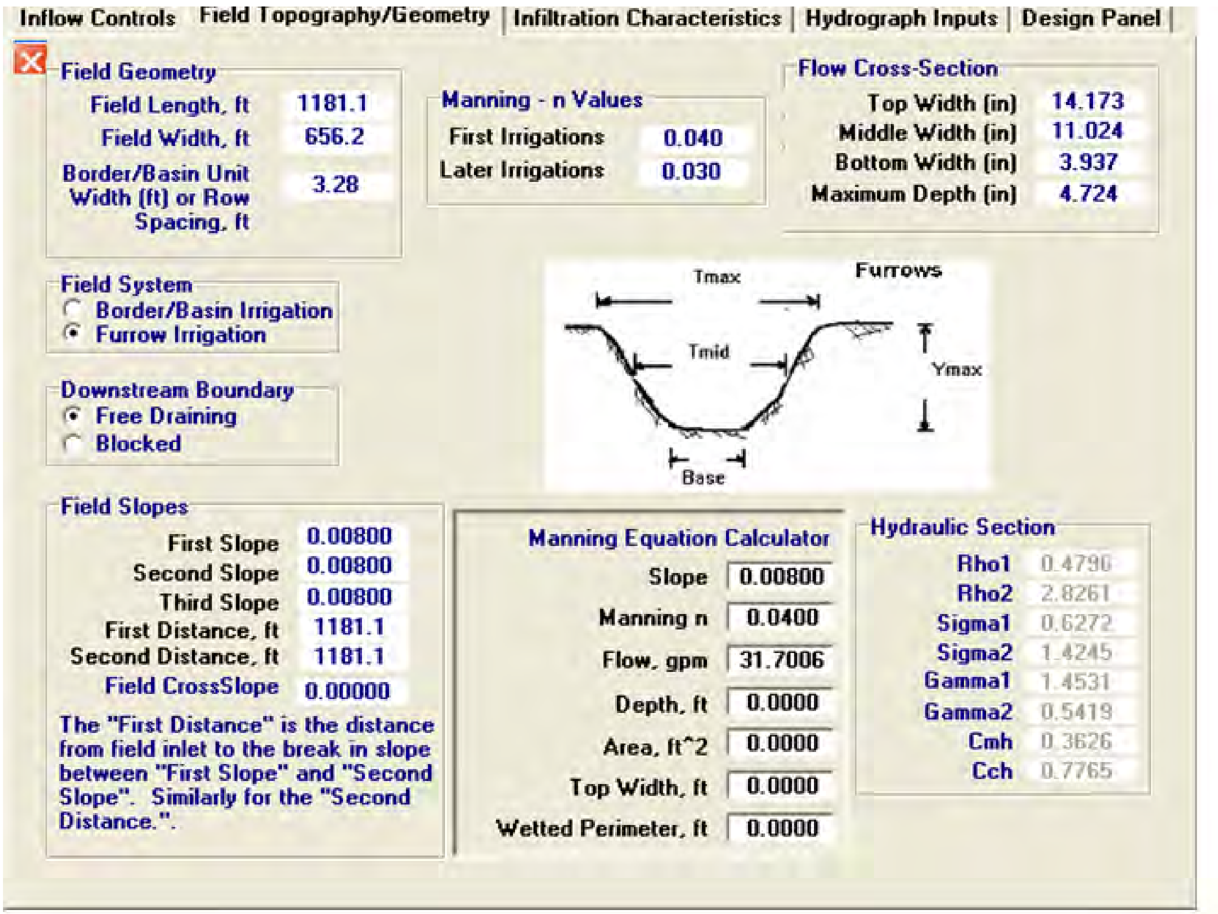
$$Cmh = \frac{\log\left[\frac{T_{max}}{T_{mid}}\right]}{\log[2]} \tag{4–51}$$

$$Cch = \frac{T_{max}}{y_{max}^{Cmh}} \tag{4–52}$$

Example—Rather than demonstrate these computations in a laborious example, open an application of the **Surface** software. From the main screen, click on the **input data** button to open the input tabbed notebook with the software's default data set (fig. 4–44).

Make sure the field system is furrow irrigation by checking the **Furrow Irrigation** button. Then enter

Figure 4–44 Cross section evaluation using the **Surface** software



15.0 inches for the top width, 12 inches for the middle width, 2 inches for the bottom width, and 4 inches for the maximum depth. As these numbers are entered, the metric values are displayed in the boxes below labeled *Rho1* through *Cch* and will change as equations 4–43, 4–44, and 4–47 to 4–52 are executed by the software.

Suppose this furrow had a slope of 0.0001, a Manning *n* of 0.025, and was conveying a flow of 17 gpm. What would be the depth, wetted perimeter, and cross-sectional area? The answer can be found by entering the slope, Manning *n*, and flow in the Manning Equation Calculator. What would the flow depth be if the system was a border of the same slope? This can be determined by clicking on the **Border/Basin** check box and re-entering the slope, Manning *n*, or the flow. The result will be 0.094 feet.

Advance and recession—Most general evaluation procedures recommend that advance and recession be measured at several points along the field. However, these data do not provide sufficient information to justify the added labor associated with the evaluation and certainly not the problems associated with trafficking within the field. The readings that are most important are those shown in the advance-recession graph in figure 4–45, namely:

- start time
- time of advance to the field midpoint
- time of advance
- time of cutoff
- time of recession at the field inlet
- recession time at the field midpoint
- time of recession

As a practical matter, the start time, time of advance, and recession time are all available from the inflow and outflow hydrographs if the field is free draining. Blocked-end fields will require the recession time to be noted when the ponded water vanishes.

Two simple equations of advance and recession can be developed. For the advance trajectory, a simple power relationship is usually sufficient:

$$x = pt_x^r \qquad (4\text{–}53)$$

in which:

$$r = \frac{\log\left(\frac{L}{.5L}\right)}{\log\left(\frac{t_L}{t_{.5L}}\right)} \qquad (4\text{–}54)$$

and,

$$p = \frac{L}{t_L^r} \qquad (4\text{–}55)$$

where:

x = distance from the field inlet to the advancing front, ft

t_x = time from the beginning of irrigation until the advancing front reaches the point x, min

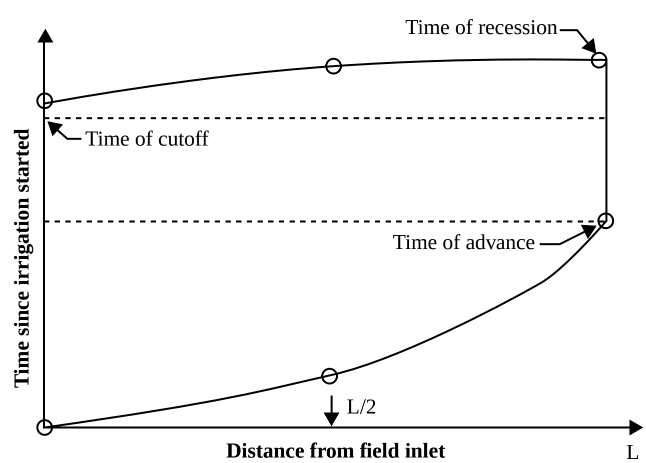
$t_{.5L}$ = time from the beginning of irrigation until the advancing front reaches the field mid point, min

t_L = advance time, min

L = field length, ft

p, r = fitting coefficients

Figure 4–45 Field measurement points for advance and recession evaluations in the field



The recession trajectory can be represented by a quadratic function:

$$\bar{t}_x = h + i \times x + j \times x^2 \qquad (4\text{–}56)$$

in which:

$$h = \bar{t}_d \qquad (4\text{–}57)$$

$$i = \frac{m^2 \bar{t}_L - \bar{t}_{.5L} - \bar{t}_d \left(m^2 - 1\right)}{L\left(m^2 - m\right)}, \text{ where } m = \frac{.5L}{L} \qquad (4\text{–}58)$$

$$j = \frac{\bar{t}_L - \bar{t}_d - i \times L}{L^2} \qquad (4\text{–}59)$$

where,

$\bar{t}_s$ = time of recession at a distance x from the field inlet, min

$\bar{t}_d$ = time of recession at the field inlet, sometimes called the time of depletion, min

$\bar{t}_{.5L}$ = time of recession at the field midpoint, min

$\bar{t}_L$ = time of recession, min

The intake opportunity time, τ, at any point x is defined as:

$$\tau = \bar{t}_x - t_x \qquad (4\text{–}60)$$

Example—In the example data set labeled FreeDrainingFurrow_2.cfg, field data are reported for advance and recession measurements in the hydrographs inputs panel of the input tabbed notebook. Calculate the advance and recession curves for this field evaluation.

The advance curve represented by equation 4–53 is determined. The advance time to the midpoint of the field given by the station at 1,013 feet is 116.0 minutes, and the advance time to the end of the field at 2,050.5 feet is 352.7 minutes. These numbers are shown under the **Two-Point** button on the infiltration characteristics panel. They are also indicated in the Advance and Recession spreadsheet on the hydrograph inputs panel. The inflow is shutoff at 1,440 minutes. The time of depletion, $\bar{t}_d$, at the inlet is 1,444 minutes as shown at the recession time in the hydrograph inputs panel. The time of recession at 1,013 feet, $\bar{t}_{.5L}$, along the furrow is 1,482 minutes, and the recession time at the end of the furrow, $\bar{t}_L$, is 1,502 minutes.

The value of *r* from equation 4–54 is

$$r = \frac{\log\left(\frac{L}{.5L}\right)}{\log\left(\frac{t_L}{t_{.5L}}\right)} = \frac{\log\left(\frac{2050.5}{1013}\right)}{\log\left(\frac{352.7}{116.0}\right)} = .63413 \qquad (4\text{–}61)$$

The value of *p* is found from equation 4–55:

$$p = \frac{L}{t_L^r} = \frac{2050.5}{352.7^{.63413}} = 49.70 \qquad (4\text{–}62)$$

The recession curve is defined by equations 4–56 to 4–59.

$$h = \bar{t}_d = 1,444 \text{ min} \qquad (4\text{–}63)$$

$$i = \frac{m^2 \bar{t}_L - \bar{t}_{.5L} + \bar{t}_d \left(m^2 - 1\right)}{L\left(m^2 - m\right)}, \text{ where } m = \frac{.5L}{L} = \frac{1,013}{2,050.5} = 0.494$$

$$i = \frac{.494^2 \left(1,502\right) - 1,482 - 1,444\left(.494^2 - 1\right)}{2050.5\left(.494^2 - .494\right)} = 0.04652 \qquad (4\text{–}64)$$

$$j = \frac{\bar{t}_L - \bar{t}_d - i \times L}{L^2} = \frac{1,502 - 1,444 - 0.04652 \times 2,050.5}{2,050.5^2} = -0.000008889 \qquad (4\text{–}65)$$

(2) Infiltration

Not only is infiltration one of the most crucial hydraulic parameters affecting surface irrigation, but it is also one of the most difficult parameters to assess accurately in the field. The importance of knowing the infiltration function to describe the hydraulics of a surface irrigation event, along with the inherent difficulties in obtaining reliable estimates of this parameter, means that the investigator should expect to spend considerable time and effort in assessing infiltration before proceeding with the design of a surface irrigation system.

In the past, the three most commonly employed techniques for measuring infiltration were cylinder infiltrometers, ponding, and inflow-outflow field measurements. For furrow irrigation, the blocked furrow method has been used, while a more recent technique is the flowing or recycling furrow infiltrometer (fig. 4–46).

Volume balance equation—An alternative to making individual point measurements of infiltration is to compute a representative intake from advance, recession, and the tailwater hydrograph, if available. This involves a two-level iterative procedure. Assuming a furrow configuration for purposes of demonstration, the first level uses a volume balance computation.

$$60Q_o t_x = \sigma_y A_o x + \sigma_z K t_x^a x + \frac{1}{(1+r)} F_o t_x x + Cx \tag{4–66}$$

where:

Q_o = inflow per unit width or per furrow at the upstream end of the field in ft^3/s

t_x = time since inflow was initiated, in min

σ_y = surface flow shape factor

A_o = flow cross-sectional area at the flow's upstream end at time t_x, in ft^2

x = the distance from the inlet that the advancing front has traveled in t_x minutes, in ft

σ_z = subsurface shape factor described by

$$\sigma_z = \frac{a + r(1-a) + 1}{(1+r)(1+a)} \tag{4–67}$$

where:

r = exponent in the power advance equation 4–53

The value of σ_y is generally assumed to be constant with values between 0.75 and 0.80. However, its value actually changes with field slope, flow shape, slope of advance trajectory, and field length. At the time of the writing of this manual, no general guidelines were available for selecting a value of σ_y except that to assume it has a constant value of 0.77. A temporary estimation is provided as follows, but users of this manual should be aware that new information will provide a better approximation in the future.

The flow velocity at the advancing front when it has reached the field midpoint can be found by differentiating equation 4–53 and then dividing the result by the average velocity at the inlet to define a dimensionless velocity.

Figure 4–46 Flowing furrow infiltrometer

$$V_{.5L}^{*}=\frac{\frac{dx}{dt_x}}{V_o}=\frac{rpt_{.5L}^{r-1}}{\frac{Q_o}{A_o}} \quad (4–68)$$

and when the advance has reached the end of the field

$$V_{L}^{*}=\frac{\frac{dx}{dt_x}}{V_o}=\frac{rpt_{L}^{r-1}}{\frac{Q_o}{A_o}} \quad (4–69)$$

The value of σ_y at both the midpoint and the field length can then be estimated as:

$$\sigma_{y|_{x=L}}=\frac{0.778}{1+0.363e^{-12.07V_L^*}} \quad (4–70)$$

$$\sigma_{y|_{x=0.5L}}=\frac{0.778}{1+0.363e^{-12.07V_{.5L}^*}} \quad (4–71)$$

Volume balance estimate of Kostiakov *a, K*, and *F*

Volume balance estimate of Kostiakov a, K, and F_o—Data from the field evaluation will have defined Q_o (and, therefore, A_o), as well as $t_{.5L}$, t_L (and, therefore, r, V_L^*, $V_{.5L}^*$, and σ_y). The unknowns in equation 4–66 are the intake parameters a, K, and F_o (or a, k, f_o, and c if the border/basin evaluation is being conducted). The value of the cracking term c or C, must be input separately, if it is known. Solving for these in equation 4–66 provides the methodology for evaluating the average infiltration function along the length of a field using basic evaluation data.

As noted above, the procedure for finding intake parameter is iterative. The steps are as follows for furrow systems specifically and are the same for border/basin systems with the appropriate intake parameters. Note that the software accomplished these steps interactively as demonstrated.

Step 1 Assume an initial value of F_o to be zero. Equation 4–66 can then be solved for any distance from the field inlet to define the volume balance at any time during the advance phase, but perhaps the two most important are the distance from the inlet to the field midpoint and to the end of the field. Doing so, but consolidating known terms on the right-hand side yields the following two volume balance expressions:

$$\sigma_z K t_L^a=\frac{Q_o t_L-\sigma_y A_{o|x=L}L-\frac{1}{1+r}F_o t_L L}{L}=I_L \quad (4–72)$$

and

$$\sigma_z K t_{.5L}^a=\frac{Q_o t_{.5L}-\sigma_y A_{o|x=.5L}(.5L)-\frac{1}{1+r}F_o t_{.5L}(.5L)}{.5L}=I_{.5L} \quad (4–73)$$

Taking the log of both equations provides a definition of a and K as follows.

$$a=\frac{\log\left(\frac{I_L}{I_{.5L}}\right)}{\log\left(\frac{t_L}{t_{.5L}}\right)} \quad (4–74)$$

Then r is computed from equation 4–49 to find σ_z from equation 4–67. Then K is found by substitution back into equation 4–72:

$$K=\frac{I_L}{\sigma_z t_L^a} \quad (4–75)$$

Step 2 Select 10 to 20 points along the field length, including the inlet and field end, and compute the depth of infiltration at each point using equation 4–27 (the Kostiakov–Lewis equation) with the a, K, and F_o parameters available from step 1 along with the intake opportunity time, τ, from equation 4–60. Then determine the total volume of infiltrated water.

Step 3 The total volume of infiltration computed in step 2 should equal the volumetric difference between the inflow and outflow hydrographs for free draining systems or the total inflow for blocked end systems. This is unlikely for the first iteration unless the value of F_o is indeed the assumed value. Generally, the volume of infiltration calculated in the first iteration will be too low, and F_o will need to be increased. If F_o is initially set to zero and the resulting volume of infiltration from steps 1 to 3 is too low, the values of a, K, and F_o are as good as the volume balance can provide. A revised value of F_o should be made based on the error in the infiltrated volume and steps 1, 2, and 3 repeated using revised values of the Kostiakov-Lewis parameters. When the least error is produced, the best estimate of the average field intake has been made with the volume balance methodology.

Example—To demonstrate this procedure,

- Open an application of **Surface.**
- Load the data file FreeDrainingFurrow_2.cfg.
- Open the input notebook by clicking the **input** button.
- Select the **Input Control** panel.
- Click the **Continuous Inflow Hydrograph** button.
- Simulate the system by clicking on the **run** button.

Figure 4–47 shows the result in the advance/recession plot, and figure 4–48 shows the tailwater hydrograph.

Except for the recession curve, the hydrograph data in the FreeDrainingFurrow_2.cfg data set are not simulated well, and the intake parameters need to be adjusted. Actually, the hydrograph data were derived from a furrow of similar characteristics but different intake parameters. The inflow for the hydrograph data is 0.033 ft^3/s, whereas, the intake parameters in the data set were derived from an inflow of 0.022 ft^3/s.

To calibrate the intake parameters using the volume balance procedure, click the **Infiltration Characteristics** panel, and set the Q_{infilt} box to 0.033 ft^3/s. Make sure the **Continuous Inflow Hydrograph** button in the Input Control is selected and that the parameters in the boxes below the **Two-Point** button are set to 352.7 minutes, 116 minutes, and 1,013 feet, respectively. Then click the **Two-Point** button, and notice that the ***a*** and ***K*** parameters are adjusted to 0.2473 and 0.01859, respectively. Repeat the simulation using these data by clicking on the button. Finally, activate the advance/recession and tailwater runoff hydrograph plots as presented in figure 4–49. The runoff hydrograph will look about the same as figure 4–48.

The volume balance procedure calibrated the intake parameters so they produced an accurate simulation of the advance trajectory, but under estimated the volume of tailwater indicating that the value of F_o is too large. To adjust the calibration so both the advance trajectory and the tailwater hydrograph are simulated accurately, reduce the value of F_o, by trial and error, click on the **Two-Point** button to adjust a and K with each F_o trial, and then re-run the simulation. When the value of F_o is about 0.00025 $ft^3/ft/min$, a is 0.3273, and K is 0.01432 $ft^3/ft/min^a$, the advance fit will appear like figure 4–49 and the tailwater plot like figure 4–50.

Adjusting infiltration for furrow wetted perimeter—Three situations exist that may require an adjustment of the infiltration parameters a, k, and f_o or a, K, and F_o. The first is when values from tables 4–4 through 4–7 need to be adjusted to distinguish between furrow and border/basin infiltration rates independently of tables 4–8 through 4–11. The second

Figure 4–47 Advance/recession curve for the example FreeDrainingFurrow_2.cfg data

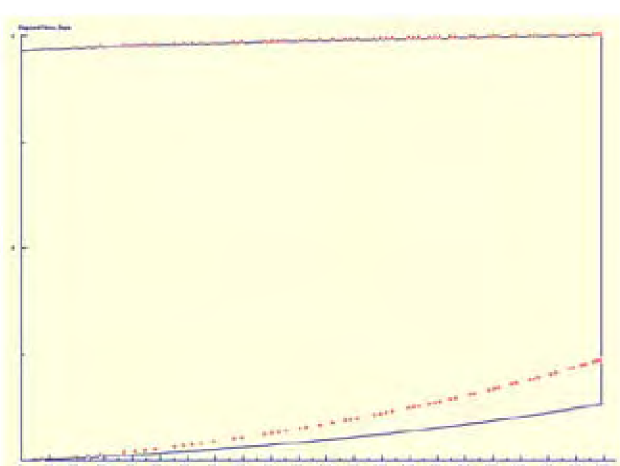
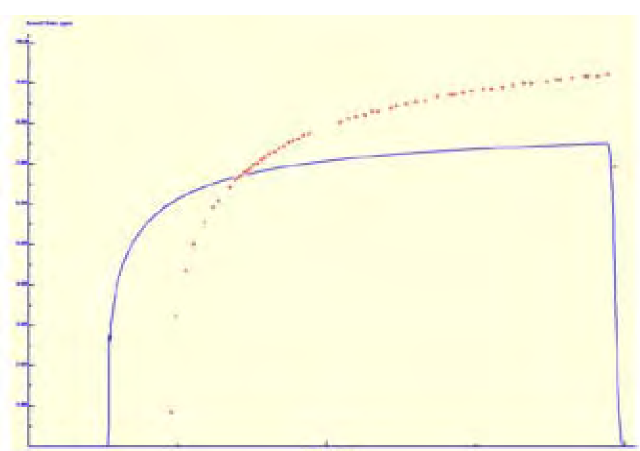


Figure 4–48 Tailwater hydrograph for the example FreeDrainingFurrow_2.cfg data



case occurs where intake coefficients might be modified and where one wishes to delineate the effects of wetted perimeter variations along a furrow. The basic argument for not making this adjustment is that simultaneous adjustments must also account for varying roughness and cross section, both of which tend to minimize the effect of wetted perimeter. The third case occurs when the furrow infiltration coefficients have been defined using furrow advance data (and derived from one value of inflow, slope, length of run, etc.), but then the simulation or design analysis is based on a different values of field parameters. This is the most important of the three possible reasons for adjusting infiltration coefficients since improving simulation or design capabilities inherently implies field definition of infiltration.

The infiltration coefficients *K*, *a*, and F_o in tables 4–4 through 4–7 and equation 4–26 are defined for furrow irrigation at a specific discharge and, therefore, a specific wetted perimeter. If the simulated flow is significantly different from the discharge where infiltration is defined, the intake coefficients should be adjusted. Although there are a number of studies that have examined ways to adjust infiltration for wetted perimeter, most require a substantially more rigorous treatment of infiltration than can be accommodated here. Consequently, a relatively simple adjustment is used. Using equations 4–39, 4–40, and 4–42, the wetted perimeter can be extracted and defined for the flow where the coefficients are determined.

$$WP_{Infilt} = \gamma_1 \sigma_1^{\frac{\gamma_2}{\sigma_2}} \left(\frac{\frac{0.4529 \cdot Q_{Infilt}^2}{3600} n^2}{S_o \rho_1} \right)^{\frac{\gamma_2}{\sigma_2 \rho_2}} \tag{4–76}$$

where:

Q_{infilt} = flow where the infiltration coefficients have been determined in ft^3/min

WP_{Infilt} = corresponding wetted perimeter, ft

Then the coefficient ξ is defined as:

$$\xi = \left[\frac{WP_o}{WP_{Infilt}} \right] \tag{4–77}$$

where:

WP_o = actual wetted perimeter at the field inlet

Then the Kostiakov-Lewis equation is revised by multiplying the *K* and F_o parameters by ξ:

$$Z = \xi \left[K\tau^a + F_o \tau \right] \tag{4-78}$$

Figure 4–49 Corrected advance/recession curve for FreeDrainingFurrow_2.cfg data

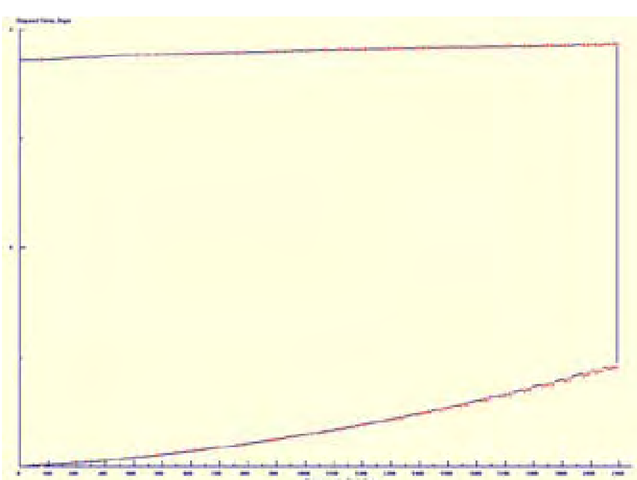
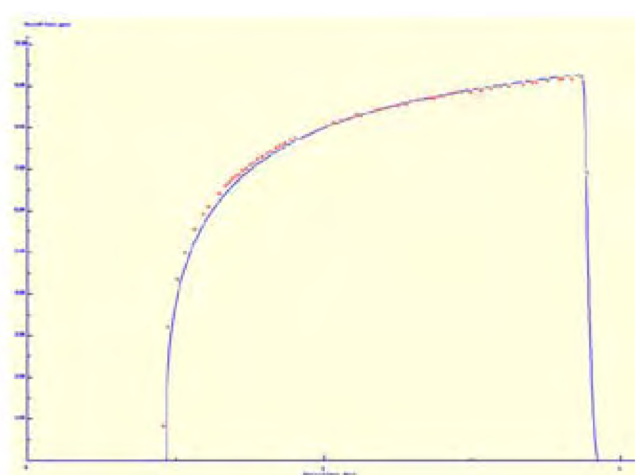


Figure 4–50 Final simulated tailwater hydrograph for FreeDrainingFurrow_2.cfg data



Then the Kostiakov-Lewis equation is revised by multiplying the K and F_o parameters by ξ:

$$Z = \xi\left[K\tau^a + F_o\tau\right] \tag{4–78}$$

General comment—The adjustment of infiltration for wetted perimeter variation along the furrow is one topic of interest to model developers. It has generated some interesting debate. On one hand, the wetted perimeter is known to vary along the furrow with the decreasing flow and should be adjusted accordingly at each computational node. This concept is technically correct as far as discharge variation is concerned but relies also on the assumption that hydraulic roughness and cross section are constant along the furrow, an assumption that is known to be weak. The other side of the argument is that two other important parameters are varying in a fashion that compensates for the diminishing discharge along the furrow. The roughness increases along the furrow as the effects of less water movement produces less smoothing of the furrow surface, thus increasing wetted perimeter. Also, with less flow along the furrow, the flow cross section is less eroded, therefore, less efficient. The result is that wetted perimeter remains nearly constant over a substantial length of furrow in spite of discharge reduction. This assumption was made in nearly all early versions of surface irrigation models. Report after report shows this to be adequate.

Another important issue in this regard is the spatial variability of infiltration and roughness. A number of studies have shown that measurements of roughness, K, a, and F_o will exhibit a great deal of variation over a field. The analysis above assumes the values input will be representative of nearly average values for the field.

623.0403 Redesigning Surface Irrigation Systems

The vast majority of design efforts in the surface irrigation arena will be devoted to modifying or fine tuning systems already in place rather than developing entirely new systems. Perhaps a more descriptive term would be redesign. One can readily see different design objectives in the two views of surface irrigation design. The focus of new system design is to create a workable, profitable, and effective system. The focus of redesign or design modification is conservation of water, labor, soil, and capital resources.

The context of this section is redesigning surface irrigation systems for improving their performance. The term design will be used in the discussion and examples to be consistent with historical practice.

(a) The objective and scope of surface irrigation design

The surface irrigation system should replenish the root zone reservoir efficiently and uniformly so crop stress is avoided. It should provide a uniform and effective leaching application when needed. Occasionally, it may need to be capable of meeting special needs such as seed bed preparation, cooling, frost protection, and chemigation. It may also be used to soften the soil for better cultivation or even to fertilize the field and apply pesticides. Resources like energy, water, nutrients, and labor should be conserved.

The design procedures outlined in the following sections are based on a target application depth, z_{req}, which equals the soil moisture extracted by the crop between irrigations. The value of z_{req} is equivalent to the soil moisture deficit. Design is a trial and error procedure. A selection of lengths, slopes, field inflow rates, and cutoff times can be made that will maximize efficiency and uniformity for a particular configuration. Iterating through various configurations provide the designer with information necessary to find a global optimum. Considerations such as erosion and water supply limitations will act as constraints on the design procedures. Many fields will require a subdivision to utilize the total flow available within a period. This is a judgment that the designer must make after weighing all other factors that are relevant to the successful operation of the system. Maximum efficiencies, the implicit goal of design, will occur when the least-watered areas of the field receive a depth equivalent to z_{req}. Minimizing differences in intake opportunity time will minimize deep percolation and maximize uniformity. Surface runoff should be controlled or reused.

The design intake opportunity time is defined in the following way from equations 4–29 and 4–30:

$$Z_{req} = K\tau_{req}^{a} + F_o\tau_{req} + C, \text{ for furrows}$$

$$z_{req} = k\tau_{req}^{a} + f_o\tau_{req} + c, \text{ for borders and basins} \quad (4–79)$$

where:

Z_{req} = required infiltrated volume per unit length and per unit width or per furrow spacing

τ_{req} = design intake opportunity time

In the cases of border and basin irrigation, Z_{req} is numerically equal to z_{req}. However, for furrow irrigation, the furrow spacing must be introduced to reconcile Z_{req} and z_{req} as follows:

$$Z_{req} = z_{req}w \quad (4–80)$$

where:

w = furrow to furrow spacing

Whether the irrigation specialist is designing a new surface irrigation system or seeking to improve the performance of an existing system, the design should be based on careful evaluation of local soil, topography, cultural, and climatic conditions. The selection of system configurations for the project is, in fact, an integral part of the project planning process.

In either case, the data required fall into six general categories as noted in 623.0400.

- nature of irrigation water supply in terms of the annual allotment; method of delivery and charge for water; discharge and duration, frequency of use, and the quality of the water
- topography of the land with particular emphasis on major slopes, undulations, locations of water delivery, and surface drainage outlets
- physical and chemical characteristics of the soil, especially the infiltration characteristics, moisture-holding capacities, salinity, and internal drainage
- cropping pattern, its water requirements, and special considerations given to assure that the irrigation system is workable within the harvesting and cultivation schedule, germination period, and the critical growth periods
- marketing conditions in the area, as well as the availability and skill of labor; maintenance and replacement services; funding for construction and operation; energy, fertilizers, seeds, and pesticides
- cultural practices employed in the farming region, especially where they may constrain a specific design or operation of the system

(b) Basic design process

The surface irrigation design process is a procedure to determine the most desirable frequency and depth of irrigation within the capacity and availability of the water supply. This process can be divided into a preliminary design stage and a detailed design stage.

(1) Preliminary design

The operation of the system should offer enough flexibility to supply water to the crop in variable amounts and schedules and thereby allow the irrigator some scope to manage soil moisture for maximum yields, as well as water, labor and energy conservation, and changes in cropping patterns. Water may be supplied on a continuous or a rotational basis in which the flow rate and duration may be relatively fixed. In those cases, the flexibility in scheduling irrigation is limited by water availability or to what each farmer or group of farmers can mutually agree upon within their command areas. On-demand systems should have more flexibility than continuous or rotational water schedules and are driven by crop demands. During preliminary design, the limits of the water supply in satisfying an optimal irrigation schedule should be evaluated. It is particularly important that water measurement be an integral component of the water supply and that it is capable of providing the appropriate depth of water to the field as indicated by equation 4–38.

The next step in the design process involves collecting and analyzing local climate, soil, and cropping patterns to estimate the crop water demands. From this analysis, the amount of water the system should supply through the season can be estimated. Comparing the net crop demands with the capability of the water delivery system to supply water according to a variable schedule can produce a tentative schedule. Whichever criterion (crop demand or water availability) governs the operating policy at the farm level, the information provided at this stage will define the limitations of the timing and depth of irrigations during the growing season.

The type of surface irrigation system selected for the farm should be carefully planned. Furrow systems are favored in conditions of relatively high bi-directional slope, row crops, and small farm flows and applications. Border and basin systems are favored in the flatter lands, large field discharges, and larger depths of application. A great deal of management can be applied where flexibility in frequency and depth are possible.

(2) Detailed design

The detailed design process involves determining the slope of the field, the furrow, border, or basin inflow discharge and duration; the location and sizing of headland structures and miscellaneous facilities; and the provision of surface drainage facilities either to collect tailwater for reuse or for disposal.

Land leveling can easily be the most expensive on-farm improvement made in preparation for irrigation. It is a prerequisite for the best performance of the surface system. Generally, the best land leveling strategy is to do as little as possible, such as to grade the field to a slope that involves minimum earth movement. Exceptions will be necessary when other considerations dictate a change in the type of system, say, basin irrigation, and yield sufficient benefits to offset the added cost of land leveling.

If the field has a general slope in two directions, land leveling for a furrow irrigation system is usually based on a best-fit plane through the field elevations. This minimizes earth movement over the entire field, and unless the slopes in the direction normal to the expected water flow are very large, terracing and benching would not be necessary. A border must have a zero slope normal to the field water flow and thus, will require terracing, contouring the borders in all cases of cross slope. The border slope is usually the best-fit sub-plane or strip. Basins, of course, are level, such as, no slope in either direction. Terracing is required in both directions. When the basin is rectangular, its largest dimension should run along the field's smallest natural slope to minimize leveling costs.

Field length becomes a design variable at this stage and, again, there is a philosophy the designer must consider. In mechanized farming, long rectangular fields are preferable to short square ones. This notion is based on the time required for implement turning and realignment.

The next step in detailed design is to reconcile the flows and times with the total flow and its duration allocated to the field from the water supply. On small fields, the total supply may provide a satisfactory coverage when used to irrigate the whole field simultaneously. However, the general situation is that fields must be broken into sets and irrigated part by part, such as, basin by basin or border-by-border. These subdivisions or sets must match the field and its water supply.

Once the field dimensions and flow parameters have been formulated, the surface irrigation system must be described structurally. To apply the water, pipes or ditches with associated control elements must be sized for the field. If tailwater is permitted, means for removing these flows must be provided. Also, the designer should give attention to the operation of the system. Automation will be a key element of some systems.

The design algorithms used are programmed in the NRCS **Surface** software discussed in section 626.0402. This section demonstrates the design and improvement processes.

(c) Basic design computations

The difference between an evaluation and a design is that data collected during an evaluation include inflows and outflows, flow geometry, length and slope of the field, soil moisture depletion, and advance and recession rates. The infiltration characteristics of the field surface can then be deduced and the efficiency and uniformity determined for that specific evaluation. Design procedures, on the other hand, input infiltration functions (including their changes during the season and as flows change), flow geometry, field slope and length to compute advance and recession trajectories, the distribution of applied water, and tailwater volumes or pond. The design procedures also determine efficiencies and uniformities. However, the design process can be applied to many more field conditions than an evaluation to determine efficiencies and uniformities through of the surface irrigation model, NRCS **Surface**.

There are five basic surface irrigation design problems:

- free-draining systems
- blocked-end systems
- free-draining systems with cutback
- free-draining systems with tailwater recovery and reuse
- surge flow systems

The philosophy of design suggested here is to evaluate flow rates and cutoff times for the first irrigation following planting or cultivation when roughness and intake are at their maximums, as well as for the third or fourth irrigation when these conditions have been changed by previous irrigations. This will yield a design that will have the flexibility to respond to the varying conditions the irrigator will experience during the season. All of the specific data required for design were enumerated in 623.0402.

(1) Free-draining surface irrigation design

All surface irrigation systems can be configured to allow tailwater runoff. However, this reduces application efficiency, may erode soil from the field, or cause similar problems associated with degraded water quality. Therefore, it is not a desirable surface irrigation configuration. However, where water is inexpensive, the costs of preventing runoff or capturing and reusing it may not be economically justifiable to the irrigator. In addition, ponded water at the end of the field represents a serious hazard to production if the ponding occurs over sufficient time to damage the crop (scalding).

Furrow irrigation systems normally allow the outflow of tailwater. Tailwater outflow from border systems is less common but remains a typical feature. As a rule, tailwater runoff is not a feature included in basin irrigation except as an emergency measure during high rainfall events or when the irrigators overfill the basin. The design algorithms are for free-draining field conditions apply primarily to furrow and border systems.

The basic design procedures for free-draining systems involve eight steps:

Step 1 Identify the field control point.

Step 2 Determine the required intake opportunity time (τ_{req}).

Step 3 Select a unit flow and compute the advance time (t_L).

Step 4 Compute the cutoff time.

Step 5 Evaluate uniformity and efficiency.

Step 6 Iterate steps 1 through 5 until the optimal system is determined, usually on the basis of maximum irrigation efficiency subject to a lower limit on storage efficiency.

Step 7 Repeat the design computation for the later irrigation conditions.

Step 8 Configure the field into sets that will accommodate the water supply.

Step 9 Determine how to uniformly apply water using pipes, ditches, and controls.

At the end of this procedure, the designer should consider whether or not the field geometry should be changed, reducing the run length, for example, or perhaps targeting a different application depth. Since the design computations can be made quickly, the designer should examine a number of alternatives before recommending one to the irrigator.

The location of the field control point is where the minimum application will occur. In free-draining furrows, this point is at the downstream end of the field. In borders, the field control point may be at either end of the field depending on the recession processes and cannot be determined until the irrigation regime is simulated by the **Surface** software. The cutoff time is approximated by the sum of the required intake opportunity time, τ_{req}, and the advance time, t_L, for furrows. Recession can usually be neglected in furrow irrigation if the design computations are being made manually. For borders, the cutoff time is either of two conditions:

- when the difference between the recession time ($\bar{t}_L$) and the advance time (t_L) equals the required intake opportunity time (τ_{req}) for the case where the field control point is at the downstream end of the field; or

- when the recession time at the field inlet (or depletion time) equals the required intake opportunity time in the case where the field control point is at the field inlet.

There are volume balance procedures for accomplishing the free-draining design process, and they work reasonably well for furrow irrigation. They can be used for free-draining borders, but the recession computations are inaccurate. Consequently, it is not recommended that volume balance be used in design, but rather the hydrodynamic features of the NRCS **Surface** software or a similar program such as the **SRFR** software.

Example Free-draining Furrow Design—Open the **Surface** software, load the FreeDrainingFurrow_1.cfg data file supplied with the software, and execute the simulation programming for the initial intake condition. At the end of the simulation, observe the distribution of infiltrated water and runoff, as well as the various efficiencies and uniformity that were determined. Then click on the **plot output results**, and from the pull-down menu **Current Data Plot Options**, select **Advance Data** and then **Tailwater Data**. These two plots are reproduced here as figures 4–51 and 4–52. The specific uniformity and efficiency terms associated with this irrigation are shown in the **Simulated System Performance** box in the lower right of the simulation screen.

The distribution of applied water from the main simulation screen is reproduced in figure 4–53, a classic case of a field that is too long for the soil intake characteristics. Even with a furrow stream of 32 gpm, the advance is not completed for almost 7 hours. At the inlet where the intake opportunity time needed was only 160 minutes to apply the 4-inch depth required, the actual depth applied is almost 9.5 inches.

To begin examining alternatives to improve this irrigation, open the input tabbed notebook by clicking on the input button. Then select **Design Panel**, shown in figure 4–54.

The first observation that can be made is the total flow required to irrigate the entire field simultaneously (shown in red) is more than 30,000 gpm, which is more than 12 times the flow available (2,400 gpm). Click on the right field layout side-to-side button until the

Figure 4–51 FreeDrainingFurrow_1 advance/recession trajectory

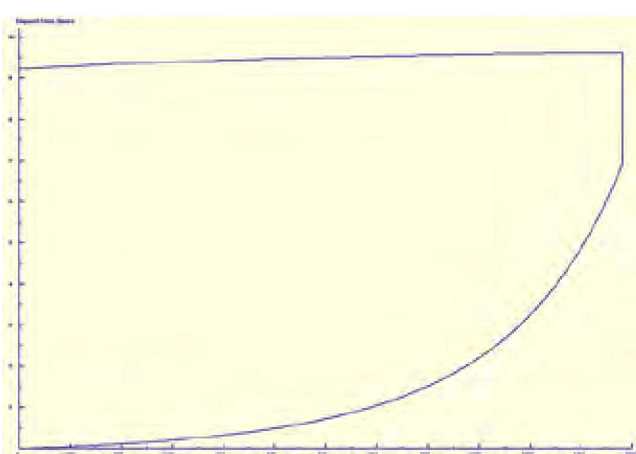


Figure 4–52 FreeDrainingFurrow_1 tailwater hydrograph

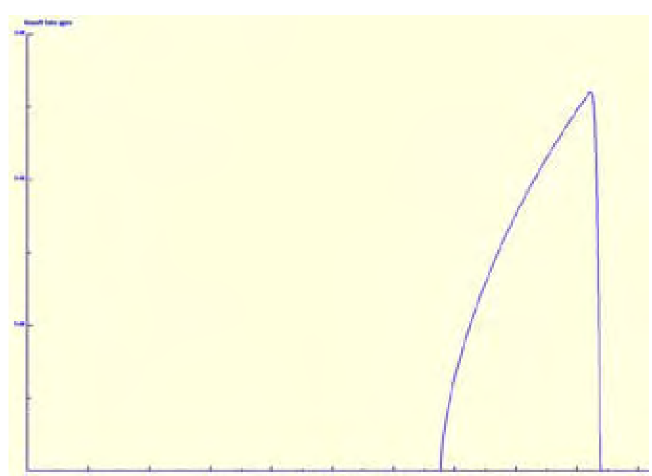


Figure 4–53 Soil moisture distribution from FreeDrainingFurrow_1 data

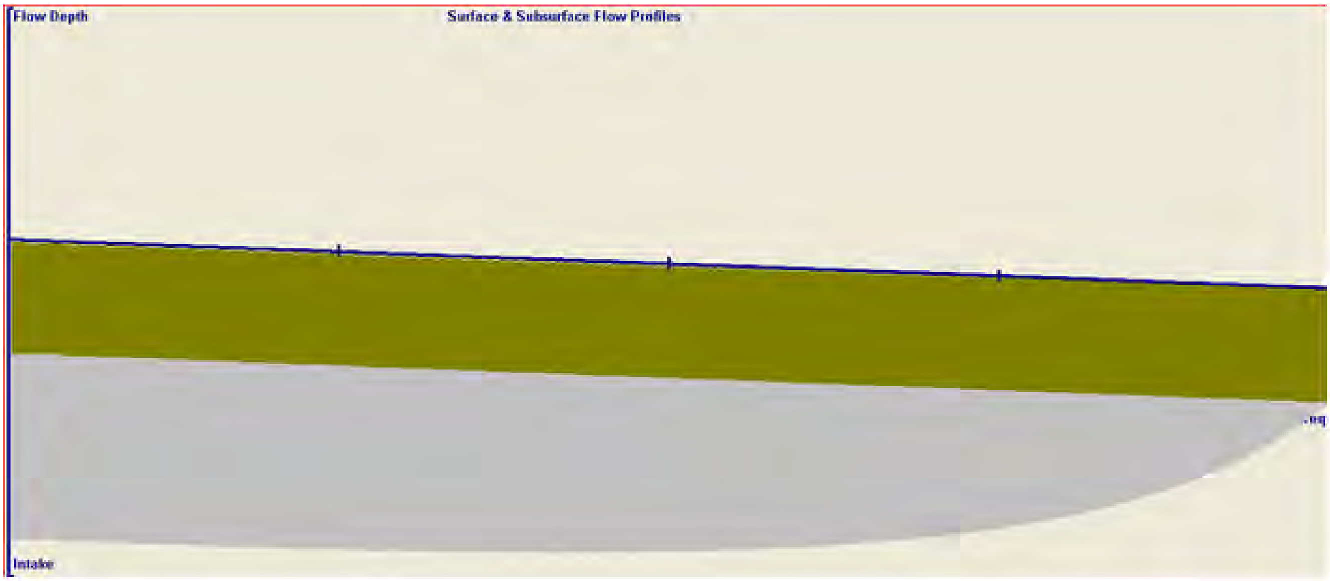
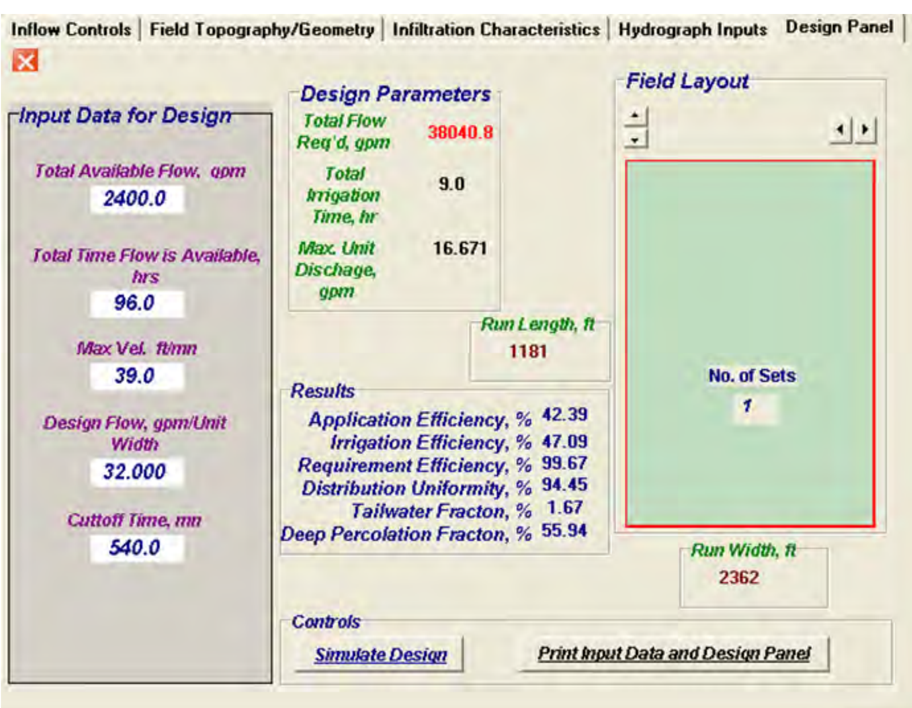


Figure 4–54 **Surface** Design Panel for initial FreeDrainingFurrow_1 condition



conflict between available flow and required flow is resolved by irrigating in sets. Thirteen sets are required to satisfy the flow constraint, but, in doing so, total time the supply needs to be available has increased to 104 hours, when, only 96 hours are allowed. There does not appear to be a feasible design option irrigating the full length of these furrows. In cases where both time and flow constraints can be managed, the next step is to determine if different flows and cutoff times would improve the irrigation.

The next redesign option is to change the run length. This can be accomplished by clicking on the left up-down button to cut the run length in half. Then the furrow stream size can be reduced along with changes in the time of cutoff to achieve a feasible and improved irrigation. Figure 4–55 is the design panel after a trial and error series of adjustments. To satisfy the constraints on total available flow and duration, it was necessary to divide the field into 18 sets, all of which are irrigated in 4 hours using a stream size of 22.5 gpm. The irrigation efficiency was increased from about 42 percent to about 68 percent. At this point, the user may wish to see if further improvements can be made.

Once the design has been made for the initial intake conditions, it needs to be repeated for the later intake conditions. This can be accomplished by selecting the check box for the later irrigation conditions on the Infiltration Characteristics panel in the input tabbed notebook (fig. 4–56), and repeating the procedure noted above. The design for the later irrigations will be left to the reader to do, but try reducing the number of sets to 9, increasing the cutoff time to 11 hours, and reducing the furrow stream to 7.5 gpm.

One of the most difficult aspects of surface irrigation is the reconciliation of the water supply characteristics and the onfield irrigation requirements. It can be observed that in the designs described, the flow required was less than the total available. This assumes the supply flow rate is flexible. If the design processes are repeated with the delivery fixed at 2,400 gpm, the efficiency at the field level might be reduced considerably. In the case of the FreeDrainingFurrow_1 example, setting the design flow to 22.86 gpm for the initial irrigations reduces the irrigation efficiency by only 1 percent. The later irrigations, in this case, are not a serious problem. By reducing the unit flow to 7.62 gpm, it is possible to accommodate the entire 2,400 gpm supply and achieve about the same application efficiency of nearly 72 percent.

Example free-draining border design—In an open instance of **Surface**, load the FreeDrainingBorder_4.cfg and execute the simulation for the initial irrigation conditions. Figures 4–57 and 4–58 show the advance and recession trajectories and the tailwater hydrograph. The resulting soil moisture distribution shows that most of the border length was under irrigated. The application efficiency is only 39 percent, primarily due to a 43 percent loss of tailwater. The 10 percent leaching fraction is more than satisfied with a nearly 17 percent deep percolation loss.

Both the discharge and the time of cutoff time are too large. By iteratively reducing the inflow and the duration of the irrigation, it is possible to substantially improve the performance of this irrigation. In this case, it is not necessary to adjust the field length since the advance is relatively rapid. Figure 4–59 shows the design panel after several iterations. The irrigation efficiency has been improved to about 75 percent, and the leaching requirement has been met on average, although, not uniformly. The irrigation set time has been decreased to 3 hours from the original 4 hours, and the inflow has been reduced from 6 ft^3/s to 4.5 ft^3/s.

The design for the later intake conditions requires adjustments to the flow and cutoff time. By decreasing the flow to 4.38 ft^3/s and extending the cutoff time to 10 hours, the field can be irrigated in three sets achieving an application efficiency of 57 percent.

Although this irrigation example has been substantially improved, the performance is relatively poor and demonstrates two inherent problems with free-draining borders. First, there can be as much as five times the amount of water on the field surface at the cutoff time as a furrow system; therefore, tailwater can be a major problem. Secondly, if a substantial leaching requirement is needed, high tailwater losses are unavoidable. The best performing borders, like basins, are those with blocked ends demonstrated.

Figure 4–55 Improved design for initial irrigations

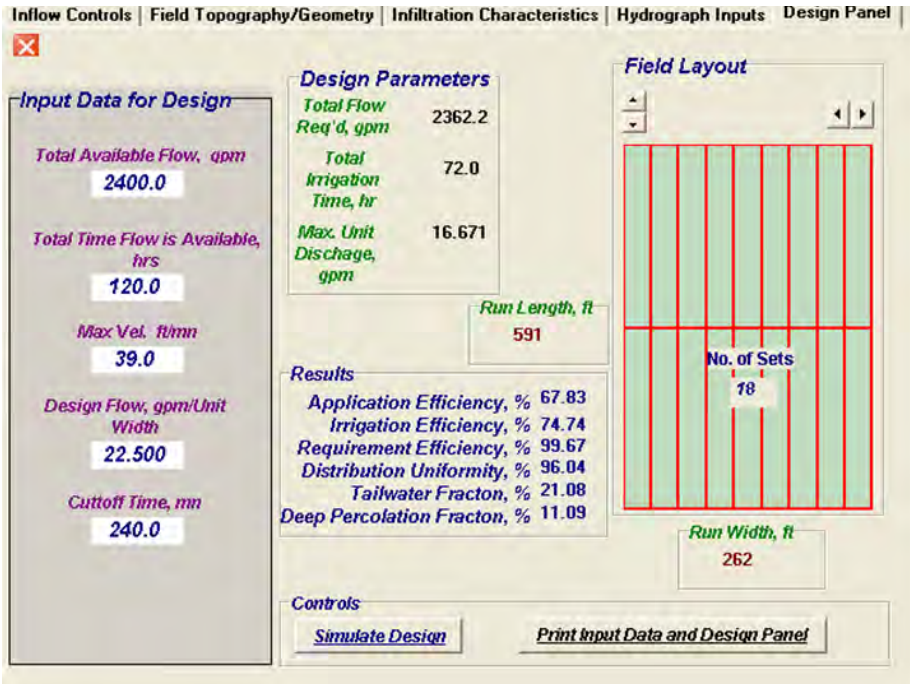


Figure 4–56 Selecting the later irrigation conditions

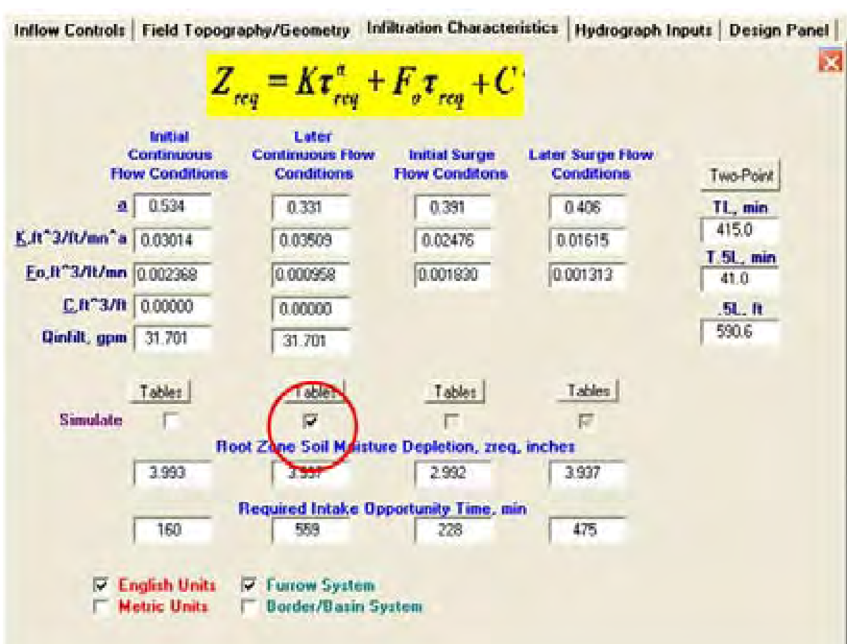


Figure 4–57 FreeDrainingBorder_4 advance and recession plots for initial irrigations

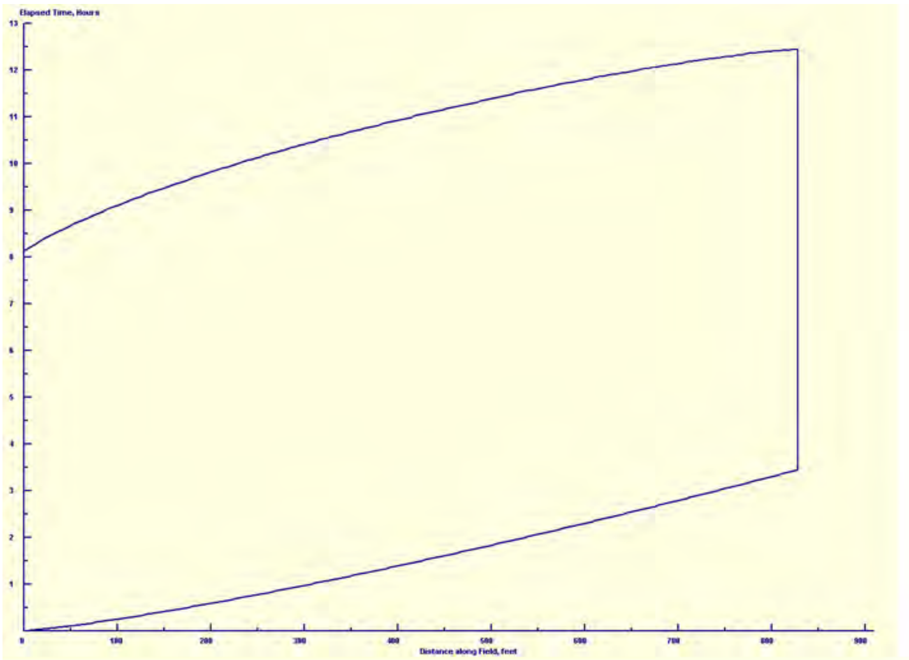


Figure 4–58 Tailwater hydrograph for FreeDrainingBorder_4 data

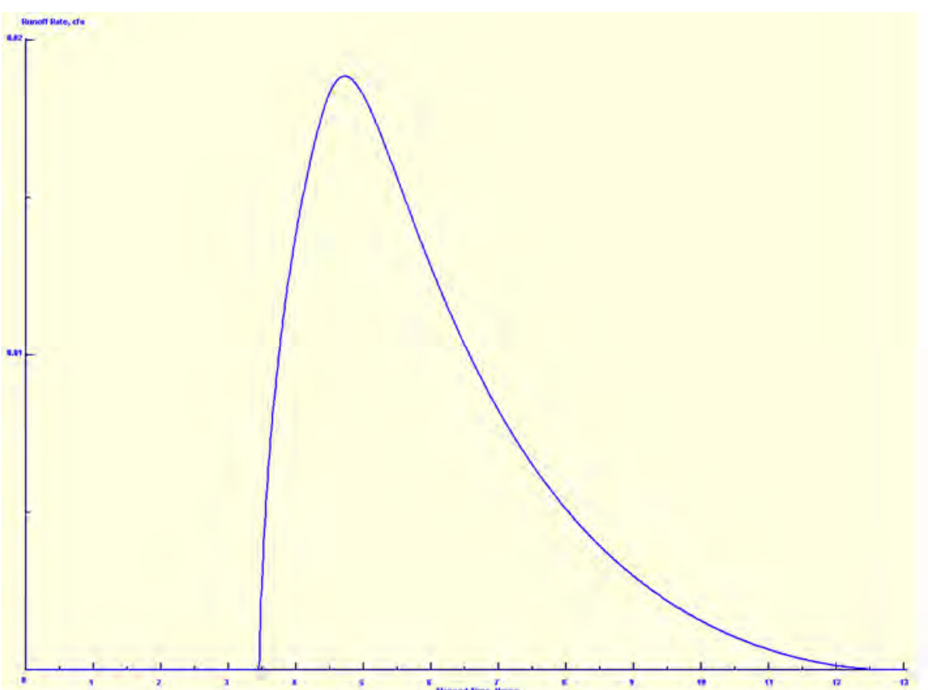
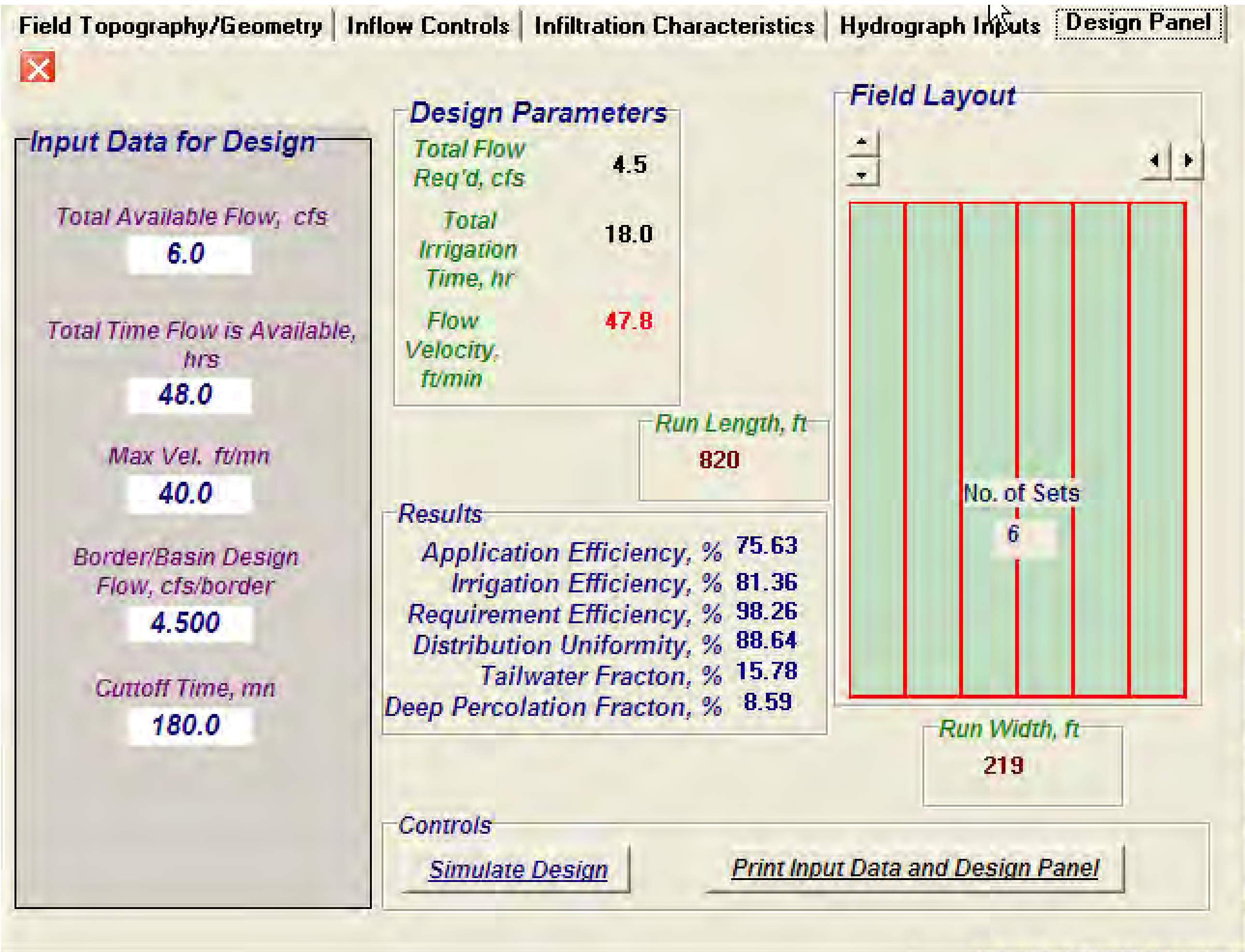


Figure 4–59 Design panel for the final design of the FreeDrainingBorder_4 initial irrigation example



The designer must now address the issue of whether the field has to accommodate the full 6 ft^3/s during each irrigation or whether it can be operated with a flexible supply flow. For the first irrigations, the field would need to irrigate with six sets, each having a reduced flow of about 6 ft^3/s. The irrigation efficiency would decrease to 58 percent indicating that the efficiency cost would be about 17 percent due to fixing the field supply rate. Later irrigations would remain the same.

(2) Blocked-end surface irrigation design

Blocking the end of basin, border, or furrow systems provides the designer and operator with the ability to achieve potential application efficiencies comparable with most sprinkle systems. While blocked-end fields have the potential for achieving high efficiencies, they also represent the highest risk to the grower. Even a small mistake in the cutoff time can result in substantial crop damage due to the scalding associated with prolonged ponding on the field. Consequently, all blocked-end surface irrigation systems should be designed with emergency facilities to drain excess water from the field.

Figure 4–60 shows the four stages of typical blocked-end irrigation. In figure 4–60(a), water is being added to the field and is advancing. In figure 4–60(b), the inflow has been terminated and depletion has begun at the upstream end of the field while the flow at the downstream end continues to advance. This is important. Typical field practices for blocked-end surface irrigation systems generally terminate the inflow before the advance phase has been completed.

In figure 4–60(c), the depletion phase has ended at the upstream end, the advance phase has been completed, and the residual surface flows are ponding behind the downstream dike. Finally, in figure 4–60(d), the water ponded behind the field dike has infiltrated or been released, and the resulting subsurface profile is uniform along the border and equal to the required or target application.

The dilemma for the designer of a blocked-end surface irrigation system is in determining the cutoff time. In practice, the cutoff decision is determined by where the advancing front has reached. This location may be highly variable because it depends on the infiltration characteristics of the soil, the surface roughness, the discharge at the inlet, the field slope and length, and the required depth of application. Until the development and verification of the zero inertia or hydrodynamic simulation models, there were no reliable ways to predict the influence of these parameters or to test simple design and operational recommendations.

One simplified procedure for estimating the cutoff time is based on the assumption that the field control point is at the field inlet for blocked-end systems. By setting the field control point at the upstream end of the field, the cutoff time is approximated by the intake opportunity time, τ_{req} and is independent of the advance time, $\boldsymbol{t_L}$. The specific cutoff time, t_{co}, may be adjusted for depletion as follows:

$$t_{co} = \kappa\tau_{req} \qquad (4\text{–}81)$$

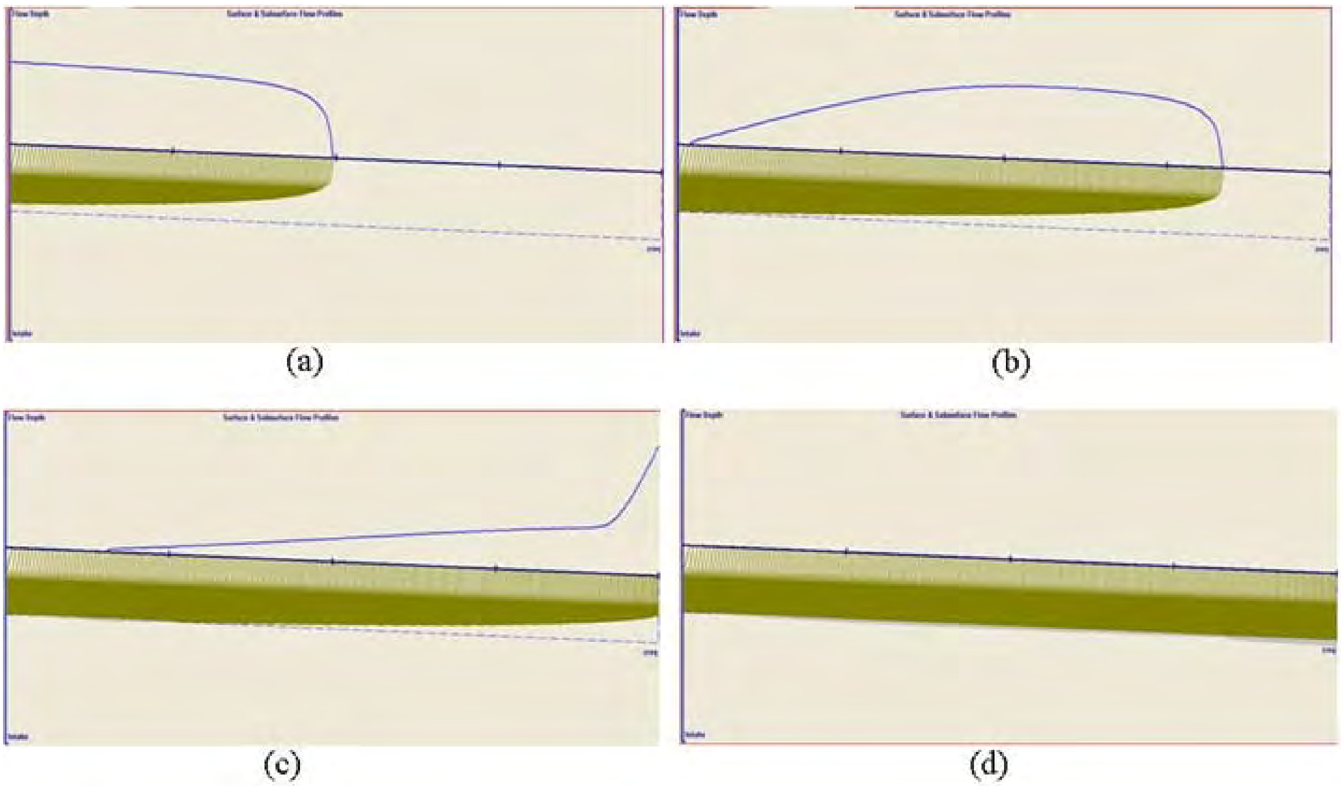
where κ is a simple fraction that reduces t_{co} sufficiently to compensate for the depletion time. As a rule, κ would be 0.90 for light textured sandy and sandy loam soils, 0.95 for medium textured loam and silty loam soils, and 1.0 for clay and clay loam soils.

The volume of water the designer would like to apply to the field is as follows:

$$V_{req} = \psi z_{req} wL \qquad (4\text{–}82)$$

in which the ψ is greater than 1.0 to allow for some deep percolation losses (leaching). If, for instance, the value of w is 1.0 foot and with L and $\boldsymbol{z}_{req}$ also in feet, then V_{req} is in ft^3. If a blocked-end system could apply V_{req} uniformly, it would also apply water with 100 percent application efficiency. Although a blocked-end system obviously cannot do so, the designer should seek a maximum value of efficiency and uniformity. Since equation 4–82 represents the best first approximation to that design, it is at least the starting point in the design process.

Figure 4–60 Stages of a blocked-end irrigation



Given that the inflow will be terminated at t_{co}, the inflow rate must be the following to apply V_{req} to the field:

$$Q_o = \frac{V_{req}}{t_{co}} \quad (4\text{–}83)$$

The procedure for selecting t_{co} and Q_o for blocked-end systems given above is very simple yet surprisingly reliable. However, it cannot work in every case and needs to be checked by simulating the results with the **Surface** software. The risk with the simplified procedure is that some of the field will be under-irrigated and using equation 4–83 to select a flow rate rather than a more rigorous approach will be conservative.

Example Blocked-end border design—Open the file BlockedEndBorder.cfg and examine the input data. The target application depth is 3 inches and with the intake coefficients given will require an intake opportunity time of nearly 312 minutes for initial irrigations and 441 minutes for later irrigations. However, from the earlier simulation in which more than 26 percent of the inflow as deep percolation, the 3-inch application is probably too small. A more realistic value is 4 inches.

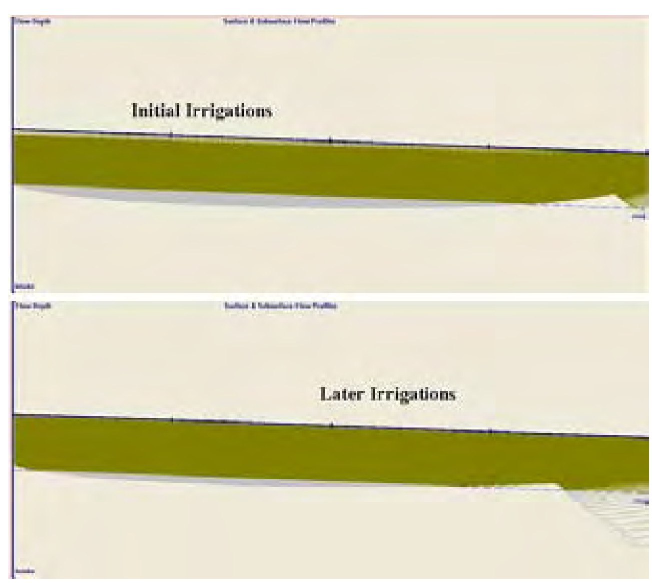
As a starting point, assume the values of κ and ψ in equations 4–81 and 4–82 are 0.70 and 1.15, respectively. Accordingly, the times of cutoff can be estimated to the nearest half hour as 300 minutes and 420 minutes, respectively. From equation 4–82, the volume needed to replace the soil moisture depletion is 460 ft^3/ft, so that from equation 4–83, the inflow should be 2.5 ft^3/s initially (460 ft^3/300 min/60 s/min x 100 ft), and then 1.8 ft^3/s later. If these values are simulated in the **Surface** software, the results, shown in figure 4–61, indicate an irrigation efficiency of more than 66 percent in both cases, but the uniformity is poor near the end of the field. Succeeding iterations can be simulated by making small adjustments to the cutoff time and the inflow, but these will produce only small improvements. Further improvements will require either shortening the run length or flattening the lower 25 percent of the field to improve uniformity at the end of the field.

(3) Design procedure for cutback systems

The concept of cutback has been around for a long time. A relatively high flow is used at the start of an irrigation to speed the advance phase along, and then a reduced flow is implemented to minimize tailwater. As a practical matter, however, cutback systems have never been very successful. They are rigid designs in the sense that they can only be applied to one field condition. Thus, for the condition they are designed for they are efficient, but as the field conditions change between irrigations or from year to year, they can be very inefficient and even ineffective. One adaptation of the concept was the cablegation system. Another was the development and adaptation of surge flow. Both have provided a flexible method of applying the cutback concept although the complexity of Cablegation is problematic.

The **Surface** software does allow one to simulate the conceptual cutback regime for both continuous and surge flow systems. Cutback irrigation involves a high continuous flow until the advance phase is nearing completion or has been completed, followed by a period of reduced or cutback inflow prior to the time of cutoff. The concept of cutback is more applicable to furrow irrigation systems than border systems and is illustrated herein.

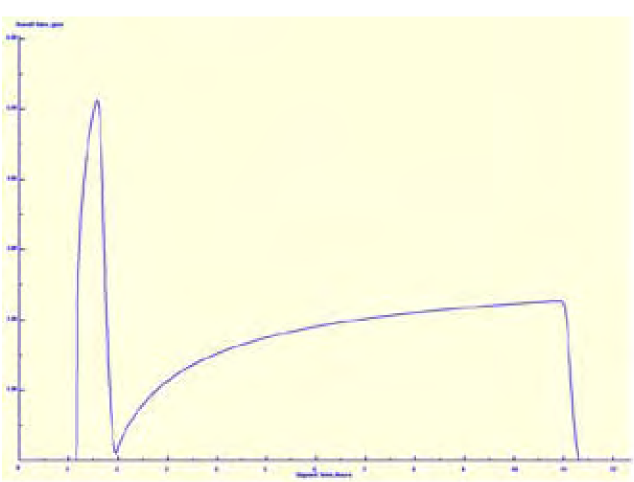
Figure 4–61 Simulation of the BlockedEndBorder.cfg data



Example furrow cutback design—Run the **Surface** software with the CutbackDesign.cfg file loaded. The data file in the input tabbed notebook indicates the inflow regime has been defined by checking the **Continuous Flow w/Cutback** box, and inputting 0.60 for the value of cutback ratio and 1.05 for the CB length fraction. After looking at the data, click on the run button. The simulated flow will complete the advance phase and then the inflow will be reduced resulting in the tailwater hydrograph (fig. 4–62).

If the cutback ratio is too small, the reduced inflow wave will reach the end of the field and the downstream end of the field will dewater. For example, set the cutback ratio to 0.50 and repeat the simulation. The version of the **Surface** software provided at the time of this manual cannot simulate this condition reliably. Consequently, an alert will be presented on the screen and the simulation stopped. As instructed, the user should adjust either the **Cutback Ratio** or the **CB Length Fraction** until the downstream does not dewater.

Figure 4–62 Simulated tailwater hydrograph using the CutbackDesign.cfg data file



(4) Design of systems with tailwater reuse

The efficiency of free-draining surface irrigation systems can be greatly improved when tailwater can be captured and reused. If the capture and reuse is to be applied to the field currently being irrigated, the tailwater reuse design is somewhat more complex than the procedure for traditional free-draining systems because of the need to use two sources of water. The major complexity of reuse systems is the strategy for recirculating the tailwater. One alternative is to pump the tailwater back to the head of the field it originated from to irrigate some part of the field. Or, water captured from one field can be reused on another field. In any case, the tailwater reservoir and pumping system need to be carefully controlled and coordinated with the primary water supply.

Experience suggests that the costs of water from tailwater recycling can be as much as 10 times the cost of water from an irrigation company or irrigation district. Further, the recycling system can be so difficult to manage and maintain that irrigators abandon them. To resolve these and related problems, it is suggested that recycling be very simple; irrigate the field it originates from primarily, and not be mixed with the primary supply, but rather irrigate a portion of the field independently.

To illustrate the design strategy for reuse systems, a manual design procedure for this simple configuration is first presented, and following, an example using the **Surface** software. A typical reuse system shown is schematically in figure 4–61 and is intended to capture tailwater from one part of the field and irrigate one of the sets.

If the surface runoff is to be captured and utilized on another field, the reservoir would collect the runoff from the n sets of figure 4–63 and then supply the water to the headland facilities of the other field. This requires a larger tailwater reservoir, but perhaps eliminates the need for the pump-back system.

In the simplest case of runoff reuse on an independent part of a field, the design is the same whether the tailwater is collected and reused on the originating field or on another field. The following procedure below deals with reuse on the originating field.

Step 1 Compute the inflow discharge per unit width or per furrow and the time of cutoff for a free-draining system that achieves as high an irrigation efficiency as possible without recycling. This discharge is a reasonable trade-off between the losses to deep percolation and tailwater and will tend to minimize the size of the tailwater reservoir.

Step 2 Evaluate the subdivision of the field into sets that will accommodate the total available flow and the duration of the supply.

Step 3 Compute the total runoff volume per unit width or per furrow, V_{ro} from the originating field.

Step 4 Compute the number of furrows or unit widths that can be irrigated from the recycled tailwater and the number that will be irrigated with the primary supply.

$$N_r = \frac{V_{ro} N_T}{\left(V_{ro} + Q_o t_{co}\right)} \qquad (4\text{–}84)$$

where:

N_r = number of unit widths or furrows that can be irrigated by the reuse system

N_T = total unit widths or furrows in the field

$$N_p = \frac{\left(F_w - N_r w\right)}{w} \qquad (4\text{–}85)$$

where:

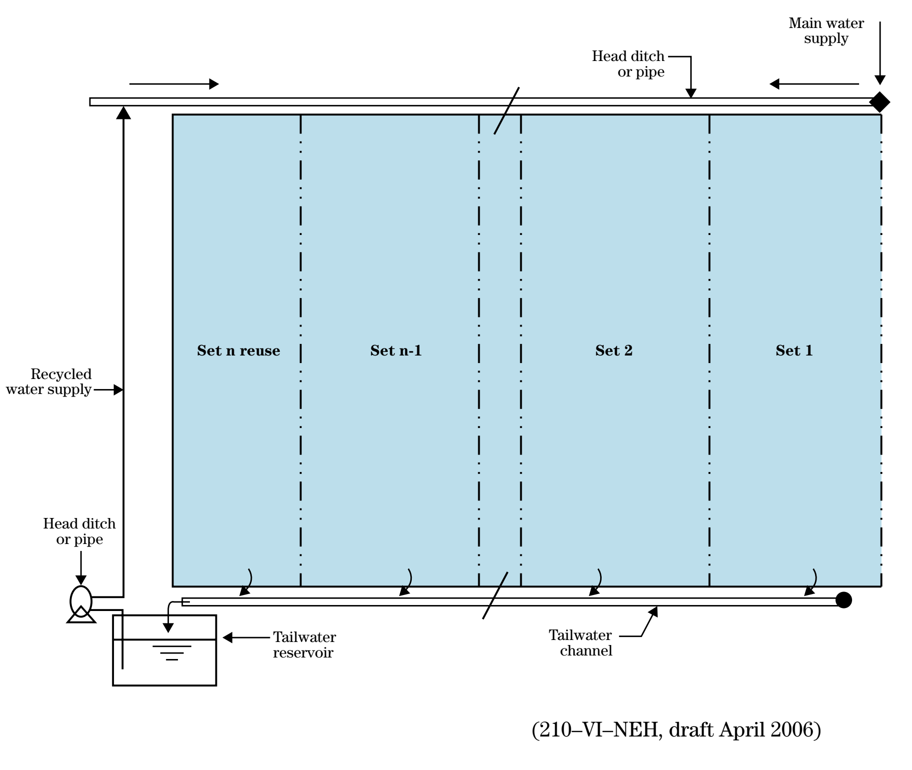
F_w = field width in feet

N_p = number of furrow or unit widths to be irrigated by the main water supply

w = the unit width or furrow spacing in feet

Step 5 Steps 1 through 3 should then be repeated with an adjusted field width equal to the actual width, F_w minus the width of the field to be irrigated with the recycled tailwater, $N_r w$.

Figure 4–63 Schematic tailwater reuse system



Step 6 The application efficiency, E_a, of this system is:

$$E_a = 100 \frac{z_{req} F_w L}{Q_o t_{co} N_p} \tag{4–86}$$

Step 7 The maximum volume of the tailwater reservoir would be equal to the total volume of recycled tailwater, $N_p Q_o t_{co}$, if the reuse system only operates after the primary supply has been shut off or directed to another field. A smaller reservoir is possible if the recycling can be initiated sometime during the irrigation of the main sets. Unless land is unavailable, the simplest system uses the maximum tailwater storage.

Step 8 The tailwater during later irrigations may not be greater than during the initial irrigations. However, performing the design for both is since the capacity of the tailwater reservoir will be dictated by the maximum runoff.

Example furrow tailwater reuse design—As an example of this procedure, consider the FreeDrainingFurrow_2.cfg data set. Following the procedure outlined above, the first step is to determine a flow and cutoff time that achieves as high of uniformity and efficiency as possible.

One of the better options is to simply reduce the inflow from 0.033 ft^3/s per furrow to 0.023 ft^3/s per furrow, and leave the cutoff time and target depth as defined. This will reduce the tailwater fraction from about 40 percent to about 20 percent.

The volume balance within each furrow is computed in the performance box in the lower right hand side of the screen. From the design panel, it can be observed that the field during this initial irrigation would need to be divided into three sets. Since the field is 2,400 feet wide, and the furrow spacing is 2.5 feet, the tailwater from the first set and the size of the tailwater reservoir, would be:

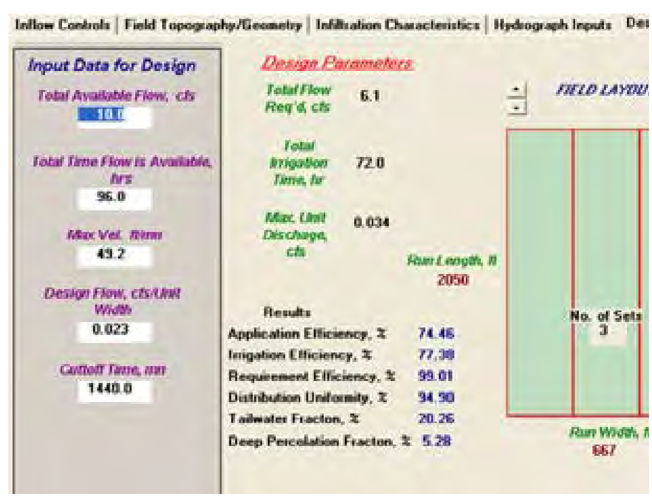
$$\frac{2{,}400 \text{ ft wide}}{2.5 \text{ ft/furrow}} \frac{1}{3 \text{ sets}} 398 \text{ ft}^3\text{/furrow} \frac{1 \text{ ac-ft}}{43{,}560 \text{ ft}^3} = 2.92 \text{ ac-ft} \tag{4–87}$$

From equation 4–83, the number of furrows that can be irrigated by reuse is:

$$\begin{aligned} N_r &= \frac{V_{ro} N_T}{\left(V_{ro} + Q_o t_{co}\right)} \\ &= \frac{\dfrac{\left(398 \text{ ft}^3\text{/furrow}\right)\left(2{,}400 \text{ ft}\right)}{2.5 \text{ ft/furrow}}}{\left(398 \text{ ft}^3\text{/furrow} + .023 \text{ ft}^3\text{/sec} \times 60 \times 1{,}440 \text{ mn}\right)} \\ &= 160 \text{ furrows} \end{aligned} \tag{4–88}$$

The width of the field that should be irrigated by the main water supply is 2,400–160 x 2.5 = 2,000 feet. The value of 2,400 feet in the Field Topography/Geometry input panel needs to be replaced by 2,000 feet to reconfigure the field width (fig. 4–64).

Figure 4–64 FreeDrainingFurrow_2.cfg design of the field using the main water supply



Computations need to be repeated for the later irrigation conditions. After a few simulations, it can be suggested that the target depth be decreased to 3 inches, the time of cutoff be increased to 30 hours (1,800 min.), the furrow stream reduced to about 4.5 gpm. This will result in a tailwater loss of about 123 ft^3/furrow, and the field can be irrigated in two sets with the 10 ft^3/s available. Following the same process, the number of furrows that can be supplied by the tailwater reuse system is 98. The reservoir volume would only need to be about 3.25 acre-feet for this condition as opposed to about 2.9 acre-feet for the initial irrigations.

(5) Design of surge flow systems

A rational design procedure for surge flow systems has not been developed and, therefore, is not included in the design features of the **Surface** software. Design is still possible. The simulation capabilities of the software can simulate most surge flow configurations, and through a trial and error process, a design can be derived that is efficient and effective.

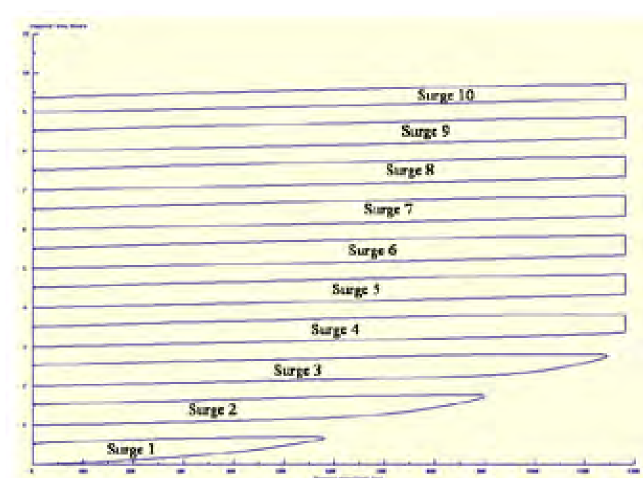
There are two critical design and operational rules for surge flow systems. First, the surges applied to the field during the advance phase should not coalesce, advance front of one should not catch up and merge with a preceding surge. The second rule is that at the end of advance when cutback or soaking is desirable, the opposite should be facilitated, each surge should coalesce.

The hydraulics of surges that do not coalesce behaves very much like the hydraulics of continuous flow at the same discharge, however, the hydraulics of coalesced surges behaves very much like a cutback discharge. The means to expedite rapid advance to minimize deep percolation are in the same irrigation management regime, as well as an effective way to implement cutback to minimize tailwater runoff during the soak cycle.

Example surge flow design—The FreeDrainingFurrow_1.cfg file was used in section 623.0403 to illustrate the problem of irrigating a long furrow in a relatively high intake soil. This is also one of the conditions that surge flow was originally thought to offer some advantage. The file FreeDrainingFurrow_1Surge.cfg uses the FreeDrainingFurrow_1.cfg data, but with surge flow selected. The Inflow Regime in the Inflow Control panel of the input tabbed notebook has been changed to a surge flow regime by checking on the box labeled **Fixed Cycle Surge Flow**. Then, under the headings of Run Parameters, the number of surges has been set to 10 surges, and the surge cycle on time to a value of 30 minutes. For the purposes of this demonstration, the furrow stream has left at 32 gpm, but the target depth of application is reduced to 3 inches. Also, the time step, Dtm, should be reduced to 0.5 minutes. Figure 4–65 shows the resulting advance/recession plot. The implementation of surge flow in this case increased the application efficiency by more than 16 percent since the nearly 55 percent deep percolation loss and 1 percent tailwater loss under continuous flow became a 20 percent deep percolation loss and a 23 percent tailwater loss under the surge flow regime.

Most commercial surge flow valves and controllers have two features that can improve the application efficiency of surge flow substantially above that achieved with a series of fixed cycles demonstrated above. The first of these features is the ability to initiate a cutback or soaking phase once the entire furrow has been wetted. This is accomplished by reducing the cycle times sufficiently so that surge coalescing occurs within the furrow. As a rule, the cycle time during the soaking phase should be 10 minutes or less. To demonstrate this, three changes are made in the FreeDrainingFurrow_1Surge .cfg input. First, the radio button labeled, **By Target Application**, *zreq* should

Figure 4–65 Surge flow advance and recession plot for FreeDrainingFurrow_1Surge example



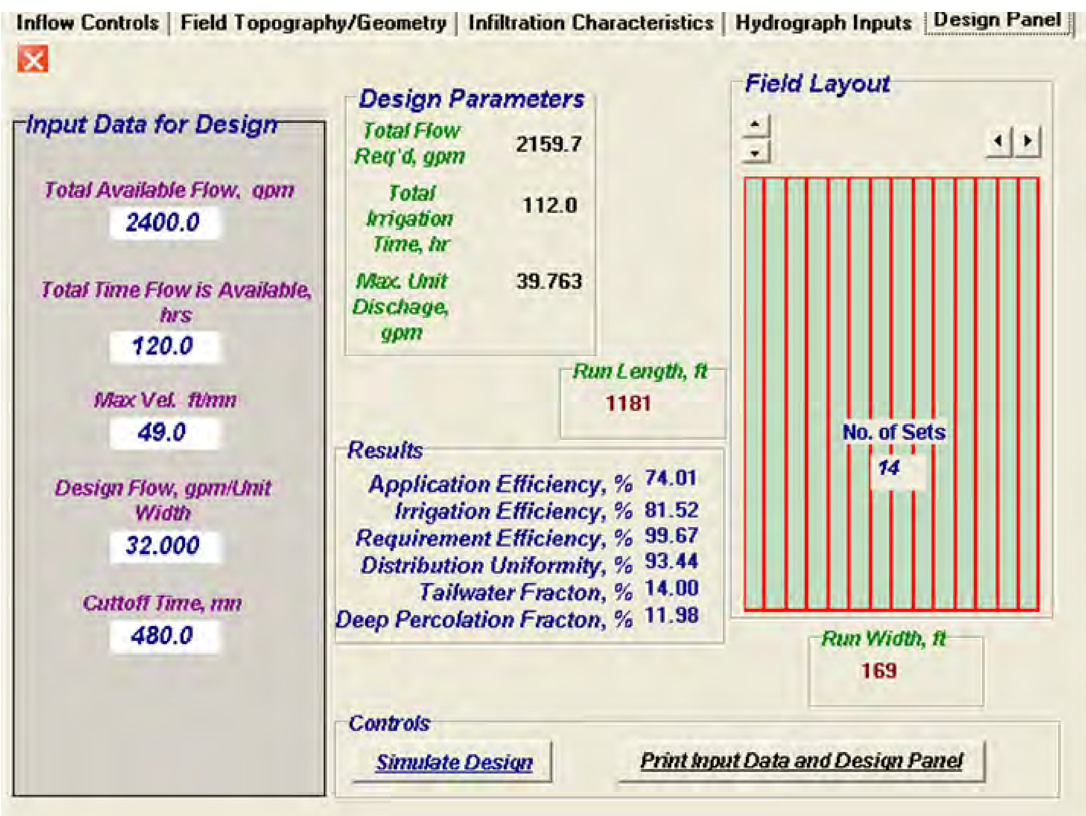
be checked in the **Simulation Shutoff Control** box of the Inflow Control tabbed panel. Then, the **Fixed Cycle Surge Flow w/ Cutback** radio button should be checked in the Inflow Regime box. Finally, the Cutback Ratio in the **Run Parameters** box should be set to 0.50. This results in an application efficiency of just more than 69 percent, or another 10 percent improvement. Another 2 percent increase can be achieved by decreasing the cycle on time to 20 minutes.

The second feature of most commercial surge flow values and controllers is the ability to expand the cycle time during the irrigation. For instance, by checking the **Variable Cycle Surge Flow w/ Cutback** radio button, setting the **Surge Cycle On-Time** to 10 minutes, and then setting the value of the **Surge Adj. Time** value to 5 minutes, the resulting application efficiency is almost 74 percent. The same expanding cycle on-time can also be implemented by setting a value of the **Surge Adj Ratio** to a value greater than 1.0. For instance, if this ratio is 1.2, the application efficiency will be just above 74 percent. Note that when using the **Surge Adj. Ratio**, the value of the **Surge Adj. Time** should be set to zero. Figure 4–66 shows the **Design Panel** for this case.

(d) Headland facilities

Water supplied to the surface irrigation system is distributed onto the field by various combinations of head ditches or pipelines equipped with outlets such as gates, siphons, spiles, and checks. Some of these are illustrated in 623.0400 and collectively are known as headland facilities.

Figure 4–66 Design Panel for the FreeDrainingFurrow_1Surge .cfg example



The design of surface irrigation headland facilities should satisfy three general criteria.

- water supply to the system must be distributed onto the field evenly
- capacity of the headland facilities must be sufficient to accommodate the supply discharge
- headland facilities should prevent erosion as the flow emerges onto the fields

It is not necessary for the individual outlets to be calibrated and capable of measuring flow, but they should be adjustable enough to regulate the outlet flows.

(1) Head ditch design

A number of standards and manuals exist for the design of open channels, and these should be reviewed in designing surface irrigation head ditches. This part of the National Engineering Handbook does not replace these documents, but presents a few simple tools and guidelines for the design of head ditches.

Head ditches come in various configurations, lined and unlined, and equipped with different ways to divert water onto the field. Some of which are shown in figure 4–67. These can be designed, as far as capacity is concerned, with the Manning Equation Calculator found on the Field Characteristics panel of the input tabbed notebook of the **Surface** software.

There are three general criteria for effective head ditch design. The first is that flatter side slopes are better than steep ones. When the head ditch is diked-up to allow the diversion of water onto the field, ditches with flat side slopes have greater storage capacity at the higher ponded depths. Most small head ditches have slopes ranging from 1:1 to 1.5:1.

The second criterion for head ditch design is that the ditch capacity should carry the design flow at two-thirds of the constructed depth when it is not diked up for irrigation. This will allow offtakes such as spiles and ditch gates to be located above the water level in the areas of the field not being currently irrigated.

The third criterion is that the maximum depth in the ditch should not exceed 90 percent of the constructed depth. This criterion will come into focus as the ditch is diked to divert water onto the fields; therefore, the design of offtakes should be such that the total flow can be diverted without exceeding the 90 percent limit. The remaining 10 percent of the ditch depth is freeboard and is necessary as a safety measure.

For example, in blocked-end border example, the flow required from the main supply was 10.0 ft^3/s. If it is assumed that the head ditch is to be a trapezoidal concrete ditch running on the 0.0001 cross slope then the question is what the ditch dimensions should be. Only certain sizes of these ditches may be available from local contractors due to equipment limitations.

For the purposes of this example, a ditch with a 3-foot depth, 2-foot bottom width, slope of 1.25:1, and Manning n of 0.018, a typical value for concrete ditches can be initially selected. Then using the Manning Equation Calculator in a trial and error manner, a channel can be designed.

This ditch would carry the 10 ft^3/s flow at a depth of 2.236 feet, which is slightly more than the 2.0 feet specified under the two-thirds rule noted above. Increasing the bottom width to 30 inches would yield a depth of just over 2 feet. The maximum depth in the ditch should not exceed 90 percent of the depth, or 2.7 feet.

This ditch is somewhat large due to the relatively flat cross slope of the field. It may be useful to construct the ditch on a steeper grade by elevating the inlet.

Sizing siphon tubes and spiles—Siphon tubes and spiles act as simple orifices. For the purpose of design, minor losses at their entrance and friction losses are assumed to be negligible. The design of these devices involves choosing a diameter that will accommodate the necessary flow. There are two conditions that typically exist in the operation of the siphons and spiles. The first is when the downstream end of the siphon or spile is submerged by the water level in the field (fig. 4–68b). The second condition occurs when the downstream end discharges freely into the air (figs. 4–68a and 4–68c). The head on these structures should be the typical difference between the operational level of the head ditch and either the field water level or the center line of the freely discharging spile or siphon. Table 4–12 provides guidelines for selecting siphon and spile diameters as a function of maximum discharge and head.

Figure 4–67 Typical surface irrigation head ditch configurations

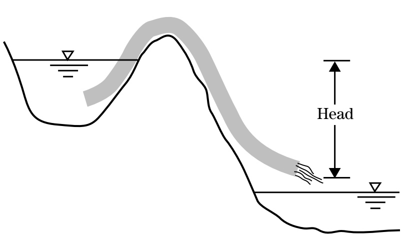
Border/basin siphons

Furrow siphons

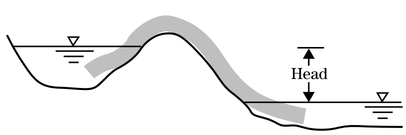
Border/basin check outlet

Border/basin gate

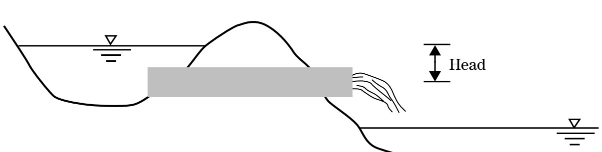
Figure 4–68 Typical operational conditions of surface irrigation siphons and spiles



(a)



(b)



(c)

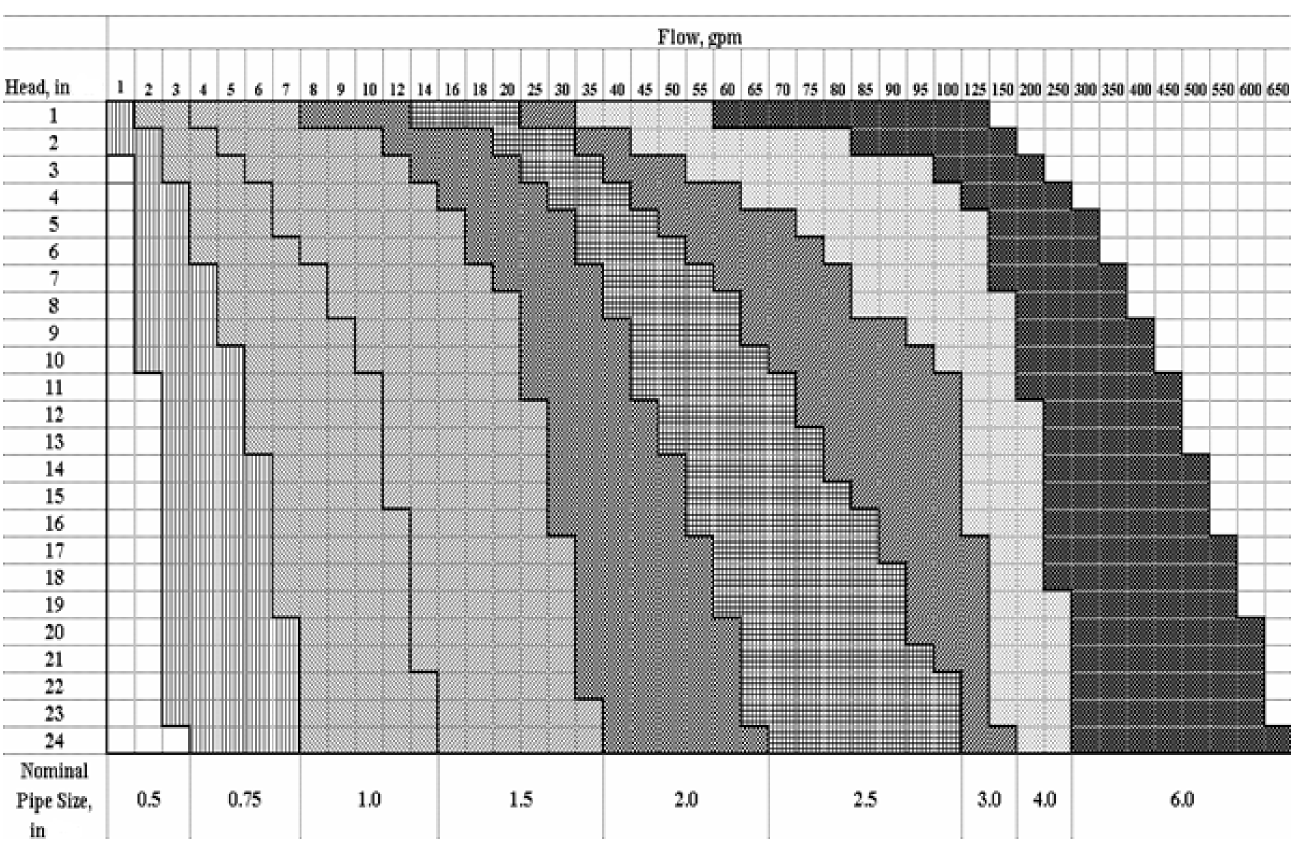
As an example, in the example in section 623.0403(c), a furrow flow of 22.5 gpm was suggested. Table 4–12 illustrates that when the head on the siphon or spile is about 1 foot or less, a 2-inch tube diameter should be selected. If the head is 1 foot or greater, the tube diameter can be reduced to 1.5 inches.

Using the information from section 623.0404(a), suppose the diversion from the ditch is to be accomplished by siphon tubes, and assume further the elevation of the water surface in the field is equal to the non-diked water elevation. The head on the siphons would, therefore, be the maximum water surface elevation in the ditch, at a depth of 2.7 feet, minus the field elevation of the field water surface, at a ditch depth of about 2 feet, or 0.7 feet, or about 8 inches.

From table 4–12, 6-inch siphons would carry about 350 gpm, and would require 13 such siphons to divert the 10 ft^3/s (4,490 gpm) ditch flow. A better and less labor intensive solution would be either larger ditch gates or check outlets.

Sizing small ditch gates—Small ditch gates (fig. 4–67) typically have round entrances and may be flush with the ditch side or recessed and vertical. The conduit through the ditch berm is also circular as a rule and submerged at the field side, making the offtake a submerged orifice. Commercial sizes from 2 to 24 inches are available. For 6 inches and smaller, the design is the same as for siphons and spiles.

Table 4–12 Minimum recommended siphon and spile sizes for surface irrigation systems



Sizing check outlets and large ditch gates—Figure 4–67 shows a typical check outlet. They are usually equipped with simple slide inserts to close the opening when not in use although many check outlets are situated above the water level of the normal water flow in the ditch. These outlets normally operated at or near a free flow regime; therefore, their flows are dependent only on the water level in the ditch. The head on these outlets is defined as the difference between the water elevation in the ditch and the elevation of the check crest.

Table 4–13 gives the suggested minimum diameter gates for full open and completely submerged conditions.

The sizing of large ditch gates, like the border/basin gates illustrated in figure 4–67 can be considered similarly to check outlets: when at the maximum flow, the gate itself is raised above the water surface. Unlike small ditch gates, the large gates are almost always rectangular in shape.

Table 4–14 gives the sizing of check outlets and large ditch gates.

Table 4–13 Minimum recommended ditch gate sizes for surface irrigation systems

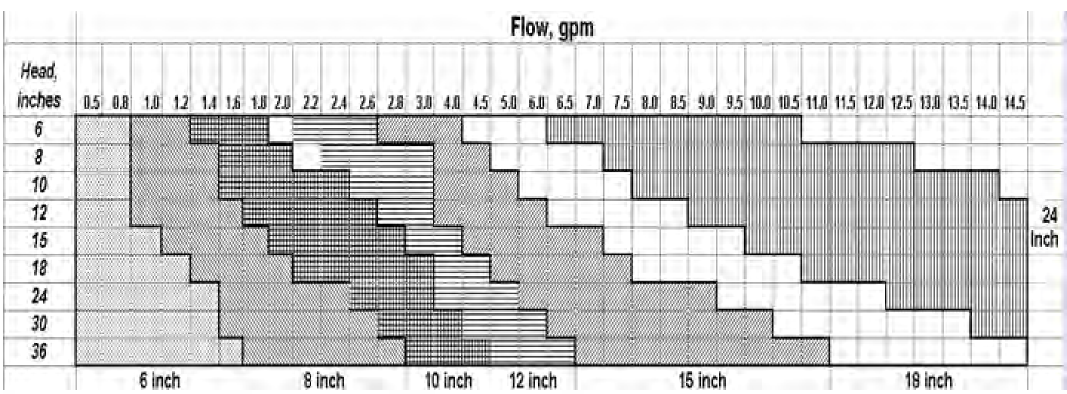
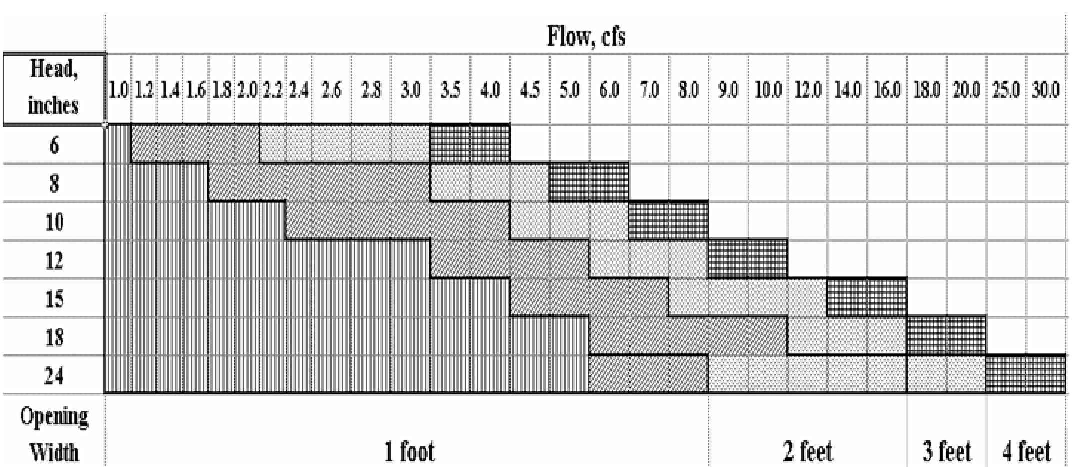


Table 4–14 Minimum recommended check outlet and large ditch gate sizes for surface irrigation systems



(2) Gated pipe design

Generally, gated pipe is used for furrow irrigation, although, in some cases, it has been used for border and basin systems. Borders and basins require larger flows than would normally be available through gated-pipe systems. Gated pipe is available in aluminum, rigid plastic (polyvinyl), and lay flat (polypipe) from various manufacturers. Aluminum pipe is available in 5-inch, 6-inch, 8-inch, 10-inch, and 12-inch diameters. Polyvinyl gate pipe is usually available in 6-inch, 8-inch, 10-inch, and 12-inch. Lay-flat gated pipe is available in the same sizes, as well as 9-inch, 15-inch 16-inch, 18 inch, and 22-inch.

The design of gated pipe involves three steps:

Step 1 choosing a pipe material

Step 2 selection and location of the gated outlets

Step 3 selection of the pipe size

Other programs like PHAUCET may assist in the design of gated pipe and polypipe. For more information, contact your state water management personnel.

***Step 1* Choosing a pipe material**—In selecting a particular type of irrigation gated pipe, irrigators must balance their needs against the cost, availability, operation, and maintenance of aluminum, rigid plastic, and lay-flat pipe.

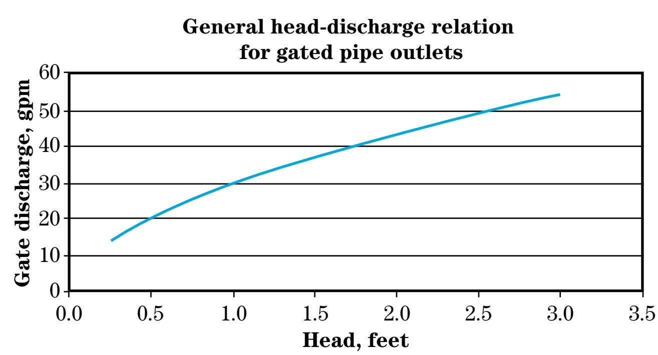
Aluminum-gated irrigation pipe has been used the longest for furrow irrigation. It is the most expensive gated pipe, but one that has the longest useful life (10 to 15 years) when proper maintenance is applied. Aluminum-gated pipe typically costs about 50 percent more than polyvinyl and three times as much as the lay-flat gated pipe. It is easy to move and install, and since it is supplied in 20-, 30-, or 40-foot lengths, it is easy to store and clean. One of the disadvantages of aluminum-gated pipe, aside from its high initial cost, is the leakage from the pipe joints when maintenance is not adequate. Once the gates are installed, the flexibility of alternative furrow spacing is reduced, as well. The sizes of aluminum pipe are somewhat restricted with the most generally available sizes being 6-, 8-, 10-, and 12-inch diameters.

Polyvinyl-gated pipe is rigid like the aluminum pipe, easy to install, and maintain, but will not be as rugged as aluminum, therefore, it should not have the expected life. It does, however, have a lower initial costs and a wider range of sizes. Polyvinyl-gated pipe can be obtained for same size of pipe as aluminum, but for 15- and 18-inch sizes on special order.

Lay-flat plastic gated pipe has become very popular in many locations in recent years. Its initial cost is low, and it may only be useable for one or two seasons. It is the disposable alternative to aluminum and polyvinyl pipe and comes in wide range of sizes, 5 to 22 inches in diameter. Lay-flat plastic gated pipe is available in rolls of several hundred feet rather than the 20- to 40-foot lengths of the rigid pipe. Thus, it is easier to install and remove, is more susceptible to tears and punctures, and is very difficult to remove sediments from the pipe due to its length. The offtakes can be installed in the field with simple tools and then replaced with inexpensive plugs if the spacing needs to be changed for other crops. The lay-flat gated pipe is the most flexible in terms of use. Lay-flat tubing has two additional disadvantages. First, the pressure head that it can accommodate is substantially below the value for the rigid pipes, and second, it is generally necessary to prevent the pipe from moving between irrigations due to wind.

***Step 2* Selection and location of gated outlets**—There are several gates used in gated pipe. They range from slide gates to simple plugs, and the discharge characteristics depend on their size and shape. Figure 4–69 shows a typical head discharge curve for fully-open slide gates and is presented for general guidance. In design practice, it

Figure 4–69 Typical head-discharge curve for gated pipe outlets



is necessary to know the specific characteristics of the gate actually used in the pipe. Figure 4–69 is intended to be an approximate tool that can be used to size the gated pipe itself.

Preceding any design of the headland facilities, the design of the field system must be completed so the unit flows and times of cutoff are known. Then, from figure 4–69, the operating head on the fully open gate can be determined, which corresponds to the design unit flow (furrow flow). This is the minimum design head in the gated pipe. The flow from gates closer to the inlet end of the pipe will require regulation by adjusting the gate opening. Finally, gates should be spaced along the pipe at the same distance as the furrow spacing even when alternate furrows are irrigated.

Step 3 **Selection of pipe size**—The design of gated pipe relies on several pieces of information. From the field design, the unit or furrow discharges are known along with the total flow available to the field. The water supply to the field should also be characterized by its energy or head at the field inlet. This information may need to be developed from the elevation of the water source if coming from a canal or ditch, or from the pressure in the main supply pipeline if otherwise. If the field cannot be irrigated in a single set, its subdivisions should also be known. This information will establish the length of gated pipe segments. Finally, the field topography should yield the slope along which the gated pipe will be laid.

For purposes of design, the discharge in the gated pipe is assumed to be the total field supply flow, even though flow diminishes along the pipe as flows are diverted through the outlets. This assumption is made to ensure the pipe diameter is adequate in the reaches that are simply conveying water to the irrigating location. The hydraulics of the pipe are described by the Bernoulli equation:

$$H_{inlet} = \frac{h_f L}{100} + \left(EL_{end} - EL_{inlet}\right) + H_{min} \qquad (4\text{–}89)$$

where:

H_{inlet} = total head (pressure plus velocity) at the inlet end of the gated pipe, ft

H_{min} = minimum head at the end of the pipe necessary to deliver the design unit flow, ft

L = length of the gated pipe, ft

EL_{end} = elevation of the end of the gated pipe, ft

EL_{inlet} = elevation of the pipe inlet, ft

h_f = friction gradient in the pipe, ft/100 ft

Equation 4–88 can be solved for h_f as:

$$h_f = \frac{H_{inlet} - \left(EL_{end} - EL_{inlet}\right) - H_{min}}{\frac{L}{100}} \qquad (4\text{–}90)$$

With a computed value of h_f, the designer can select the proper pipe diameter from table 4–15.

Example gated pipe design—In the example given in FreeDrainingFurrow_1 example, the field was 1,180 feet long and 2,362 feet wide. The field design for initial irrigations called for 18 sets to be organized by subdividing the length into two parts and the width into nine parts (fig. 4–55). The cross slope was 0.0001. The design furrow flow is 22.5 gpm, and the total flow is 2,362 gpm.

Suppose this field is to be irrigated by a gated-pipe system supplied by a buried pipe mainline (fig. 4–70), in which the basic supply enters the field in a 1,500-foot pipe from the upper left hand corner, traverses to the middle of the field width, then turns 90° and extends to the mid-point of the field length. The supply pipe connects to a canal offtake in which the water elevation is 15 feet higher than the 90° turn. Optimally, the pressure head at the 90° turn should be 6 feet.

A conservative estimate of the friction loss in the supply pipe can be determined from equation 4–90 by using the canal free surface as the reference point.

$$h_f\Big|_{supply\ pipe} = \frac{0 - \left(0 - 15\text{ feet}\right) - 6}{1500/100} = 0.6\text{ ft/100 ft} \qquad (4\text{–}91)$$

From table 4–15, it can be seen that a 2,400 gpm flow with a 0.6 ft/100 foot friction gradient can be conveyed with a 16-inch pipe.

Figure 4–70 Layout of FreeDrainingFurrow_1 gated pipe system

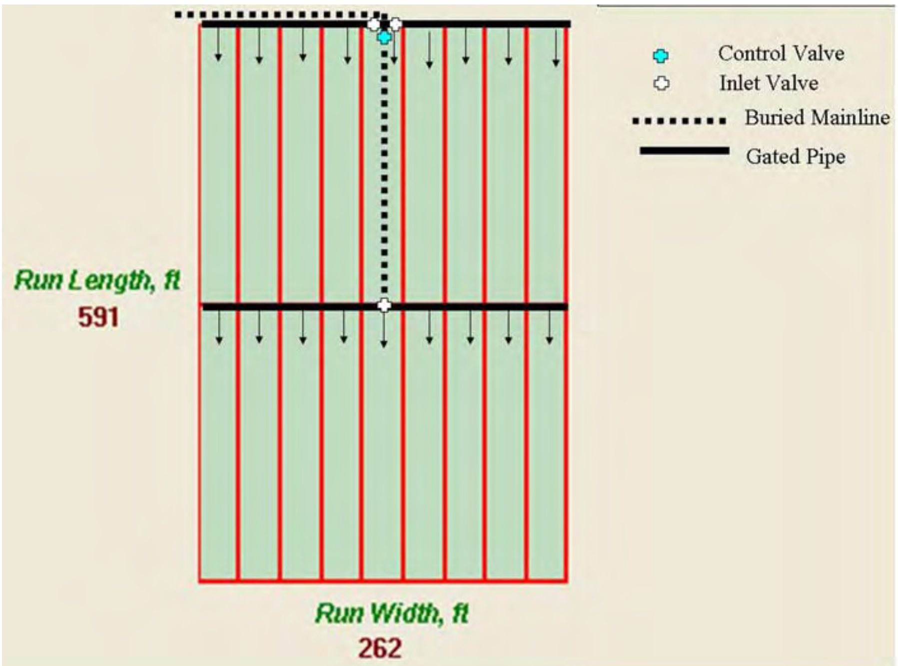
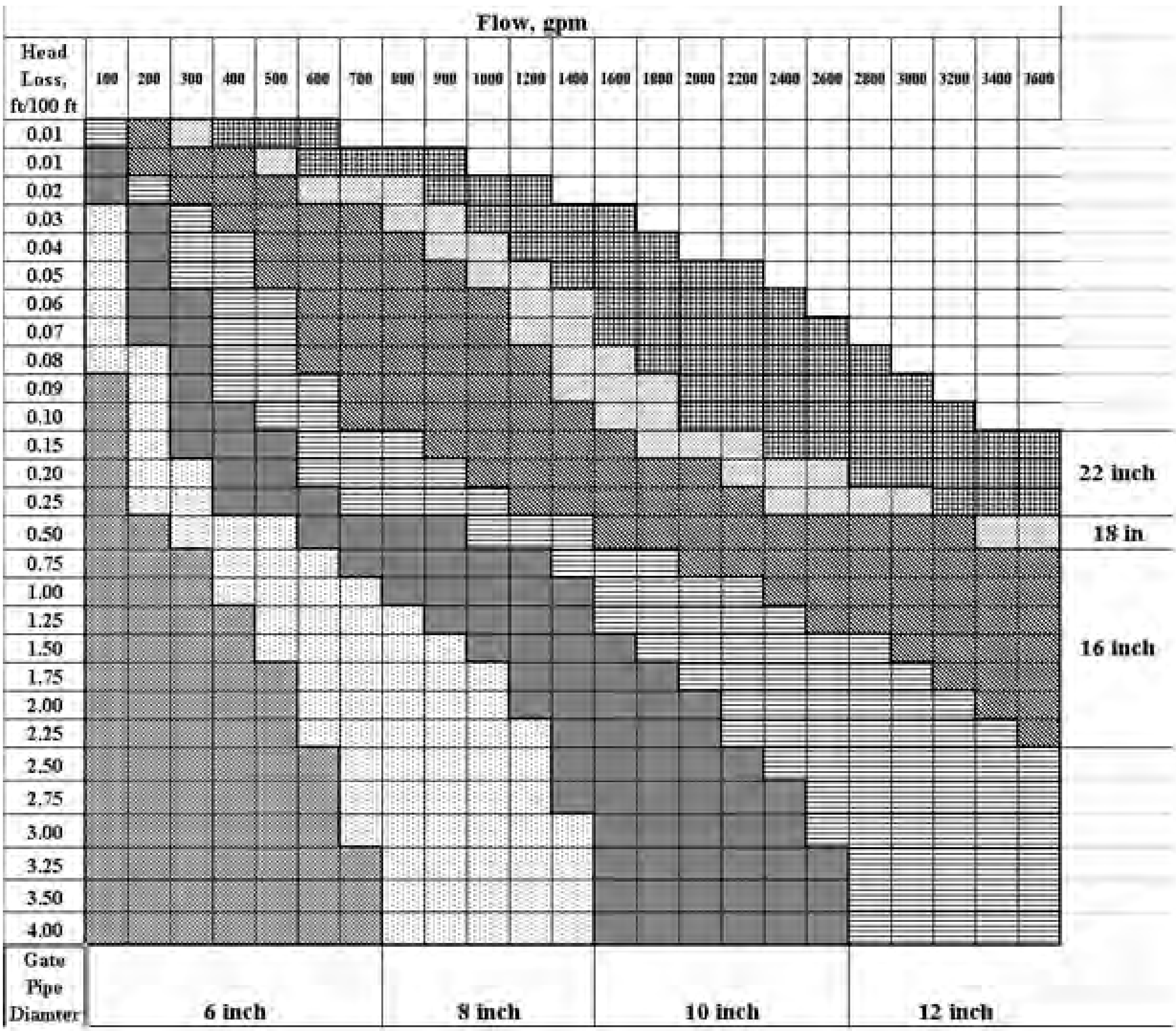


Table 4–15 Minimum recommended gated pipe diameters for various friction gradients



The pressure head at the 90 degree turn into the field is 6 feet. Three valves are situated at the upper end of the field to regulate flow to the left and right branches of the gated pipe, as well as to control to the lower section. At the midsection of the field, a two-way valve can be located to shift the flow into the right or left branches. The gated pipe sections extend in either direction for 1,180 feet. From figure 4–69, a flow of 22.5 gpm will require a head of about 0.6 feet. The friction gradient computed from equation 4–90 for the pipes running uphill is:

$$h_f = \frac{6-(0+0.0001\times 1{,}180)-0.6}{1{,}180/100} = 0.448 \text{ ft/100 ft} \qquad (4\text{–}92)$$

From table 4–15, the gated pipe should be at least 16 inches in diameter. Generally, pipe this large could only be supplied as lay-flat plastic tubing.

It may not be desirable to use large diameter, lay-flat gated pipe. To reduce the diameter and allow the irrigator a choice between aluminum, PVC, and lay-flat pipe, the main supply pipes need to be reconfigured.

Figure 4–71 shows an alternative design in which the gated pipe layout is subdivided to reduce the size of the pipe. In this case, the supply pipes still carry the entire 2,400 gpm and are the same diameter as above. There are nearly 1,200 feet more of these pipes, however. The individual gated pipes are now only 390 feet long. The friction gradient for this case is:

$$h_f = \frac{6-(0+0.0001\times 390)-0.6}{\frac{390}{100}} = 1.375 \text{ ft/100 ft} \qquad (4\text{–}93)$$

From table 4–15, this would probably require only a 12-inch pipe and, therefore, could be lay-flat, aluminum or polyvinyl. However, the irrigator and designer might consider it unlikely that the savings in gated pipe cost would compensate for the additional buried mainline.

(3) Comparing alternatives for headland facilities

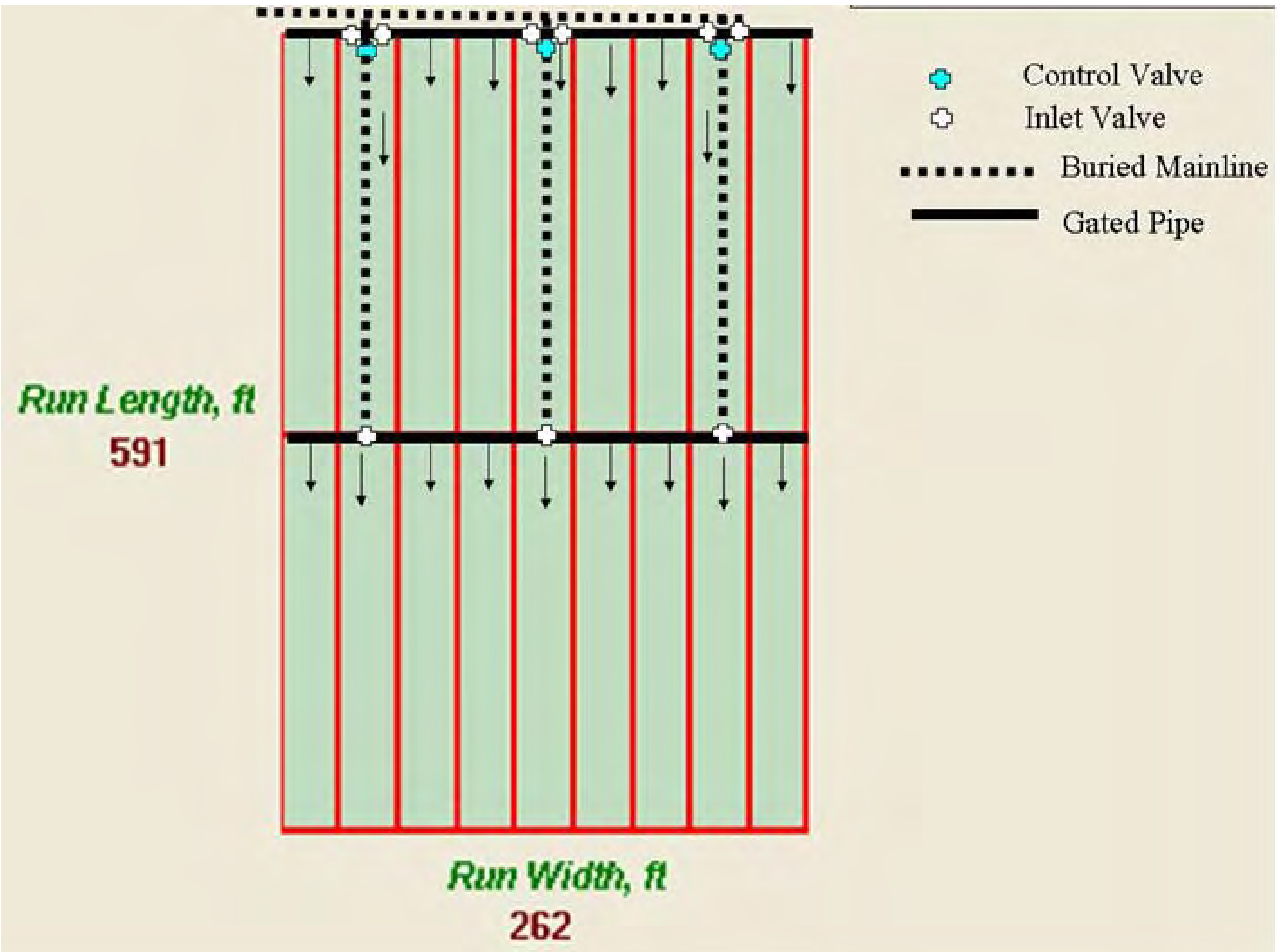
This section is not meant to be a comprehensive treatment of headland facility design, but to illustrate some basic principles and methodologies. Keeping in mind that most work to modernize or improve surface irrigation systems will occur within existing systems, a workable, if perhaps suboptimal, solution will present itself upon initial inspection. Specifically, one indication of what should be done to improve the function and efficiency of headland facilities is to improve what already exists.

There are no reliable criteria that would allow a designer to determine the best head ditch or pipe with their various offtake options without a site assessment. A visit is needed to an irrigated area to find many combinations of headland facilities doing essentially the same tasks, but doing so in a manner that suits the irrigator best. Historically, selecting irrigation facilities has been primarily concerned with the cost of the purposed facilities. However, with the goal of modernization in mind and anticipating that effectiveness will become increasingly important, irrigation efficiency will be substantially more important in the future.

Perhaps one of the most important features of surface irrigation systems of the future will be the capability to precisely regulate the unit flows onto the field. This requires that the total flow to the field be known accurately and that the unit flows can be achieved precisely. Earlier sections of this chapter have demonstrated that when the proper flow is added to a border, basin, or furrow, high uniformities and efficiencies will result. This suggests that adjustable gates are better selections than checks, spiles, or siphons. Seepage and leakage losses from the headland facilities should be minimized, which suggests lined head ditches or pipelines.

One of the most important factors in choosing a particular type of headland facility, a head ditch or pipe, for instance, is the type of surface irrigation system being serviced. As a rule, pipes that carry the flow necessary for border or basin irrigation are far more expensive than lined or unlined ditches. Outlets from head ditches for border and basin irrigation systems should have a high-flow capacity; therefore, the outlets are generally slide gates or checks. The smaller ditch gates, siphons, and even gated pipe should not be

Figure 4–71 Alternative gated pipe layout for FreeDrainingFurrow_1.cfg



ruled out where the soils have low intake rates and/or the fields have relatively high slopes. Furrow irrigation systems, on the other hand, work best when flows to individual furrows can be regulated. This can be accomplished by siphon tubes, spiles, or ditch gates from a head ditch or by gated pipe. Since the gated pipe outlets are more easily regulated than siphons, spiles, or ditch gates, many irrigators engaged in improving their systems' performance choose gated pipe.

Another important factor is the flexibility to accommodate changes in cropping patterns. The crop rotations of some farming units involve border irrigation for some crops and furrow irrigation for others. A head ditch with ditch gates works well in both circumstances, but gated pipe might be equally effective, particularly if intake rates are low.

Finally, labor is rapidly becoming the farm's most critical shortage, and any surface irrigation system modernization and improvement program must reduce the labor required to operate it effectively if efficiency is to be increased. Automation is the ultimate labor saving technology. Thus, all things being equal, the best headland facilities might be those that can be automated.

However, once the headland facilities are selected, they must be capable of delivering the proper unit flow to the field under varying conditions through the season and from year to year.

Appendix A A Note on the Development of the Original NRCS Intake Families and Their Modifications for Furrow Irrigation

Introduction

In the 1950s, various personnel of the USDA Natural Resource Conservation Service (NRCS, formerly Soil Conservation Service (SCS)) began a concerted effort to develop general intake relationships to support surface irrigation assessments when field measurements were not available. In the 1950s, 1,670 ring infiltrometer tests were made in grass and alfalfa fields of Colorado, Wyoming, North Dakota, South Dakota, and Nebraska. Most, but not all, of the tests were conducted within irrigated fields. The individual tests were averaged in groups of five for analysis.

In 1959, J.T. Phelan proposed the intake families now found in the USDA NRCS National Engineering Handbook (NEH), Border Irrigation and Furrow Irrigation. As the need to revise the NEH to make it current with existing surface irrigation technology emerged in the late 1990s, so, too, did the need to re-examine and revise the intake families.

Evolution of the original concept

The ring infiltrometer data collected in the 1950s were evaluated in several ways using principally regression. One of the first concepts explored was that of the basic intake rate which was defined as, that rate when the change of the rate per hour was one-tenth of its value in inches per hour. In assuming initially that intake could be represented by the function,

$$z = k\tau^{a} + c \qquad \text{(A–1)}$$

where:
z = the cumulative intake in inches
τ = the intake opportunity time, in minutes
k = empirical constant
a = empirical constant
c = empirical constant

The definition of basic intake rate, I_b, in inches per hour, was then,

$$I_b = \frac{\partial z}{\partial \tau}\bigg\| \text{ when } \frac{\partial^2 z}{\partial \tau^2} = \text{abs}\left(0.10\frac{\partial z}{\partial \tau}\right) \qquad \text{(A–2)}$$

This relationship occurs when,

$$\tau = -600(a-1) \qquad \text{(A–3)}$$

The basic intake rate thus defined was extracted from the ring infiltrometer data and grouped into 10 layers represented by averages of all the tests within the layer. The time to infiltrate 1, 2, 3, 4, and 6 inches were interpolated from each of the 5-reading averages and then averaged over the layer as shown in table A–1. Then, the Philip equation was used to fit the data in table A–1. The expression of the Philip equation is:

$$z = S\tau^{0.5} + A\tau \qquad \text{(A–4)}$$

where:
S = soil sorptivity
A = soil transmissivity

The resulting fit with the layer ring data produced the following relations

$$S = 0.1766 \times I_b^{0.392} \qquad \text{(A–5)}$$

and

$$A = 0.01282 \quad I_b - 0.00175, \quad B \geq 0 \qquad (A\text{–}6)$$

Values of S and A were then computed for Ib values corresponding to the NRCS (formally SCS) Intake Family designation, 0.05 in/hr to 4 in/hr. Rather than use these values as the basis for the intake families, it was decided to convert equation A–4 to the form of equation 4–31.

$$z = k\tau^{a} + c \qquad (A\text{–}7)$$

This was accomplished by using equations A–4 through A–6 to compute values of τ for three values of z, 1, 3, and 9 inches. Then values of k, a, and c were computed from the three points and became the NRCS Intake Family values in use until the publication of this chapter.

Modifications for furrow irrigation

Throughout the 1950s and 1960s, a small group of NRCS personnel also wrestled with the question of how to represent infiltration in furrow irrigation. Field data were sparse, but there were some data which suggested that intake could be related to flow, slope, and roughness—in other words, wetted perimeter. There was also some understanding that infiltration from the furrow sides was occurring at different rates than from the furrow bottom.

The methodology for developing intake relationships from advance, recession, and inflow-outflow was not well understood. Nevertheless, NRCS personnel were making field measurements and attempting to determine intake parameters. By the late 1960s, these analyses generally centered on adjusting the original intake family coefficients for wetted perimeter. Specifically, furrow irrigation intake was expressed as:

Table A–1 Layered SCS ring infiltrometer data

		Average					
Range of I_b, in/hr	No. of test groups	I_b, in/hr	τ_1, min	τ_2, min	τ_3, min	τ_4, min	τ_6, min
Under 0.1	7	0.084	262	1146	2913	5770	15600
0.11–0.20	21	0.141	136	545	1288	2407	6002
0.21–0.40	35	0.291	65.1	209	439	731	1510
0.41–0.70	49	0.542	40.5	119	223	344	626
0.71–1.25	80	1.02	22.0	64.8	118	176	313
1.26–1.80	54	1.49	12.9	39.5	75.1	119	239
1.81–2.40	23	2.16	11.4	32.1	53.9	78.5	132
2.41–3.40	29	2.89	7.85	22.5	40.2	59.6	101
3.41–4.80	18	3.93	6.38	17.5	30.6	42.6	73.2
Over 4.80	18	5.71	4.27	11.1	21.2	30.7	51.3
Total	334						

$$z = \left(k\tau^{a} + c\right)\left(\frac{wp}{w}\right) \quad \text{(A–8)}$$

where:
wp = furrow wetted perimeter in ft
w = irrigated furrow spacing in ft

The *wp/w* adjustment was limited to a value no greater than 1.0.

A substantial effort was made to express wetted perimeter as a function of flow, Manning *n*, furrow slope, and furrow shape. Values of Manning *n* were typically 0.03 or 0.04, and the furrow shape generally was represented as trapezoidal. The concept of a furrow-based basic intake rate was maintained. In the end, the concept of relating basic intake rates in cylinder and furrow tests was abandoned. Instead, a fairly large number of values of wetted perimeter were computed using trapezoidal shapes ranging from a 0.2-foot bottom width and 1:1 side slopes to 0.5-foot bottom widths with 2:1 side slopes. Values of flow, slope, and Manning n were included in the analysis. The data were then simulated by the following relation:

$$wp = 0.2686\left(\frac{Qn}{\sqrt{S}}\right)^{0.4247} + 0.0462 \quad \text{(A–9)}$$

where:
wp = wetted perimeter in ft
Q = flow in gpm
S = the furrow slope
n = Manning *n*

The differences between lateral and vertical infiltration were introduced by adjusting the 0.0462 constant in equation A–9 by 0.7 to a new value of 0.7462. The basis of this adjustment is described in chapter 5 (second edition), Furrow Irrigation, or the NEH as:

> To account for both vertical intake, which is influenced by gravitational forces, and horizontal intake, which is influenced by suction forces, the wetted perimeter is increased by an empirical constant of 0.700. This factor is an average value derived from studies that indicate that horizontal intake is a function of the 0.4 power of intake opportunity time.

Modifications for border, basin, and furrow irrigaiton

NRCS intake family designation

The basic infiltration rate generally occurs substantially beyond the time when the change of the rate per hour was one-tenth of its value in inches per hour. A more rationale and understandable concept for an intake family would be the average 6-hour intake rate. Figure A–1 shows a plot of the 6-hour intake rate for each of the previous NRCS intake curves. Given the ambiguity of the definition of basic intake and the problems associated with this definition in the Kostiakov intake equations, it seems reasonable to modify the concept of the intake family to one based on the average 6-hour intake rate in inches/hour. Furthermore, the ring data originally used to develop the intake families have two very serious limitations. First, they do not deal with the initial irrigations following cultivation. Second, they do not represent the physical condition where water flows over the surface and displaces soil. Thus, a change in how the families are defined can be made without serious physical limitations.

Adjusting Intake for Furrow Irrigated Conditions

Furrow intake is independent of furrow spacing until the wetting patterns between furrows begin to interact or overlap. When the original SCS manuals were written with the furrow adjustments based on the ring infiltrometer equations, there were few actual furrow intake measurements and measurement methods in place. Thus, it was necessary and rational to accommodate furrow irrigation by adjusting one-dimensional ring functions in the late 1960s. It is no longer rational because more data are available, and more sophisticated analyses have been developed.

In addition, there are now two fundamental pieces of data associated with furrow intake measurements that render equations A–8 and A–9 obsolete. First, the flow of each furrow measurement, as well as the actual wetted perimeter, is known. It is no longer necessary to approximate neither Manning n nor the furrow shape. Consequently, the reference state for any furrow intake measurement is the flow and wetted perimeter in the furrow at the time of the measurement. Any adjustment for different flows or different shapes and wetted perimeters on the same soil should be made on the basis of an adjusted wetted perimeter and not the furrow spacing. The revised intake families of section 623.0402 are based on this modification.

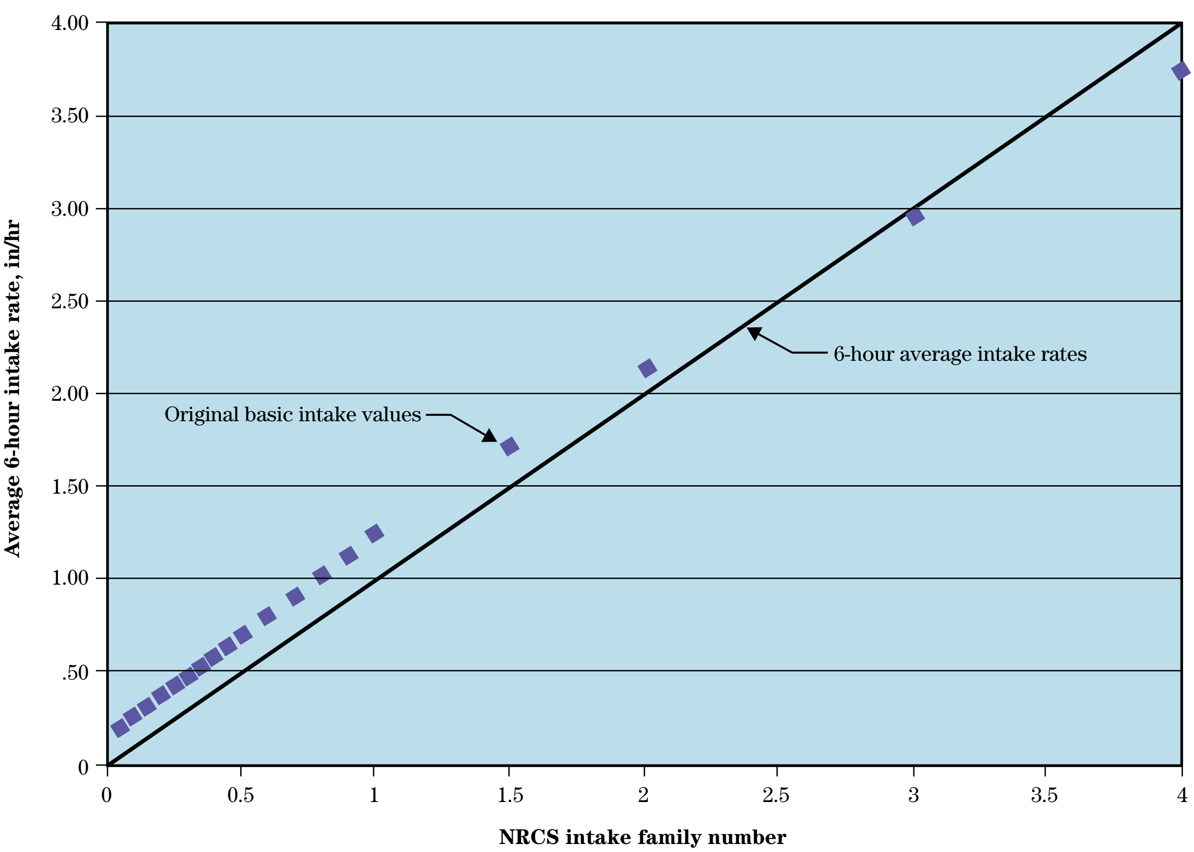
Converting between border/basin infiltration and furrow intake

At the time of this manual preparation, the number of furrow intake measurements available for evaluation in the general sense is substantially greater than measurements corresponding to border/basin irrigation. Consequently, it is suggested that the historical practice found in earlier NRCS documents in which the furrow intake is derived from border/basin infiltration should be reversed. Furthermore, it is no longer realistic to ignore the intake characteristics of the initial irrigations. In this manual, the reference intake family has been based on the estimated 6-hour intake rates of freshly formed furrows with a corresponding reference flow and wetted perimeter. Estimates of border/basin infiltration curves are then derived by multiplying the furrow K and F_o and parameters by the ratio of furrow wetted perimeter to the unit width to determine their border/basic counterparts, k and f_o:

$$k = \frac{K}{WP_r}, \; f_o = \frac{F_o}{WP_r} \qquad \text{(A–10)}$$

in which WP_r is the reference wetted perimeter at which the furrow families are defined.

Figure A–1 Comparison between the average 6-hour intake rate and the basic intake rate of the original SCS intake families



Glossary

Ac-ft A common English unit for water volume is acre–foot. It is the volume of water required to cover an acre with water 1 foot deep. One ac-ft equals 325,851 gallons or 1,233 m^3, and 43,560 ft^3.

Advance phase The period of time between the introduction of water to surface irrigated field and the time when the flow reaches the end of the field.

Advance time (tL) The elapsed time between the initiation of irrigation and the completion of the advance phase. Usual units are minutes or hours.

Application efficiency (Ea) The ratio of the average depth or volume of the irrigation water stored in the root zone to the average depth or volume of irrigation water applied to the field. Inefficiencies are caused by deep percolation and tailwater losses.

Available water (AW) Soil moisture stored in the plant root zone between the limits of field capacity (FC) and the permanent wilting point (PWP). Sometimes referred to as allowable soil moisture depletion or allowable soil water depletion. Usual units are inches of water per inch of soil depth.

Basic intake rate (f_o) The final or steady state infiltration rate of a ponded soil surface. Usual units are cubic feet per foot of length per minute for furrows and feet per minute for borders and basins.

Basin irrigation Irrigation by flooding level fields. The perimeter of basins is usually fully contained by surrounding dikes.

Block-end The practice of using dikes at the downstream end of the surface irrigated field to prevent or control runoff (tailwater).

Border irrigation A surface irrigation configuration in which irrigation is applied to rectangular strips of the field. Borders typically have a slope in the direction of irrigation, but not laterally.

Bulk density (γ_b) Mass of dry soil per unit volume. Typical values in irrigated soils range from about 65 pounds per cubic foot (lb/ft^3) (1.05 g/cm^3) for a clay soil to as much as 100 lb/ft^3 (1.6 g/cm^3) for sandy soils.

Cablegation An automated surface irrigation system employing a continuously moving plug in sloping gated pipe. Outlet flows are highest near the plug and diminish away from it thereby creating a cutback regime.

Chemigation The process of applying chemicals to an irrigated field through the irrigation stream. Chemigation is also referred to as fertigation when used to define through-system fertilizer applications.

Consumptive use The water extracted by plants from the soil during their growth process or evaporated from the cropped surface (plant and soil). Usual units are inches.

Contour irrigation The practice of arranging furrows, borders, or basins along the natural contours of a field.

Conveyance efficiency (Ce) Ratio of the water delivered, to the total water diverted or pumped into an open channel or pipeline at the upstream end. Inefficiencies are caused by leakage, spillage, seepage, operational losses and unaccountable water due to poor measurement.

Conveyance loss Water lost from the conveyance system due to evaporation, seepage from the conveyance (ditch, pipe, canal, etc.), leakage through control and turnout structures or valves, or is unaccounted for due to measurement errors.

Cropping pattern The term cropping pattern has two connotations. The first is the seasonal sequence of crops grown on a single field. The second is a more general term describing the distribution of cropped acreages in an area in any one year.

Crop root zone The soil depth from which crop extracts the water needed for its growth. This depth depends on the crop variety, growth stage, and soil. Usual units are inches or feet.

Cumulative intake (z, Z) The depth (z) or volume per unit length (Z) of water infiltrating a field during a specified period, usually the time between the initiation of irrigation and the end of the recession phase. Usual units are feet or inches for z and cubic feet per foot of length for furrows.

Cutback irrigation The practice of using a high unit discharge during the advance phase and a reduced one during the wetting or ponding phase to control runoff.

Cutoff time (t_{co}) Cumulative time since the initiation of irrigation until the inflow is terminated. Also referred to as set time. Usual units are minutes or hours.

Cycle time Length of water application periods, typically used with surge irrigation. Usual units are minutes.

Deep percolation (DP) The depth or volume of water percolating below the root zone. The depth or volume of deep percolation divided by the average depth or volume of water applied to a field is the deep percolation ratio (DPR).

Deficit irrigation The practice of deliberately under-irrigating a field in order to conserve water or provide a capacity to store expected precipitation.

Depletion time (t_d) The elapsed time between the initiation of irrigation and the recession of water following cutoff at the field inlet. Usual units are minutes.

Distribution uniformity (DU) In surface irrigation, the distribution uniformity is the ratio of the depth or volume infiltrated in the least irrigated quarter (sometimes called the low quarter) of the field to the average depth or volume infiltrated in the entire field.

Distribution system The network of ditches or pipes, and their appurtenances, which convey and distribute water to the fields.

Ditch Constructed open channel for conducting water to fields.

Ditch gate Small controlled opening or portal in a ditch used to divert water directly to furrows, borders, or basins.

Distribution uniformity (DU) See uniformity.

Effective precipitation Portion of total precipitation which becomes available for plant growth.

Evapotranspiration See consumptive use.

Fertigation See chemigation.

Field bay A narrow strip at the head of an irrigated field which is constructed slightly below field elevation used to redistribute water flowing from a pipe or ditch before flowing over the field.

Field capacity (W_{fc}) The dry weight soil moisture fraction in the root zone when vertical drainage has effectively ceased following irrigation or heavy rainfall. Generally, field capacity is assumed to occur at a negative one-third atmosphere or one bar of soil moisture tension.

Field length The dimension of the irrigated field in the direction of water flow. Usual units are feet.

Flow rate (q, Q) The volume of water passing a point per unit time per unit width (q) or per furrow (Q). Another term for flow rate is discharge. See also unit discharge. In surface irrigation, flow rate is typically expressed in units of cfs or gpm.

Flood irrigation An alternative expression for surface irrigation.

Furrow irrigation The practice of surface irrigation using small individually regulated field channels called furrows, creases, corrugations, or rills.

Gated pipe Portable pipe with small individually regulated gates installed along one side for distributing irrigation water onto a field.

gpm Acronym for gallons per minute.

Head ditch A small channel along one part of a field that is used for distributing water in surface irrigation.

Infiltration The process of water movement into and through soil.

Infiltration rate (I) The time-dependent rate of water movement into a soil. Usual units are inches or feet per minute or hour.

Infiltrometer A device, instrument, or system to measure infiltration rates.

Intake family Grouping of intake characteristics into families based on average 6-hour intake rates.

Intake rate A term often used interchangeably with infiltration rate, but in technical terms is the process of infiltration when the surface geometry is considered such as in furrow irrigation.

Intake reference flow (Q_{infilt}) The discharge at which intake is measured or evaluated in a surface irrigation system. Usual units are ft^3/s or gpm.

Irrigation efficiency In general terms, the efficiency or performance of an irrigation system is measured or expressed as the amount of water used beneficially by the crops divided by the total amount of water made available to the crops. To provide more specific assistance in evaluating irrigation performance of surface irrigation systems at the field level, the following terms have been defined:

Irrigation efficiency (Ie) At the field level, irrigation efficiency is the ratio of the average depth or volume of irrigation water stored in the root zone plus the depth or volume of deep percolation that is needed for leaching to the average depth or volume of irrigation water applied. Inefficiencies are caused by tailwater and deep percolation losses above the leaching requirement.

Irrigation interval The interval between irrigation events. Usual units are days.

Irrigation requirement Quantity of water, exclusive of effective precipitation, that is required for crop demands including evapotranspiration and leaching, as well as special needs such as seed bed preparation, germination, cooling or frosts protection. Where there is an upward flow from a shallow ground water, it should reduce the amount of water required from the irrigation system. The irrigation requirement is often called the net irrigation requirement. Recognizing that no irrigation system can exactly supply the irrigation requirement due to inefficiencies, a gross irrigation requirement is often estimated by dividing the irrigation requirement by an irrigation efficiency term. Usual units are inches.

Irrigation set A subdivision of the field that is individually irrigated. Sets are generally required whenever the supply flow is too small to irrigate the entire field at once.

Land leveling A general reference to the process of shaping the land surface for better movement of water. A more correct term is land grading. When land grading is undertaken to make the field surface level, the term land leveling can be used as a specific reference. Related terms are land forming, land smoothing, and land shaping.

Leaching The process of transporting soluble materials from the root zone in the deep percolation. The most common of these materials are salts, nutrients, pesticides, herbicides and related contaminants.

Leaching fraction (LF) Ratio of the depth of deep percolation required to maintain a salt balance in the root zone to the depth of infiltration. Also referred to as the leaching requirement.

Management allowable depletion MAD (z_{req}, Z_{req}) An abbreviation for management allowable depletion or maximum allowable deficiency. MAD is the soil moisture at which irrigations should be scheduled. In the evaluation or design of surface irrigation systems, MAD is referenced as a required depth per unit length, zreq, or a volume per unit length per unit width or furrow spacing, Zreq.

Opportunity time (τ_{req}) The cumulative time between recession and advance at a specific point on the surface irrigated field. Usual units are minutes or hours.

Permanent wilting point (W_{pw}) Moisture content, on a dry weight basis, at which plants can no longer obtain sufficient moisture from the soil to satisfy water requirements and will not fully recover when water is added to the crop root zone. Classically, this occurs at about -15 atmospheres or15 bars of soil moisture tension.

Porosity (ϕ) The ratio of the volume of pores in a soil volume to the total volume of the sample.

Pump-back system See tailwater reuse system.

Recession phase A term referring to the drainage of water from the field surface following the termination of inflow.

Recession time (tr) The interval between the initiation of irrigation and completion of the recession phase. Usual units are minutes or hours.

Resistance coefficient (n) A parameter in the Manning Equation that provides an expression of hydraulic resistance at the boundary of the flow.

Return flow Deep percolation, tailwater, conveyance seepage, and spills from an irrigation system which flow into local streams, rivers, lakes, or reservoirs.

Run length (RL) Distance water must flow over the surface of a field to complete the advance phase. The field length is the longest run length. Usual units are feet.

Runoff A general term describing the water from precipitation, snow melt, or irrigation that flows over and from the soil surface. In surface irrigation, runoff is used interchangeably with tailwater.

Run time (RT) See cutoff time.

Saturation (S) The ratio of the volume of water to the volume of pore space in a soil.

Siphon tube Relatively short, light-weight, curved tube used to divert water over ditch banks.

Slide gate A regulated ditch or canal offtake used to divert water to irrigated borders and basins. See also ditch gate.

Soil dry weight The weight of a soil sample after being dried in an oven at 95 to 105° C for 12 to 24 hours. Usual units are grams since as metric units are typically used for these measurements.

Soil moisture content (θ) The ratio of the volume of water in a soil to the total volume of the soil.

Soil moisture depletion (SMD) The depth or volume of water that has been depleted from the available water in a soil. This can also be viewed as the amount of water required to return the soil moisture to field capacity.

Specific gravity (Bs) The ratio of the unit weight of soil particles to the unit weight of water at 20 °C.

Spile A small pipe or hose inserted through ditch banks to transfer water from an irrigation ditch to a field.

Storage or requirement efficiency (Er) Ratio of the amount of water stored in the root zone during irrigation to the amount of water needed to fill the root zone to field capacity. Inefficiencies are caused by under-irrigating part of the field.

Subbing The horizontal movement of water from a furrow into the row bed.

Surface irrigation A broad class of irrigation systems where water is distributed over the field surface by gravity flow. See border, basin and furrow irrigation.

Surge irrigation Surface irrigation by short pulses or surges of the inflow stream during the advance phase and then by high frequency pulses or surges during the wetting or ponding phase.

Tailwater See runoff.

Tailwater reuse system An appurtenance for surface irrigation systems where there is tailwater runoff. The tailwater is first captured in a small reservoir and then diverted or pumped back to the irrigation system, i.e., either to the same field or to another in proximity.

Uniformity Irrigation uniformity is a qualitative measure of how evenly water is applied by the surface irrigation system.

Unit discharge The discharge or flow rate of water applied to an irrigated field per unit width or per furrow. Typical units are cfs and gpm.

Wetted perimeter Length of the wetted contact per unit width between irrigation water and the furrow, border, or basin surface, measured at right angles to the direction of flow. Usual units are inches or feet.

Wetting or ponding phase The period of time in an irrigation event between the completion of advance phase and the cutoff time.

Wild flooding Surface irrigation system where water is applied to the soil surface without flow controls and without management of flow rate and cutoff time.

Icons

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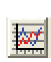 Plotted

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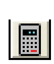 Simulate