Farm Irrigation System Evaluation: A Guide for Management

(Third Edition)

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Logan, Utah
1978

FARM IRRIGATION SYSTEM EVALUATION:

A GUIDE FOR MANAGEMENT

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PREFACE

Widespread interest in Irrigation System Evaluation and Improvement, by J. L. Merriam as a guide to better irrigation practice has been encouraging. It has been used by irrigators, land managers, technicians, and students who have had varied experience in irrigation. Some found the explanations excessively detailed, but others expressed the wish to see more advanced information published. This new text, which incorporates much of the earlier material, has been written to promote wider use of the evaluation techniques and the suggestions for better practices in irrigation management.

Professor John L. Merriam of the Agricultural Engineering Department at California Polytechnic State University has been largely responsible for reorganizing and expanding the surface irrigation concepts by including basin and basin-check irrigation, simplified techniques for use with furrow and border methods, and more explanation of standard procedure and management practices.

Dr. Jack Keller, who is Professor of Irrigation Engineering at Utah State University, has had the major responsibility for the sprinkle and trickle irrigation sections. The information about sprinkle irrigation has been expanded by including descriptions and discussions of the many variations of sprinkle systems which include sprinkler-lateral, perforated pipe, orchard sprinkler, traveling sprinkler, center pivot, and gun sprinkler systems. The book has been further enhanced by additional new information about trickle (drip) systems.

Together the authors have almost 75 years of combined design, field and teaching experience in irrigation engineering. During their many years of practical field irrigation engineering experiences, they have had direct field involvement with all of the evaluation techniques and management practices discussed.

To avoid confusion with certain similar but more general terms, three important terms used frequently in the earlier text have been renamed. Irrigation System Efficiency is now called *Potential Application Efficiency of the Low Quarter;* Actual Application Efficiency is now called *Application Efficiency of the Low Quarter;* and Distribution Efficiency has been changed to *Distribution Uniformity.*

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ABSTRACT

This manual describes and explains detailed procedures for field evaluation of the performance of several types of sprinkle, surface, and trickle (drip) irrigation systems and of management practices. Most chapters include lists of equipment needed for performing these evaluations, give step-by-step instructions for gathering data in the field, show sample forms for recording and organizing these field data, and present sample studies that demonstrate the entire process. The book includes analyses and recommendations for a few actual case studies.

The introduction states and explains the general concepts of uniformity, efficiency, and management that are used in evaluating each system and improving their use. Individual chapters describe procedures for both full and simple evaluations of performance of the various systems of irrigation.

Key Words: Irrigation, Efficiency, Uniformity, Sprinkle, Center Pivot, Traveler, Trickle, Drip, Basin-check, Border-strip, Furrow, Soil, Moisture, Evaluation.

CHAPTER I
INTRODUCTION

Need for System Evaluation

Irrigation systems may or may not be well designed and properly used. The techniques for system evaluation described in this book are designed for evaluating *actual* operation and management and for determining the *potential* for more economical and efficient operation. This type of study is necessary to provide direction to management in deciding whether to continue existing practices or to improve them.

Improved management of water on the farm may conserve water, labor, and soil and may also increase yields of crops. A system evaluation should measure and show the effectiveness of existing irrigation practice. Careful study of the system evaluation will indicate whether improvements can be made and will provide management with a reasoned basis for selecting possible modifications that may be both practical and economical.

Most modifications suggested here for improvement of irrigation systems require only simple changes in management practices. Evaluations frequently indicate the need for estimates of soil moisture deficiency and for better maintenance practices for systems. These often save both water and labor. Sometimes it is worthwhile to invest the capital necessary to mechanize or even automate an irrigation system.

Operation of *sprinkle irrigation systems* may be improved greatly by such simple changes as altering operating pressures, nozzle sizes, heights of risers, and durations of water application; operating at different pressures at alternate irrigations; using alternate set sequencing; obtaining larger sized lateral pipes; and by tipping risers along the edge of the field.

For *furrow* and *border strip irrigation systems*, any of the following simple changes may greatly improve performance: use of larger, smaller, or cut-back streams; irrigation at a different soil moisture deficiency; using different spacing or shape of furrows; revising strip width or length; using supplemental pipe lines and portable gated pipe; and using return-flow systems to recover runoff water. Capital investment for such projects as grading land to provide a smoother surface or more uniform slope and soil conditions, constructing reservoirs, increasing capacity for water delivery, and automation or semi-automation often proves profitable where it improves efficiency of water and labor.

Basin irrigation systems may be improved greatly by relocating a dike conforming to changes in the surface texture of the soil; grading land more carefully to achieve, as nearly as possible, a level surface and uniform intake; or changing the basin area so that it more nearly matches the volume of water from the available stream.

Trickle irrigation systems may require a different duration of application, a different frequency of irrigation, additional infiltration, or a *higher* density of emitters.

Possibilities for saving water and labor usually are best when the water supply is flexible in frequency, rate, and duration. Flexibility in *frequency* means that the water is available on or near the day when it is needed to match the moisture demands of the crop. Flexibility in *rate* means that the rate of supply can be changed to match different sizes of fields, to cutback sizes of streams, to accommodate varied rates of infiltration, and to smooth out the irrigators workload. Flexibility in *duration* means that the water can be turned off as soon as the soil moisture deficiency has been supplied and requirements for leaching have been satisfied. These types of flexibility are necessary for achieving efficient use of water.

A principal cause of low efficiency is overirrigation. When either furrow or border strip irrigation is used, a major part of any excess water is runoff, which may be recovered by using a return-flow system. Most excess water used in basin, basin-check, sprinkle, and trickle systems, infiltrates and adds to the groundwater supply. Such water may be recovered from wells, but it may cause a drainage problem if subsurface flow is restricted at a shallow depth.

Basic Concepts and Terms

Certain concepts are implicit in the design and operation of every irrigation system. Likewise, certain terms and their definitions are basic in describing these systems and in evaluating their operation. Some of the most frequently used terms are listed and briefly explained here; others are included in the Glossary and are explained in detail.

Evaluation is the analysis of any irrigation system based on measurements taken in the field under the conditions and practices normally used. It also includes on-site studies of possible modifications such as changing sprinkler pressures, having larger or smaller streams in furrows, and changing duration of application. Measurements needed for an analysis include: soil moisture deficiency prior to irrigation, rate of inflow, uniformity of application and infiltration, duration of application, rate of advance, soil conditions, rates of infiltration, and adequacy of irrigation.

Soil moisture

Soil moisture deficit (hereafter called *SMD*) is expressed numerically as a depth (in inches) indicating the dryness of the root zone at the time of measurement. This depth is identical to the depth of water to be replaced by irrigation under normal management. For this reason, the idea of moisture deficit in the root zone is preferable to the commonly used concept of depth of water currently in the soil. Knowledge is needed of how dry the soil should be before irrigation and is related to the soil moisture tension at that *SMD* and to how well the crop will grow under that stress. Some plants produce better when they are kept moist by frequent irrigations, but they may be more subject to diseases and insect pests under such a regime. Other plants may produce more efficiently when the soil is allowed to become quite dry. Infrequent irrigating also reduces costs of labor and generally increases efficiency.

Management allowed deficit (hereafter called *MAD*) is the desired *SMD* at the time of irrigation. *MAD* is an expression of the degree of dryness that the manager believes the plants in a given area can tolerate and still produce the desired yield. The *MAD* is related to *SMD* and resulting crop stress. It may be expressed as the *percent* of the total available soil moisture in the root zone or the corresponding *depth* of water that can be extracted from the root zone between irrigations to produce the best economic balance between crop returns and costs of irrigation.

Evaluation of furrow and border-strip irrigation systems should be made at about *MAD*, since infiltration rate, water movement, and duration of the irrigation are greatly affected by soil moisture deficit. Because the *MAD* appreciably affects all these factors, small variations in the *MAD* become a useful management tool for improving the operation of certain surface irrigation systems, especially the border-strip system.

Efficient operation of an irrigation system depends as much or more on the capability of the irrigator as on the quality of the system. Any system may be properly used or misused. To determine what is the best use requires a thorough evaluation of the system or appreciable experience combined with shortcut evaluation procedures. The two following questions must always be considered to obtain the maximum efficiency from any given system:

1. Is the soil *dry* enough to start irrigating?
2. Is the soil *wet* enough to stop irrigating?

The irrigator must carefully estimate the *SMD*; if it is the same as *MAD* or greater, the soil is dry enough to start irrigating. The simplest method for evaluating *SMD* is field observation of the soil.

This requires comparing soil samples taken from several depths in the root zone (preferably to the full rooting depth) with Table I-1. This chart indicates approximate relationship between field capacity and wilting point. For more accurate information, the soil must be checked by drying samples of it. The descriptions at the top of each textural column correspond to the condition of zero soil-moisture deficiency, i.e., field capacity. Those descriptions at the bottom of a column describe a soil having the maximum deficiency, i.e., wilting point. The soil-moisture deficiency at this condition is numerically equal to the available moisture range of the soil. Intermediate soil-moisture deficiency descriptions occur opposite corresponding numerical values of inches of water per foot of depth at which the soil is deficient. This chart describes a specific group of soils and though it has been found to have general application, it may not apply to many other groups. Where this is the case, new descriptions will need to be prepared corresponding to particular soil-moisture deficiency, feel, and appearance relationships.

Other methods for estimating *SMD* include the use of tensiometers when *MAD* values are low (high moisture situation) and resistance blocks or similar equipment when *MAD* values are high (low moisture content). Weighing and drying soil samples is precise but slow and cumbersome and neutron soil moisture probes are expensive.

Water budgets based on the depth of evaporation from a pan and other methods for estimating the water consumed by the plants (potential evapotranspiration) are also satisfactory for estimating *SMD*. The *SMD* estimated from water budgets should be checked occasionally by field observations of the lower part of the root zone to see that *SMD* is not accumulating. Such checks show deficient irrigation but unfortunately do not reveal overirrigation.

The second question, namely, when is soil wet enough to stop irrigating, is equally important because all water applied to the root zone after the *SMD* and leaching requirements have been satisfied is completely wasted. A probe, typically a 5/16-inch or 3/8-inch steel rod about 4 feet long having a somewhat bulbous (not pointed) tip and a tee handle, can be used in most soils to quickly check the depth of penetration of irrigation at numerous points throughout the field. Such a probe easily penetrates to a moderate depth (about 3 feet) through the nearly saturated soil being irrigated, but it encounters considerable resistance when it meets plow pans or drier soil below the wetted soil. The proper depth of probe penetration is appreciably less than the desired final depth of water penetration because water continues to percolate deeper after the irrigation stops. This requires that the depth to which the probe penetrates during irrigation be calibrated later with depth penetrated after an adequate irrigation.

Table I-1. Soil Moisture and Appearance Relationship Chart[1]

Moisture deficit in./ft.	SOIL TEXTURE CLASSIFICATION				Moisture deficit in./ft.
	Coarse (loamy sand)	Light (sandy loam)	Medium (loam)	Fine (clay Loam)	
	(field capacity)	(field capacity)	(field capacity)	(field capacity)	
0.0	Leaves wet outline on hand when squeezed.	Appears very dark, leaves wet outline on hand; makes a short ribbon.	Appears very dark; leaves a wet outline on hand; will ribbon out about one inch	Appears very dark; leaves slight moisture on hand when squeezed; will ribbon out about two inches	0.0
0.2	Appears moist; makes a weak ball.				0.2
0.4	Appears slightly moist, Sticks together slightly.	Quite dark color; makes a hard ball.	Dark color; forms a plastic ball; slicks when rubbed.	Dark color; will slick and ribbon easily.	0.4
0.6	Very dry, loose; flows through fingers. (wilting point)	Fairly dark color, makes a good ball.	Quite dark, forms a hard ball.	Quite dark, will make a thick ribbon; may slick when rubbed.	0.6
0.8		Slightly dark color, makes a weak ball.	Fairly dark, forms a good ball.	Fairly dark, makes a good ball.	0.8
1.0		Lightly colored by moisture will not ball.			1.0
1.2		Very slight color due to moisture. (wilting point)	Slightly dark, forms a weak ball.	Will ball, small clods will flatten out rather than crumble.	1.2
1.4			Lightly colored; small clods crumble fairly easily.		1.4
1.6				Slightly dark, clods crumble.	1.6
1.8			Slight color due to moisture, small clods are hard. (wilting point)		1.8
2.0				Some darkness due to unavailable moisture clods are hard, cracked. (wilting point)	2.0

[1] Taken from "Field Method of Approximating Soil Moisture for Irrigation," 1960, John L. Merriam. Transactions of the ASAE 3(1):31-32.

Alternately, to anticipate when the soil will be wet enough to stop, divide the *SMD* by the minimum rate of application at the soil surface. This will give the duration of irrigation needed to replace the *SMD*.

Several devices for sensing soil moisture can indicate when to start and stop irrigating, but none are less expensive and easier to understand and use than the auger and simple probe described above. Some electrical or mechanical sensing devices may be connected to turn the irrigation system on and off automatically. However, their operation must be correlated with soil moisture values at the sensing point which, in turn, must be related to values representative of the entire field under control.

The rate or volume of application by sprinkle and trickle irrigation systems is usually known. When application is reasonably uniform, depth of application can be controlled easily by controlling duration of the irrigation. However, under all methods of irrigation field conditions must be checked to assure that the desired depth of application has been reached and that no excess water is being applied.

Information about soils and crops is fundamental to all planning for irrigation. The optimum *MAD* depends on the specific soil, crop, depth of root zone, climate, and system of irrigation. The *MAD* should be established because it affects the depth, duration, and frequency of irrigation.

The available moisture, rate of infiltration, adaptability of method, and choice of crop are all related to soil texture; but depth of root zone, rate of intake, lateral wetting, perched water tables, and adaptability to land grading are mostly affected by soil profile and structure. The uniformity of soil in a field is important because it affects the uniformity of infiltration and therefore the choice of method of irrigation. Field surveys must thoroughly investigate soil uniformity. For all methods of irrigation in fields having more than one type of soil, the frequency and depth of irrigation should be governed by the soil that permits the lowest *MAD*.

Sprinkle or trickle irrigation is best for fields that have varied soils and topography because depth of application of the water is independent of surface variations. For the areas where the rate of intake is slowest, the rate of application should be less than the basic rate of infiltration to prevent runoff.

Reasonable uniformity of soil surface is important to assure efficiency for furrow, border strip, or basin irrigation. It must be fully appreciated that the basic objective of land grading is to improve irrigation, not merely to produce a plane surface. The possibility of improving uniformity of the soil within each field should not be overlooked during land grading. In basin and basin-check irrigation, uniformity of the intake rate is even more important than in furrow and border strip irrigations. However, uniformity of intake often can be improved by making boundaries of the basin conform to boundaries of areas having uniform soil texture. Low ridges can be farmed over or temporarily removed as needed, and the shapes or sizes of basins may be varied as required.

Irrigation techniques

There are seven basic techniques or methods of irrigation, most of which have several variations. Each technique and variation has characteristics that are adaptable for different locations and crops. The basic component and operation for each of the seven techniques are:

1. Basin: A level area of any size or shape bounded by borders or ridges retains all the applied water until it infiltrates. Any loss of water results from either deep percolation or surface evaporation.

2. Basin-check: A fairly level area of any size or shape bounded by borders and with no depressions which cannot be readily drained. The borders (or ridges) retain all the applied water for a sufficient time to obtain a relatively uniform depth of infiltration over the area and then the remaining water is drained off the surface and used to irrigate an adjacent border-check. Water is lost chiefly by deep percolation and evaporation.

3. Border-strip: A sloping area, usually rectangular, is bounded by borders or ridges that guide a moving sheet of water as it flows down the bordered strip. There should be little or no slope at right angles to the direction of flow. The onflow of water is usually cut off when the advancing sheet has flowed six- to nine-tenths of the distance down the strip. Water is lost chiefly by deep percolation and runoff.

4. Furrow or corrugation: A small sloping channel is scraped out of or pressed into the soil surface. For high uniformity of wetting, the irrigation stream should reach the end of the channel in about one-fourth of the time allotted for the irrigation; but the stream is not shut off until the root zone soil at the lower end of the furrow is adequately irrigated. Water in the soil moves both laterally and downward from the channel. Water is lost chiefly by deep percolation and runoff.

5. Sprinkler: Any of numerous devices for spraying water over the soil surface. Water discharged from a sprinkler into the air should infiltrate the soil where it falls, but it should not saturate the soil surface. For high uniformity of wetting, the spray patterns from adjacent sprinklers must be properly overlapped. Evaporation, wind drift, and deep percolation are chief causes of loss of water.

6. Trickle (or drip) emitter: A device used in trickle (or drip) irrigation for discharging water at some very low rate (less than 3 gallons per hour) through small holes in tubing placed near the soil surface. Water moves through the soil both sideways and downward away from the point of application to form a "bulb" of wet soil. Typically, only a portion of the soil mass is kept quite moist by very frequent or continuous application. Water loss is mainly by deep percolation.

7. Water table: In certain areas the water table can be adequately controlled and periodically raised to subirrigate the crop's root zone. Precise control of the water table requires certain natural conditions: pervious soil, level soil surface, naturally high water table, and low salinity of water.

Table I-2 summarizes and compares the major physical characteristics that affect the adaptability of each of the seven basic irrigation techniques. It also evaluates the probable *Potential Application Efficiency of Low Quarter* of a well designed and properly used system, employing each technique where appropriate. Most systems can be mechanized or even automated in order to reduce labor. This table leaves no allowance for such items as salinity and control of microclimate and takes no account of costs or personal preferences of the irrigator.

Uniformity and efficiency of irrigation

Figure I-1 is a stylized description of a water-soil-plant system. The infiltrated water, evaporation from plant and free water surfaces, wind drift, and runoff water must equal the total depth of applied (rain or irrigation) water. Furthermore, the sum of transient and stored water, deep percolation, transpiration, and evaporation from the soil surface must equal the depth of infiltrated water. Transient water in the soil root zone may be transpired by a growing crop before it is lost to deep percolation. However, some deep percolation is usually necessary to maintain a satisfactory salt balance since evaporation and transpiration (the only other ways to remove water from the root zone) leave the dissolved salts in the root zone. Transpiration and evaporation are interrelated and depend on atmospheric, plant, and soil-moisture conditions.

Table I-2. Major physical requirements and potential application efficiencies of the low quarter for the basic irrigation techniques.

	Physical requirements at site					
Irrigation method	Soil uniformity	Infiltration rate	Ground slope	Water supply	Labor intensity	*PELQ* Percent
Basin	Uniform within each basin	Any	Level, or graded to level	Large intermittent	High at infrequent intervals	60-85
Basin Check	Uniform within each basin	All but extremes	Fairly smooth with no depressions	Large intermittent	High at infrequent intervals	60-80[1]
Border strip	Uniform within each strip	All but extremes	Mild and smooth	Large intermittent	High at infrequent intervals	70-85[1]
Furrow or corrugation	Uniform along each furrow	All but very rapid	Mild or "contour"	Medium to large intermittent	High at infrequent intervals	70-75[1]
Sprinkle	Soils may be intermixed	All but very slow[2]	Any farmable slope	Small continuous	High to very low daily[3]	65-85 depending on var.
Trickle (drip or subsurface)	Soils may be intermixed	Any	Any farmable slope	Small continuous	Very low daily	75-90
Water Table Control	Uniform within each field[4]		Level, or graded to level	Large relative to area	Very low	50-80

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[1] Values of 90% can be attained under ideal conditions if runoff water is reused.

[2] Except for center pivot and traveling sprinklers, which are best suited to use on soils that have medium and high infiltration rates.

[3] Labor inputs range from high intensity for hand move, moderate for mechanical move, to low for automatic sprinkle irrigation systems.

[4] Surface soils with medium capillarity must be underlain with very pervious subsoils.

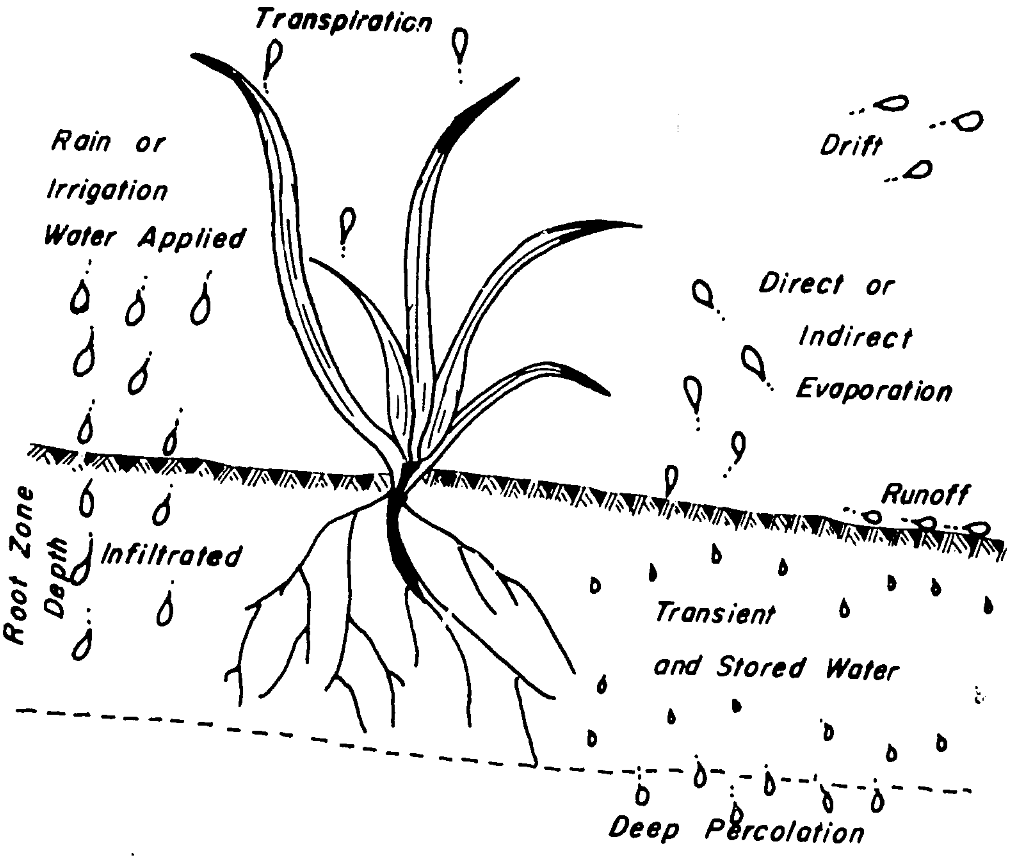

Figure I-1. Stylized description of a water-soil-plant system.

Terms used to designate or rate the *efficiency* with which irrigation water is applied by a given system have been widely defined. To avoid confusion, the three primary terms that are used in field evaluation procedures (Distribution Uniformity, Application Efficiency of Low Quarter, and Potential Application Efficiency of Low Quarter) are defined below. These terms differ from those used in the first edition of this work and in some other publications; they should help avoid confusion with other terms and their definitions. The numerators and denominators of the definitions are expressed in equivalent depths of free water (volumes per unit area) for surface and most sprinkle irrigated fields. However, water volume may be a more appropriate measure for trickle and sprinkle systems, which give only partial coverage.

High efficiency in operation of an irrigation system is not necessarily economical, but a manager must evaluate efficiency of any system in order to rationally decide whether he should merely modify his operation or adopt a different system. Efficiencies computed from ordinary field data are seldom more accurate than to the nearest 5 percent. Therefore, variations of less than 5 percent in computed efficiency values are not significant except where identical data are being used for comparisons of alternative operational procedures.

Distribution Uniformity (hereafter called *DU*) indicates the uniformity of infiltration throughout the field.

$$DU = \frac{\text{average depth infiltrated in the lowest one quarter of the area}}{\text{average depth of water infiltrated}} \times 100$$

The average low quarter depth of water infiltrated is the lowest one-quarter of the measured or estimated values where each value represents an equal area. For sprinkle and trickle irrigation, the depth infiltrated is presumed equal to the depth applied or caught on the soil surface if there is no runoff.

The *DU* is a useful indicator of the magnitude of distribution problems. A low *DU* value indicates that losses due to deep percolation are excessive (and that the water table is likely to be too high) if adequate irrigation is applied to all areas. Although the concept of a *low DU* is relative, values less than 67 percent are generally considered as unacceptable. For example, if the desired depth of infiltrated water is 4 inches and the *DU* is 67 percent, the average depth infiltrated must be 6 inches and the deep percolation loss will be 2 inches. However, if deep percolation is limited by reducing the applied depth and the *DU* value is low, any area that receives the low quarter depth of irrigation will be seriously under irrigated.

Application Efficiency of Low Quarter (hereafter called *AELQ*) achieved in the field indicates how well a system is being used.

$$AELQ = \frac{\text{average low quarter depth of water stored in the root zone}}{\text{average depth of water applied}} \times 100$$

When the average low quarter depth of irrigation water infiltrated exceeds the *SMD*, which is the storage capacity of the root zone, *AELQ* can be expressed as follows:

$$AELQ = \frac{SMD}{\text{average depth of water applied}} \times 100$$

The average low quarter depth of water infiltrated and stored in the root zone is the average of the lowest one-fourth of the measured or estimated values where each value represents an equal area of the field. Thus about one-eighth of the irrigated area receives less than the average of the low quarter. "Irrigated area" means the area receiving water; for most systems this is the entire field. However, where a limited area is being wetted, the term refers only to that part of the area receiving water.

Implicit in *AELQ* is a measure of uniformity, but it does not indicate adequacy of the irrigation. It merely shows that, for any value greater than zero, all the area is receiving water. Low values for *AELQ* indicate problems in management and/or use of the system. Additional factors, which will be presented later, must be considered when any field is intentionally under irrigated.

Potential Application Efficiency of Low Quarter (hereafter called *PELQ*) indicates a measure of system performance attainable under reasonably good management when the desired irrigation is being applied.

$$PELQ = \frac{\text{average low quarter depth infiltrated when equal to } MAD}{\text{average depth of water applied when } MAD \text{ just satisfied}} \times 100$$

The *PELQ* is the precise value of *AELQ* when the low quarter depth of water infiltrated is just sufficient to satisfy the *SMD* when $SMD = MAD$ in all parts of the field. Low *PELQ* usually is associated with inefficient system design, but may be intentional for economic reasons. The difference between *PELQ* and *AELQ* is a measure of management problems, whereas low values for *AELQ* merely indicate the possible existence of such problems.

Modifications of systems or methods can be compared meaningfully only by comparing values of *PELQ*. Such comparisons must be made when applying similar *MAD* depths. Economic comparisons should include costs of both irrigation and crop production as well as expected returns.

DU_a, *AELA*, and *PELA* may be used in place of *DU*, *AELQ*, and *PELQ* respectively, to denote the use of absolute minimum depth instead of the average low quarter infiltrated. For convenience in the evaluation of surface irrigation systems, the depth of infiltration at the downstream end of the furrow (or borders) is often used in place of the average low quarter depth. This depth would be the absolute minimum depth infiltrated if the soil infiltration and furrow (or border) characteristics were uniform throughout the field. The absolute minimum should not be used for method comparisons.

Intentional Underirrigation

Irrigation systems are usually managed so as to fill the *SMD* throughout the root zone at each irrigation; however, this should not always be the objective. Sometimes the interval between irrigations is extended to reduce the rate of water use below peak volumes by using a high *MAD*. This practice is used to aid other agricultural practices, to reduce requirements for system capacity, and/or to obtain maximum crop yields per unit of water or per unit of capital cost and is called stress irrigation. Another variation is to replace less than the *SMD* leaving the bottom portion of the root zone somewhat drier and is called limited irrigation. This type of intentional underirrigation may be imposed rather uniformly throughout the field, or only in areas receiving minimum infiltration, or selectively. Intentional underirrigation also enables better utilization of rainfall than full irrigation.

Limited irrigation is any of a group of procedures which result in underirrigation to conserve water but do not reduce yields. If the root zone is full of moisture at the beginning of the period of peak water use, limited underirrigation by not fully replacing *SMD* on the whole area can improve efficiency of water use without reducing crop yields. However, yields can be maintained only if the period of peak use is relatively short and is followed by either a period of less use or by harvest. Moisture stored deep in the root zone from early or off-season irrigation and rainwater are consumed during periods of underirrigation. This plus the irrigation water are available for crop production. This practice reduces losses from deep percolation if *DU* is high but allows a cumulative *SMD* to develop in the bottom portion of the root zone. The depletion of deep moisture augments the limited irrigation supply. Frequent checks of the *SMD* are essential for obtaining the maximum benefit from this practice and to avoid the danger of running out of deep moisture reserves and stressing a crop at a critical period, such as corn at tasseling. The area of land irrigated should not exceed what can be irrigated economically with the limited supply of irrigation water plus the available reserve of deep soil moisture.

Another means for maximizing efficiency of water use and reducing required system capacity without reducing yields is to irrigate only part of the area at any one time. This method is effective in orchard or vineyard irrigation by furrows, emitters, or orchard sprinklers because trees and vines have extensive root systems. The full soil profile throughout the area should be wet annually from rain or early season irrigation. During the period of deficient water supply, irrigation should be restricted to applying the *SMD* to a reduced area near each plant. This substantially reduces loss of water by surface evaporation and thereby increases the percentage of irrigation water transpired by the crop. A high *MAD* in the area wetted stresses the crop slowly as it draws moisture from the unirrigated areas and the lower root zone. Location of the area watered is relatively unimportant because root systems in a mature orchard of vineyard are extensive. This technique of limited irrigation utilizes the available supply of water very efficiently.

Certain cultural practices such as harvesting and propping trees suggest modification in planning and managing irrigation; this may result in using limited irrigation. For example, depth of the preharvest irrigation can be reduced by spreading the limited amount of available water wider and shallower. This permits the large mass of roots near the surface to function normally and thus reduces crop stress and improves crop quality.

Sometimes area is reduced since furrows cannot be plowed close to trees because of low branches or props. Often sprinklers have to be placed only in the tree row so as to reduce foliar interception.

A common practice in young orchards under basin, furrow, sprinkle, or trickle irrigation is to irrigate only the area immediately adjacent to the trees until their root systems become extensive. Even in mature orchards, much of the surface area is left dry to improve trafficability. In fact, ability to do this is a prime advantage of trickle and furrow irrigation, which is never intended to wet the total soil area of an orchard. Planned reduction of the area to be wetted is compensated by more frequent irrigation in inverse proportion to the wetted area. For example, if only half an area is to be wetted, it is wetted at twice the normal frequency; this is a prime example of *limited irrigation*. However, great caution should be exercised if one plans to design a system to irrigate less than one-third of the volume of potential root soil.

An excellent variation of limited irrigation is the use of *alternate side* irrigation. In this practice all or part of the area on one side of the plant is wetted at a time, i.e., the full *SMD* is replaced on half the field. At the next irrigation the *SMD* is replaced on the other side of the plant. At each irrigation only half the usual application is applied but at half the usual frequency.

Stress irrigation applies to any of a number of practices which result in underirrigation to conserve water at the expense of some reduction in potential yields. Irrigation procedures that are likely to stress a crop can be combined with *alternate side irrigation* to reduce the maximum stress.

Maximizing crop production from a limited amount of water is important either when the water supply is inadequate or when the value of water is measured by crop production per unit of water. In such areas, operating at a high *MAD* extends the interval between irrigations. This practice of stress irrigation may reduce yields per unit area but may produce more total crop per unit of water on an enlarged area and thereby produce a greater net return.

Except for some of the special variations mentioned below, intentional underirrigation puts a premium on having high values of *DU* and *AELQ* to reduce losses of water and results in a higher percentage of the irrigation water being transpired by the crop.

Reducing system capacities as discussed above, and/or accepting a lower *DU* enables the reduction of capital investment. When a system that achieves only low *DU* is used, the *SMD* may not be fully replaced in portions of the field even when the water supply is adequate. In such areas, management simply plans to accept a reduced yield from the dry portions of the field. Such systems require careful management, logical design, checks of *SMD*, and periodic evaluations of the success of the operation.

The above design logic anticipates moderate to low values of *DU* and *AELQ* as a trade-off for reducing costs of system development. Wide spacing of sprinklers and operation at low pressures may reduce costs, but they may also cause deficiencies of soil moisture to cumulate in the drier spots. The dry spots may produce less crop, but profits may be increased because the reduced cost of capital more than offset the crop losses. To eliminate the dry spots, abnormally large quantities of water must be applied which may be uneconomical or cause drainage problems.

For furrows and border strips, reduced land grading or use of longer-than-normal lengths of run are possible means for decreasing costs for capital and labor. However, these practices should be used only where resultant reductions in cost substantially exceed the losses resulting from reduced production at the underirrigated end of the furrow or strip. Furthermore, salt accumulated in dry areas which are not leached by occasional rainfall may become a hazard.

Before using any of these forms of *stress irrigation*, a manager should determine that the resulting savings in capital, labor, water, and management will more than offset the value of the estimated decrease in crop yield per unit area.

High Frequency Irrigation

Both movable and permanent solid set (or full coverage) sprinklers, center pivot, and trickle (or drip) systems are normally managed to apply light frequent irrigations. High frequency irrigation is used to achieve any or all of three major objectives: (1) to maintain a continuous low-stress high level of soil moisture to produce high yields or better quality of crops; (2) to avoid the runoff that often accompanies high rates of application (see section on center pivot sprinklers, Chapter V); and (3) to control temperature, humidity, and/or wind erosion. Under some conditions, high frequency irrigation may be conducive to diseases or excessive vegetative growth.

Under high frequency irrigation, depth of each application is usually less than 1 inch. Unless an area is being intentionally underirrigated; the *SMD* would also be less than 1 inch. It is practically impossible to estimate the *SMD* precisely enough for it to be useful in determining whether soil is dry enough to require irrigation when the *MAD* is so low.

Estimates of the rate of a crop's use of water give a reasonable basis for scheduling high frequency irrigation. A crop's use of water can be estimated from weather data, taken from measurements from evaporation pans, or can be based on experience. Except where underirrigation is intended, ideal system management would exactly replace the water consumed in the areas that receive the minimum application.

It is impractical to attempt to estimate exactly the volume of water actually consumed between irrigations. Since overirrigation is difficult to measure, it is good management to underirrigate slightly when using systems other than trickle irrigation. The *SMD* can be checked periodically to spot areas where deficits of soil moisture have cumulated. For such areas, scheduling of irrigation can be corrected accordingly. This practice of underirrigation should not be risked if only a small portion of the root mass is irrigated as in trickle irrigation.

High frequency irrigation is particularly well suited for use in conjunction with *limited irrigation* where the deep soil moisture is being gradually depleted over a whole area, as sometimes happens under center pivot and other automatic sprinkle irrigation systems. Light frequent watering of the top soil plus the gradual withdrawal of moisture from the subsoil can produce optimum crop yield when the irrigation system capacity is limited. However, where subsoil moisture is inadequate, light frequent irrigation, causing heavy moisture losses from evaporation, may be inefficient use of a limited supply of water and also increase salinity. Therefore, less frequent deeper irrigations may produce better crops.

While using supplemental irrigation in areas that receive high rainfall, it is good practice to apply shallow irrigation frequently while maintaining an *SMD* between 1 and 2 inches in the lower part of the root zone. Thus, the soil always has some storage capacity for rain but also has plenty of water for the crop.

Uniformity, Efficiency, and Economics

The efficiency of any operation, including irrigation, is a measure of how well its performance compares with some ideal level of performance. The following evaluation procedures usually imply that full irrigation with high *DU* and *AELQ* is the desired ideal. The concept of full irrigations in the areas receiving the average low quarter depth of application is useful for standardizing evaluation procedures in the field. However, this concept may provide a poor basis for evaluating and managing a system to optimize profit or any other value such as production per unit of land, production from a given quantity of water, or production per unit of energy input.

Intentional underirrigation of areas that are receiving the average low quarter depth of application may provide the optimum profitability. Rather than replenishing the water in almost all of the area, as is implied by *PELQ*, it may be more economical to leave a substantial area underwatered. This would be especially true for deep-rooted crops, low value crops, and for crops growing in humid regions.

A detailed study is needed to optimize profit which would be beyond the scope of the following evaluation procedures described here. In addition to evaluation of system performance in the field, which indicates both the location and magnitude of water losses, such a study would require thorough knowledge of system costs, plus the relation between water and crop production in the area studied.

CHAPTER II
SPRINKLER-LATERAL IRRIGATION

There are similarities between the procedures and logic underlying the evaluation of all types of sprinkle irrigation systems. Chapters II through VII describe and discuss techniques for evaluating the six most commonly used types of sprinkle irrigation systems. They also evaluate certain management practices associated with each of them. The irrigation systems can be divided into *periodic move systems* in which the sprinklers remain at a fixed position while irrigating, and *continuous move systems*, in which the sprinklers move in either a circular or a straight path while irrigating. The periodic move systems include sprinkler-lateral, overlapped hose-fed sprinkler grid, perforated pipe, orchard sprinklers, and gun sprinklers. The dominant continuous move systems are center pivot and traveling sprinklers.

In Chapter II both the simple and the full techniques used for evaluating *sprinkler-lateral* systems are described. Both techniques are useful for evaluating all the over-canopy or open field systems that irrigate by rotating sprinklers spaced along a lateral pipe set at fixed positions with overlapping patterns of water distribution. Sprinklers on all of these systems distribute water in a circular pattern and depend on overlap from several sprinklers arranged and spaced in a grid pattern to produce relatively uniform wetting over the entire area to be irrigated. Such systems are used over a major portion of sprinkle-irrigated acreage.

Among the first sprinkle systems to be used extensively were the sprinkler-lateral type; they were equipped with rotating sprinklers spaced along portable "hand move" lateral pipe. To reduce labor, the lateral pipelines may be moved mechanically after each set. These systems can be laid out with enough pipe and sprinklers so that an entire field or orchard can be irrigated merely by switching valves on and off. Since no pipe needs to be moved, labor is minimum. Sprinkler-lateral systems, which can be evaluated by methods described in this chapter, include: hand move, side roll, end tow; side move with multiple trail lines (or block move), portable full coverage (or solid set), and permanent solid set. (See Figures II-1, II-2, and II-3.)

Overlapped hose-fed sprinkler grid systems employ hoses to supply individual small sprinklers which are operated at pressures as low as 5 to 10 psi. These systems can also produce relatively uniform wetting providing the sprinklers are moved in a systematic grid pattern

Figure II-1. Hand move sprinkler lateral pipeline in operation.

Figure II-2. Side roll sprinkler lateral pipeline in operation.

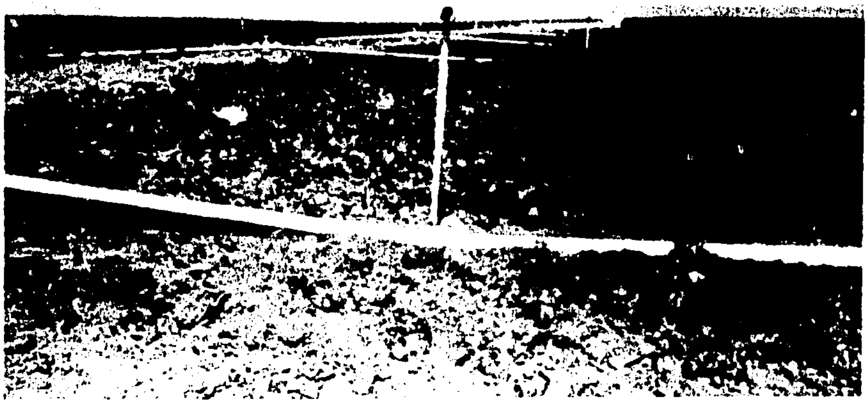

Figure II-3. Solid set sprinkler lateral pipelines connected to buried mainline.

Figure II-4. Measuring pressure at sprinkler nozzle with gauge connected to pitot tube.

with sufficient overlap. However, these systems are not in common use except in home gardens and turf irrigation although they do hold promise for rather broad use on small farms in developing countries where capital and power resources are limiting and labor is relatively abundant. Only slight common sense modifications of the sprinkler-lateral evaluation techniques are required to evaluate these systems. Therefore, a special chapter is not presented for the evaluation of overlapped hose-fed sprinkler grid systems.

Most sprinkle systems are designed to meet the peak demands for moisture imposed by evapotranspiration during the irrigation season. The manager should know his system's capabilities so he can adapt its operation to changing conditions imposed by the crop and weather. A simple evaluation, performed quickly with simple equipment, can reveal obvious management problems with minimum effort, but it does not provide information needed for designing changes in the system. By contrast, a full evaluation not only identifies problems but also indicates alternatives that can be used in corrective design.

Simple Evaluation

The procedure for simple evaluation is designed to identify fairly basic problems or errors in design, operation, and management of any sprinkler-lateral system.

Equipment needed

The only equipment the evaluator needs is:

1. A pressure gauge (0-100 psi) with pitot attachment. (See Figure II-4.)
2. A stopwatch or watch with an easily visible second hand.
3. A large container of known volume clearly marked (1 gallon or larger for large sprinklers).
4. A 4-foot length of flexible hose having diameter appreciably larger than the outside diameter of nozzles. (See Figure II-5.)
5. A soil probe or soil auger.

Field measurements

The following few simple measurements and observations can be taken in the field:

Figure II-5. Measuring sprinkler discharge using a hose to direct the water into a container of known volume.

Operating pressures. Operating pressures should be within the median range specified by the manufacturer for each size of nozzle and should not vary greatly throughout the system. When measuring sprinkler pressures (Figure II-4), the pitot tube must be centered in the jet, and the jet must impinge directly into its tip. The tip may be rocked slowly. Note the highest pressure reading shown while the pitot tube is being held about 1/8 inch from the sprinkler nozzle. Median pressures produce jets that have a variety of sizes of water drops and assure smooth sprinkler operation. Large drops travel further than small drops; small drops fall close to the sprinkler. Having varied sizes of water drops helps to produce uniform coverage when spray patterns from several sprinklers overlap.

To aid in spotting excessive variations of pressure within a system, a few sprinklers should be observed while operating at the widest available range of pressures--high, medium, and low. Excessively high pressure produces fogging or irregular turning; the fogging contains a disproportionately large number of small drops, which fall close to the sprinkler. Too low pressures cause improper jet breakup, which produces a "doughnut" type of spray pattern; under such operation very little water falls close to the sprinkler.

Proper operating pressure can be determined only by using more elaborate techniques of evaluation.

Flow rates. Rates of flow are determined by recording the time required to collect a given volume of water from a sprinkler. (See Figure II-5.) For example, if a sprinkler fills a 2-gallon container in 45 seconds, flow rate is computed thus:

$$\textit{Sprinkler flow rate} = 2.0 \times \frac{60}{45} = 2.7 \textit{ gpm}$$

A typical design limit allows a 10% difference of flow between the first and last sprinklers on a lateral line. This corresponds to a pressure differential of approximately 20%, which usually does not alter sprinkler patterns enough to produce unacceptable lack of uniformity; however it may not be the most economical design.

Checking the measured rates of flow against catalog specifications for equipment indicates actual operation pressures that should confirm the field estimates of what correct pressure should be. Nozzles often become eroded by silt or sand carried in the irrigating water causing their orifices to enlarge. This, in turn, causes flows to be greater than catalog ratings specify. The amount of nozzle enlargement can be easily checked with a feeler gauge such as a drill bit having the diameter specified for the nozzle.

Uniformity. Uniformity of the sprinkler pattern may be checked by probing the soil at numerous spots within the area between two sprinklers. This should be done on the side of the lateral that was irrigated during the previous set. Areas having minimum infiltration are readily identified by such probing, especially late in the season when deficits of soil moisture have cumulated. Probing cannot be used to check uniformity where full or excess irrigations have always been applied however; in such areas the probe indicates adequate moisture by deep penetration everywhere.

Properly overlapping sprinkler-wetted areas show uniform application. The amount of overlap required to achieve a given uniformity of wetting depends on nozzle size, water pressure, operating characteristics of the sprinkler, and wind conditions. Optimum uniformity is a function of economics that usually results in a compromise between the medium uniformity achieved by wider spacing of the sprinklers (and the consequently reduced operating costs) and reduced returns from crops.

To obtain medium uniformity, the spacing of sprinklers along the lateral should be closer than the wetted radius of the sprinkler. The spacing between laterals is usually such that in areas where wind speeds are low, one line of sprinklers throws water about two-thirds of the distance to the next line. Where wind speeds typically exceed 5 mph the lines should be closer together.

Runoff. Runoff from higher to lower areas in a field not only reduces the uniformity of irrigation but also may cause waterlogging and crop loss in low areas. The first sign that runoff may be a problem is surface ponding in areas where the application rate exceeds the infiltration rate. These areas are most likely to be near the sprinklers or midway between them on the side of the lateral which received water from the previous set. Runoff usually increases late in the season after numerous irrigations have somewhat sealed the soil surface.

Increasing pressures (to the high range recommended by the manufacturer), decreasing the nozzle size (which may necessitate decreasing the distance between lateral moves), and shortening the duration of application will help reduce or prevent surface ponding and runoff. Increasing pressures and/or decreasing nozzle sizes reduces the size of water drops. Even though application rate may have been increased by increasing pressure, smaller drops are less detrimental to the soil surface, thus maintaining a higher infiltration rate.

Analysis and recommendations

All sprinklers should be erect, i.e., their risers should be perpendicular to the ground surface. All nozzles should permit free flow of water and sprinklers should be turning uniformly. Maintenance and correct operation are essential for efficient use. Where irrigation water carries trash, adequate screening devices should be installed at the system's inlet and at the inlet of each lateral.

Alternate setting is the practice of setting any lateral midway between previously used sets for every other cycle of hand or mechanically move systems. Usually it greatly improves uniformity of water distribution, but obviously it cannot be used by permanent or solid set systems.

Tipping the risers is helpful at borders of fields where there is no overlap. For the typical situation where the lateral pipeline lies from a third to a half move distance from the boundary, some water is thrown outside the field. For crops not subject to damage by impact from the sprinkler jet, all risers should be tipped toward the boundary so the jets barely reach the edge of the field. This produces fairly uniform coverage along the boundary, especially where the lateral line is only one-third of the distance of a full move inside; it also eliminates much of the objectionable over-throw. Tipping the end sprinkler by bending the riser gives similar favorable results at ends of lateral lines. For uniform coverage, end sprinklers should be set closer than normal to the boundary. Using a half-circle sprinkler with two-thirds of the standard discharge and operating at the edge of the field is also practical.

Adjustment of irrigation duration to the most efficient duration can be calculated from the rate of sprinkler application, the *SMD*, and an estimate of the *Potential Application Efficiency of Low Quarter (PELQ)*. The first step is to find the average rate of water application, *R*, in inches per hour, iph, which is computed by:

$$R = \frac{96.3 \text{ X individual sprinkler discharge (gpm)}}{\text{sprinkler spacing (feet X feet)}}$$

in which the number 96.3 is a conversion factor for these specific units of measurement. Using an estimate of *PELQ*, which is usually between 70 and 80%, the assumed minimum rate, R_n, at which water is infiltrated in the area can be computed by:

$$R_n = R \frac{PELQ}{100}$$

and the duration of irrigation, T_i, in hours is computed by:

$$T_i = \frac{SMD}{R_n}$$

For example, assume that *PELQ* is 80%, *SMD* is 4.0 inches, the flow rate of the sprinkler is 4.4 gpm, the sprinkler spacing on the lateral is 30 feet, and the lateral move distance is 50 feet. The average application rate then is:

$$R = \frac{96.3 \text{ X } 4.4}{30 \text{ X } 50} = 0.28 \text{ iph}$$

and

$$R_n = 0.28 \text{ X } 80/100 = 0.23 \text{ iph}$$

Then the required duration of irrigation is:

$$T_i = \frac{4.0}{0.23} = 17.5 \text{ hours}$$

If the system is operated for 17.5 hours, the *Application Efficiency of Low Quarter (AELQ)* would equal the assumed *PELQ* of 80%. If the system is operated for 23 hours with one set per day, the last 5.5 hours of watering would be wasted and *AELQ* would be reduced to about 60%. The excess 5.5 hours of operation at 0.28 iph would result in a loss of 1.54 inches. This loss would be mostly to deep percolation which, in turn, could contribute to high water table problems.

If the evaluator does not know the *SMD* and therefore cannot calculate the required time of application as shown above, he can use a probe to indicate when the soil is wet enough to stop irrigating. He can use the probe to follow the wetting front and when water has penetrated deep enough for a full irrigation, he can turn it off. Gaining sufficient experience to use a probe effectively is important, because proper use of the probe helps answer the question, "Is it wet enough to stop irrigating?"

Summary of simple evaluation

An experienced observer can obtain much useful information for evaluating operation of a sprinkler system by judicious use of some simple equipment and by computing certain values from information thus obtained. He can determine whether operating pressures need be adjusted upward or downward; he can also analyze flow rate and sprinkler overlap in different parts of the system and can determine whether he should adjust them. Analysis of the system's performance can reveal whether management of the water supply and the use of labor have been efficient; if management has not been efficient, simple analysis can show where it could be improved.

Full Evaluation

The general procedures for full evaluation of sprinkler-lateral systems can also be used for overlapped hose-fed sprinkle grid systems with only minor modifications. (The test data from a single hose-fed sprinkler must first be overlapped to simulate a sprinkler-lateral test.) Full evaluation requires the following information:

1. Duration of normal irrigations.
2. *MAD* and *SMD*.
3. Spacing of sprinklers along lateral lines.

4. Spacing of lateral lines along the main lines.

5. Measured depths of water caught in catch containers at a test location.

6. Duration of the test.

7. Water pressures at the sprinkler nozzles at the test location and along laterals throughout the system.

8. Rate of flow from the tested sprinklers.

9. Additional data specified on Form II-1.

It is useful to know what wetting patterns the operation produces at different pressures and also operating pressures at the pump and along the main line and laterals. General study of data obtained in the field enables determination of *DU*, *PELQ*, and *AELQ*. Further study enables determination of the uniformity and economics of the spacings and/or alternate sets, the economics of sizes of pipes used for mains and laterals, the desirability of using other operating pressures and other durations of application, and the effect of wind.

Equipment needed

The equipment the evaluator needs is:

1. A pressure gauge (0-100 psi) with pitot attachment. (see Figure II-4.)

2. A stopwatch or watch with an easily visible second hand.

3. A large container of known volume clearly marked (1 gallon or larger for large sprinklers).

4. A 4-foot length of flexible hose having diameter appreciably larger than the outside diameter of nozzles. (See Figure II-5.)

5. From 50 to 100 (or more depending on sprinkler size) catch containers such as 1-quart oil cans or plastic freezer cartons.

6. A measuring stick (or ruler) to measure depth, or a 500-ml graduated cylinder to measure volume of water caught in containers.

Form II-1. SPRINKLER-LATERAL IRRIGATION EVALUATION

1. Location *Field C-22*, Observer *JLM*, Date *9-30-75*
2. Crop *Tomatoes*, Root zone depth *4.0* ft, MAD *50* %, MAD *4.4* in
3. Soil: texture *clay loam*, available moisture *2.2* in/ft, SMD *4.4* in
4. Sprinkler: make *Rain Bird*, model *29B*, nozzles *5/32* by ____ in
5. Sprinkler spacing *30* by *50* ft, Irrigation duration *23.5* hrs
6. Rated sprinkler discharge *4.4* gpm at *40* psi giving *0.28* in/hr
7. Lateral: diameter *2* in, slope *1½* %, Riser height *18* in
8. Actual sprinkler pressure and discharge rates:

	Sprinkler location number on test lateral					
	1	*4*	*5*	*6*	*10*	*15* end
Initial pressure (psi)	*45*	*40*	*40*	*40*	*39*	*40*
Final pressure (psi)	*45*		*40*		*39*	*40*
Catch volume (gal)	*1.0*	*1.0*	*1.0*	*1.0*		*1.0*
Catch time (min or sec)	*0.21*	*0.22*	*0.22*	*0.22*		*0.22*
Discharge (gpm)	*4.8*	*4.6*	*4.6*	*4.6*		*4.6*

9. Wind: direction relative to
   Part 10: initial ↘, during ↙, final ↙
   Speed (mph): initial *2 ±*, during *5 ±*, final *5 ±*
10. Container grid test data in units of *ml*, Volume/depth *200* ml/in
    Container grid spacing *10* by *10* ft
    Test: start *2:55 pm*, stop *4:30 pm*, duration *1* hr *35* min = *1.58* hr

			32 *.10*	*68* *.21*	*77* *.24*	*90* *.28*	⑥ ↑	*73* *.23*	*66* *.21*	*9* *.03*		*ml* *iph*	
			35 *.11*	*66* *.21*	*84* *.16*	*100* *.31*		*100* *.31*	*52* *.16*	*3* *.01*			
			32 *.10*	*50* *.16*	*60* *.11*	*104* *.32*	⑤	*99* *.31*	*48* *.15*	*12* *.04*			
			31 *.10*	*74* *.23*	*88* *.27*	*104* *.32*		*86* *.27*	*56* *.17*	*11* *.03*			
			27 *.08*	*64* *.20*	*80* *.25*	*96* *.30*		*112* *.35*	*62* *.19*	*9* *.03*			
			20 *.06*	*49* *.16*	*59* *.19*	*107* *.33*	④	*87* *.27*	*36* *.11*	*13* *.04*			

11. Evaporation container: initial *2.15* final *2.10* loss *0.05* in
12. Sprinkler pressures: max *45* psi; min *39* psi, ave *40* psi
13. Comments *Test duration was too short. Depths caught measured in 1000 ml graduated cylinder. Wind velocities are less than normal.*

7. A soil probe or auger.

8. A 50- to 100-foot tape for measuring distances in laying out catch container grid.

9. A shovel for smoothing spots to set containers and for checking soil, root, and water penetration profiles.

10. Form II-1 for recording data.

11. Manufacturers' sprinkler performance charts showing the relationship between discharge, pressure, and wetted diameter plus recommended operating pressure ranges.

12. A set of drill bits ranging in size from 3/64- to 1/4-inch in diameter in increments of 1/64-inch makes a handy set of feeler gauges to check nozzle wear.

Field procedure

The information obtained from the following field procedure should be entered in a data sheet similar to Form II-1.

1. Choose a location along a lateral for the test. It may be either a single location at which the pressure is typical (or average) for the entire system, or two locations near the ends of a lateral to permit study of effects of differences in pressure. Loss of pressure due to friction in a lateral that has only one size of pipe is such that about half of the pressure loss occurs in the first 20 percent of the length and over 80 percent of the pressure loss occurs in the first half of the lateral's length. (See Figure II-6.) On a flat field the most representative pressure is at about 40 percent of the distance from the inlet to the terminal end.

When pressure varies greatly within the system, selection of sampling locations should represent the full range of operating pressures encountered. Pressure variation, spacing of sprinklers, and size of nozzles all affect *DU*. (See Figure II-7.)

2. Set out at least 24 catch containers (See pattern in Figure II-8.) on a grid having a spacing not to exceed 10- by 10-foot for testing along a single lateral line. The catch containers' pattern should be laid out to cover two adjacent areas between three sprinklers since sprinklers may not apply water at precisely uniform rates. Each catch container is assumed to give the representative depth of catch over the square having the same dimensions as the can spacing in which it is centered. (See dotted grid lines in Figure II-8.)

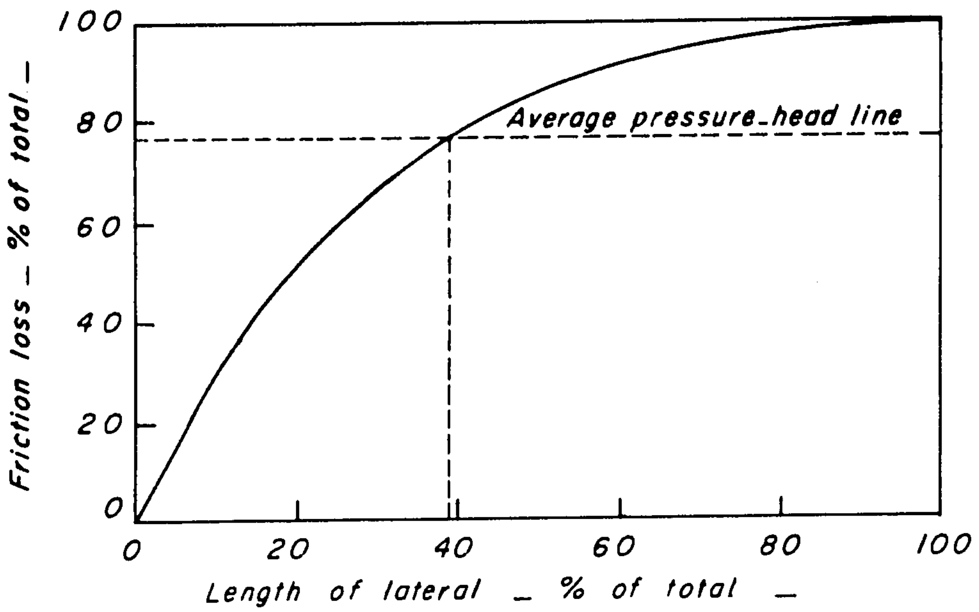

Figure II-6. Loss of pressure due to friction along a lateral having only one size of pipe.

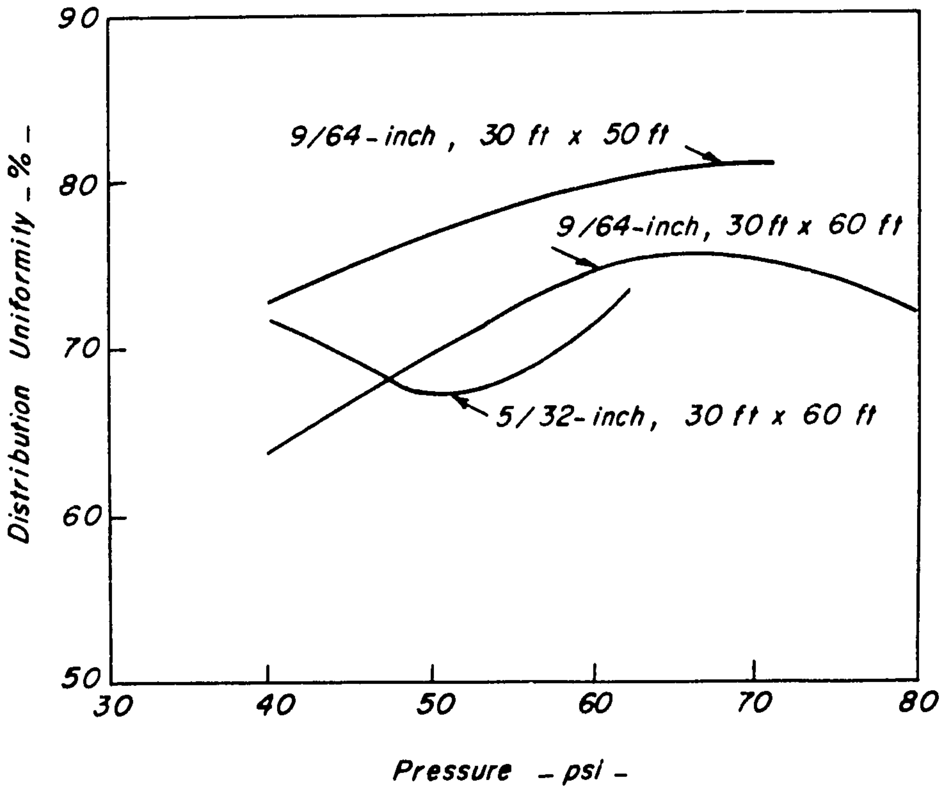

Figure II-7. Variations in *DU* for various pressures, move distances, and nozzle sizes in steady state, 5 mph winds blowing at a 45° angle to the sprinkler layout.

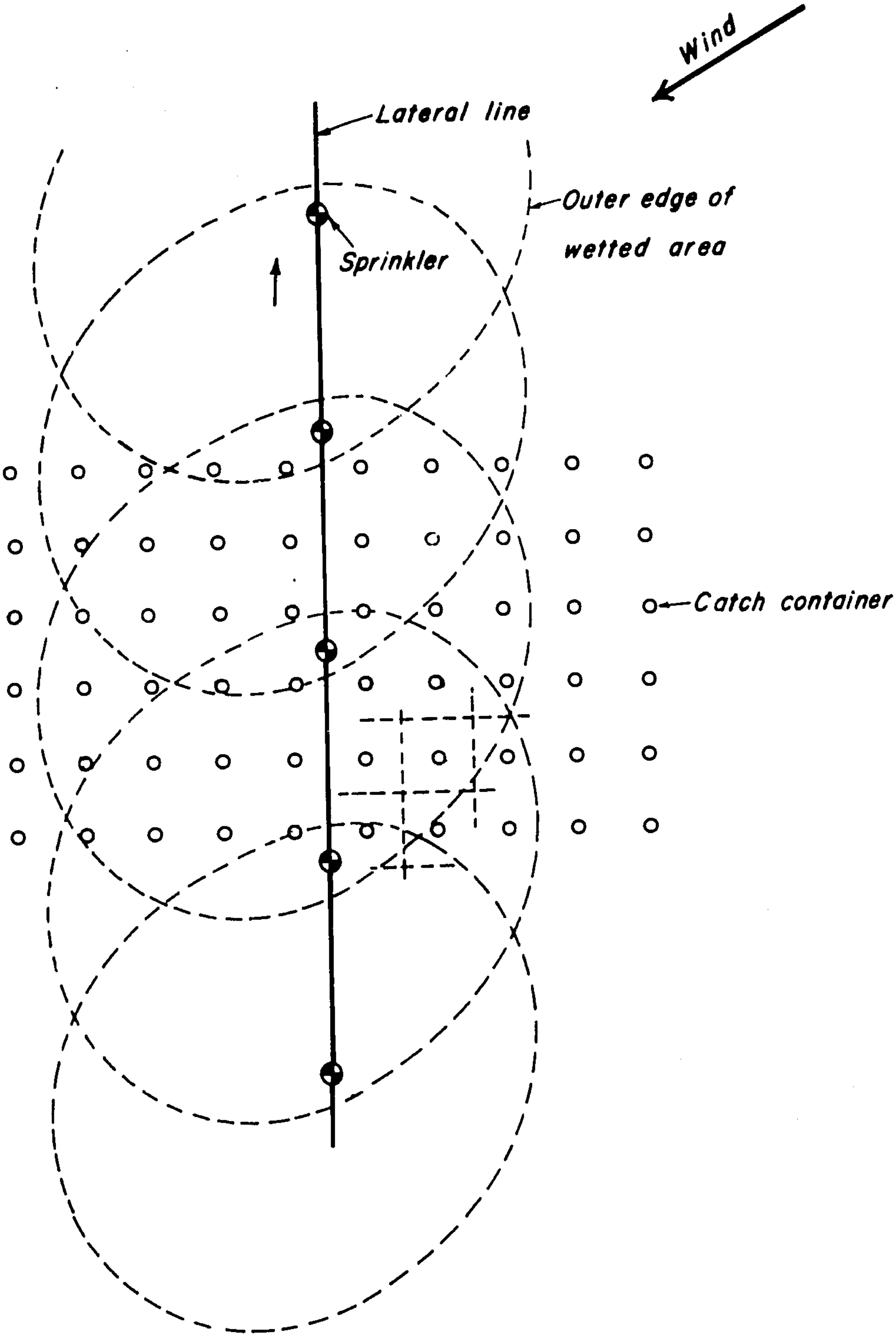

Figure II-8. Layout of catch containers for testing the uniformity of distribution along a sprinkler lateral line.

For solid set or block move systems where several adjacent laterals operate simultaneously, the catch containers should be placed in the area between two adjacent laterals. Caution should be exercised to allow for any water that could enter the test container area from adjacent blocks. These tests cannot be used to study other lateral spacings.

Each container should be located within a foot of its correct grid position and set carefully in an upright position with its top parallel to the ground; any surrounding vegetation that would interfere with a container should be removed. When it is windy, it may be necessary to fasten containers to short stakes with rubber bands, and weight them with a known depth of water or a stone (which is later subtracted from the total depth shown after the catch); or they may be set in shallow holes. The most accurate means for measuring the catch can be achieved volumetrically by using a graduated cylinder. These measurements can be converted to depths if the area of the container opening is known. For 1-quart oil cans, 200 ml corresponds to 1.00 inch depth. Other suitable catch containers may be square or cylindrical plastic freezer containers with sides tapered slightly for nesting or any similar container.

Determine and record the container grid spacing and the ratio of volume to depth of catch. Also indicate the position of the lateral and record the location and position numbers of the sprinklers on the lateral. (See Form II-1, part 10.)

3. Determine the soil texture profile and *MAD*; then estimate the available soil moisture capacity in the root zone and check the *SMD* in the catch area on the side of the lateral that was not irrigated during the previous set. These values should be recorded in parts 2 and 3.

4. Check and record the make and model of the sprinkler and the diameter of the nozzles.

5. Obtain the normal sprinkler spacing, duration, and frequency of irrigation from the operator and record them. The standard way of expressing the sprinkler grid spacing is __- by __-foot; this indicates the sprinkler spacing on the lateral and the spacing between laterals in that order.

6. Read and record the rated sprinkler discharge, pressure, the computed average design application rate from the system design data and manufacturer's sprinkler catalogs.

7. Check and record the size and slope of the lateral pipe and the height and erectness of the risers.

8. Before starting the test, stop the rotation of the sprinklers at the test site to prevent water from entering the containers. A short piece of wire or stick wedged behind the swinging arm facilitates this.

Turn on the water to fill the lateral lines. When the test lateral is full, turn the pressure up slowly to observe the trajectory, breakup of drops, and effect of wind at different pressures. Then set the pressure at the value desired for the test.

Measure and record the pressure at the sprinklers to be tested at several places along the line and at both ends to observe the differences in pressure. Pressures should be checked at both the beginning and end of the test period and recorded in part 8. When measuring sprinkler pressures (Figure II-4), the pitot tube must be centered in the jet, which must impinge directly onto its tip. The tip may be rocked slightly. Record the highest pressure reading shown while the pitot tube is being held about 1/8 inch from the sprinkler nozzle.

Also in part 8, record how long it takes each sprinkler in this test area to fill the large container of known volume. Do this by slipping the short length of hose over the sprinkler nozzle and collecting the flow in the container (Figure II-5). To improve accuracy, measure the nozzle output several times and compute the average. (If the sprinkler has two nozzles, each can be measured separately with one hose.) Often the measured sprinkler discharge rate is greater than what the manufacturer specified at the given pressure. This occurs because sprinkler nozzles often erode during use and become enlarged, or because the hose fits too tightly and creates a syphoning action. You can check nozzle erosion with a feeler gauge such as a drill bit that has the diameter specified for the nozzle.

9. Note the wind speed and direction and record the wind direction in part 9 by drawing an arrow relative to the direction of water flow in the lateral.

10. Empty all catch containers before starting the test; start the test by releasing all sprinklers surrounding the test site so they are free to rotate and note the starting time in part 10.

11. Set outside the catchment area a container holding the anticipated amount of catch to approximately check the volume of water lost by evaporation. (See Form II-1 part 10.)

12. While the test is in progress, check sprinkler pressures at 20 to 40 systematically selected locations on other laterals (for

example, at the two ends and quarter points along each lateral) and record the maximum, minimum, and average pressures encountered in part 12.

13. Terminate the test by either stopping the sprinklers surrounding the test site in a position such that the jets do not fall into the containers, or by deflecting the jets to the ground. Note the time, check and record the pressure, and turn off the water. It is most desirable for duration of the test to be equal to the duration of an irrigation to get the full effect of wind and evaporation. Ideally minimum duration tests should apply an average of about 0.5 inches of water in the containers.

Measure the depth of water in all the containers and observe whether they are still upright; note any abnormally low or high catches. As shown in part 10, caught depths or volumes are recorded above the line at the proper grid point, which is located relative to the sprinkler and direction of flow in the pipe line. For long runs, where maximum depths exceed 2.0 inches, a measuring stick provides suitable accuracy up to ± 0.1 inch.

Utilization of field data

Convert the depths or volumes of water caught in the containers to rates and record them (iph) below the line on the data sheet part 10. Assuming that the test is representative and that the next set would give identical results, the right-hand side of the catch pattern may, as if it were a subsequent set, be overlapped (or superimposed) on the left-hand side to simulate different lateral spacings. For lateral spacings that are whole units of the container spacings, the summation of the catches of the two sets represents a complete irrigation (Figure II-9 illustrates overlapping). For very close lateral spacings, water may overlap from as many as four lateral positions. The above concept of overlapping is not suggested where winds are likely to change appreciably between subsequent lateral sets. It is most valid for 24-hour sets.

Distribution Uniformity

In order to determine whether sprinklers are operating at acceptable efficiency, the *DU* should be evaluated. (See Chapter I, page 11.) The *DU* is based on the average rate or depth recorded for the lowest one-fourth of the catch locations; hence, about 1/8 of the area may actually have received slightly less water. If an individual low value was due to a poor field measurement, perhaps no area actually received less. If the average low quarter depth infiltrated just matches the *SMD*, the percent of the infiltrated water going too deep would be approximately equal to *100 - DU*.

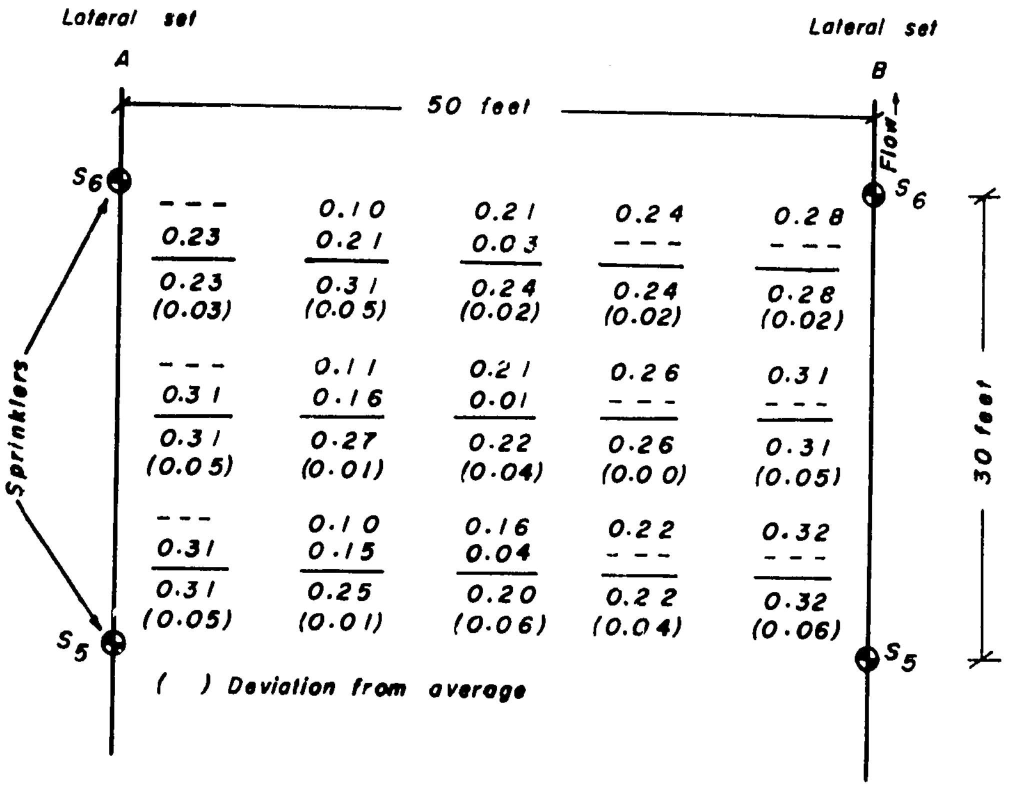

Figure II-9. Combined catch pattern iph between sprinklers 5 and 6 for a 50-foot lateral spacing.

Figure II-9 shows the data gathered between sprinklers 5 and 6 from Form II-1 overlapped to simulate a 50-foot lateral spacing. The sprinklers were spaced 30 feet apart on the lateral; thus, the sprinkler spacing is referred to as a 30- by 50-foot spacing. The right side catch is added to the left side catch; the totals at each point represent a complete 1.0-hour irrigation for a 30- by 50-foot spacing. For the simulated 50-foot lateral spacing, the total catch at all 15 grid points is 3.97 which gives:

$$\text{Average catch rate} = \frac{3.97}{15} = 0.26 \text{ iph}$$

The average of the lowest one-quarter of the catch rates (use 4 out of 15) is:

$$\text{Average low quarter rate} = \frac{0.20 + 0.22 + 0.22 + 0.23}{4} = 0.22 \text{ iph}$$

and

$$DU = \frac{0.22}{0.26} X\ 100 = 84\%$$

Repeating the above procedure for a 40-foot lateral spacing gives:

$$Average\ catch\ rate = \frac{3.97}{12} = 0.33\ iph$$

$$Average\ low\ quarter\ catch\ rate = 0.27\ iph$$

$$DU = \frac{0.27}{0.33} X\ 100 = 82\%$$

In the 50-foot lateral spacing, *DU* was slightly better than for the 40-foot spacing. However, the accuracy of the application rate is to the nearest 0.01 iph; thus, the accuracy of the *DU* value is no better than ± 3%.

Alternate sets. It is usually desirable to use alternate sets in which the lateral line is always placed midway between the positions used during the preceding irrigation. This results in a *DU* for the complete cycle of two irrigations which is the same as if all moves were one-half the normal distance. Figure II-10 shows the combined catch overlapped to simulate a 60-foot move.

The total catch in the 18 cans was 3.97 as before, giving:

$$Average\ catch\ rate = \frac{3.97}{18} = 0.22\ iph$$

$$Average\ low\ quarter\ rate = \frac{0.12 + 0.13 + 0.14 + 0.15}{4} = 0.14\ iph$$

$$DU = \frac{0.14}{0.22} X\ 100 = 64\%$$

Figure II-11 shows the right half (3 columns) of Figure II-10 superimposed on the left to simulate two irrigations with 60-foot moves offset halfway, i.e., 30 ft. Since both sides of the new pattern are identical, only 30 feet of the pattern needs to be computed from the already combined values for the 30- by 60-foot spacing shown in

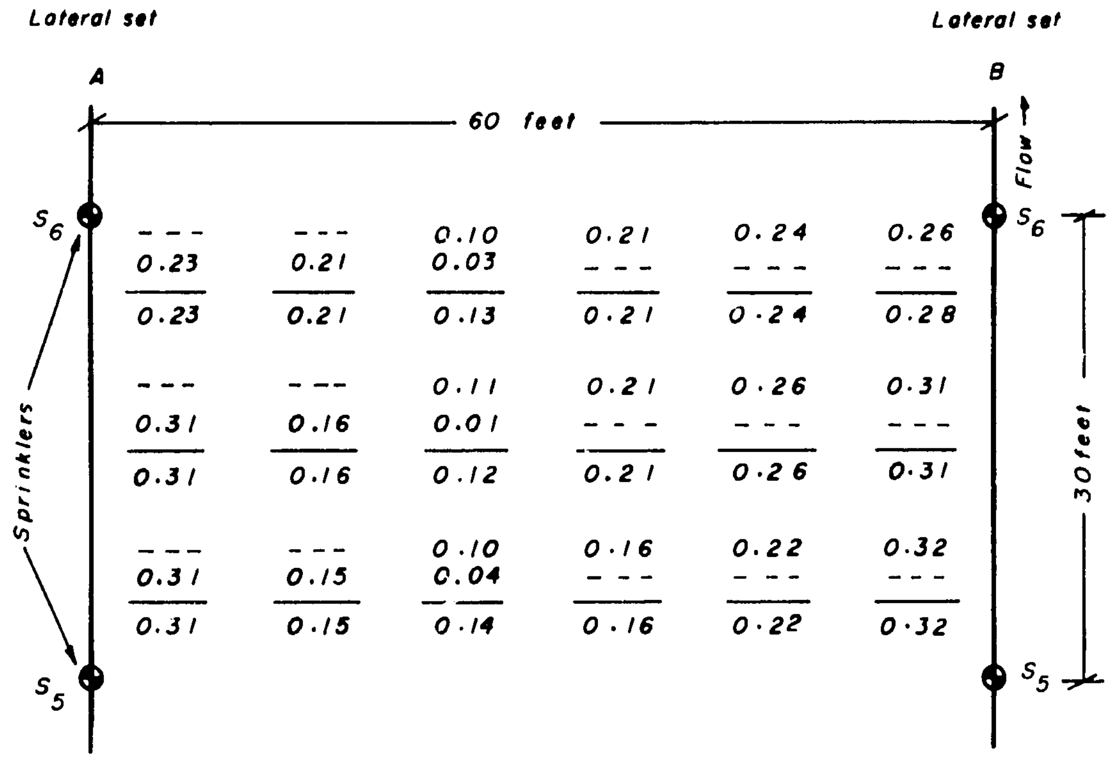

Figure II-10. Combined pattern (iph) between sprinklers 5 and 6 for a 60-foot lateral spacing.

Figure II-10. The data in Figure II-11 represent the catch from two 1-hour sets. Again, the total catch in the 9 cans for two irrigations is 3.97, giving:

$$\text{Average catch rate} = \frac{3.97}{9} = 0.44 \text{ in/2 hrs}$$

$$\text{Average low quarter rate} = \frac{0.37 + 0.42}{2} = 0.40 \text{ in/2 hrs}$$

$$DU = \frac{0.40}{0.44} \times 100 = 91\%$$

Note that the simple management program of alternate sets using a 60-foot lateral spacing improved the *DU* from a low of 64% for a

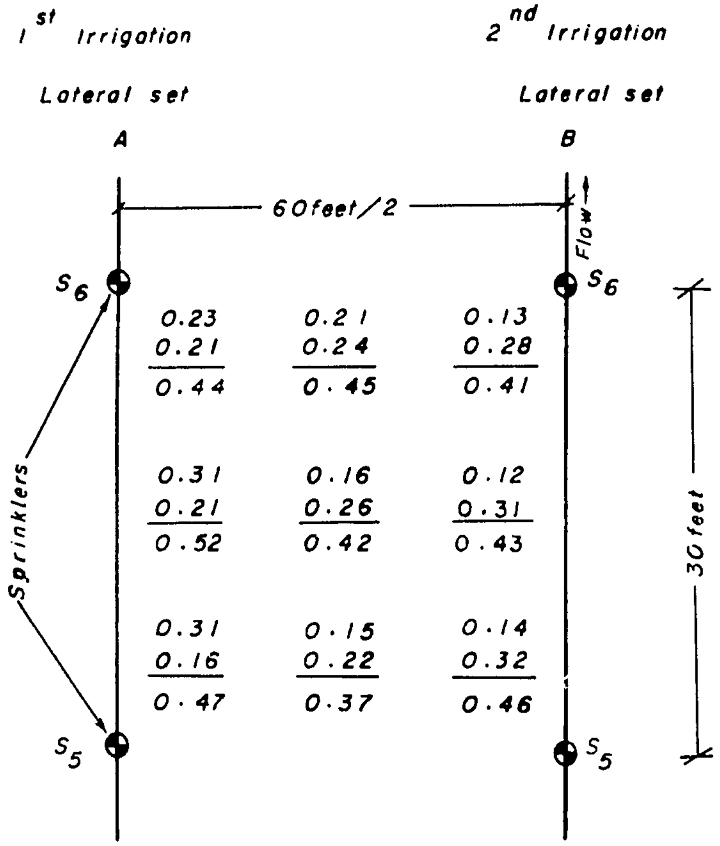

Figure II-11. Combined catch pattern (inches in 2 hours) between sprinklers 5 and 6 for a 60-foot lateral spacing offset 30 feet for a second irrigation.

single irrigation to 91% for the sum of two irrigations. The alternate set procedure does not prevent an inadequate irrigation depth between the laterals. This inadequate depth may excessively stress the crop during the intervals between the two full irrigations. However, moderate underirrigation in the mid-area is not detrimental if adequate moisture is applied in the upper portion of the root zone and if irrigations are frequent.

Coefficient of Uniformity

A common way to evaluate sprinkler uniformity is the *UC*, a statistical representation of the catch pattern. When expressed as a percentage, it is calculated by:

$$UC = \left(1 - \frac{\text{average deviation from the average catch}}{\text{average catch}}\right) X\ 100$$

From Figure II-9 for the 50-foot lateral spacing and a 1.0-hour irrigation, the summation of the deviations from the average catch rate of 0.26 iph is 0.51. For the 15 grid points, the average deviation is 0.51 divided by 15 and it follows that:

$$UC = \left(1.0 - \frac{0.51 \div 15}{0.26}\right) X\ 100 = 87\%$$

Applying DU and UC

The *DU* is computed by using the average rate or depth of catch in the *low quarter* of the pattern. *UC* computed from the same data would be considerably higher, since it is more nearly related to the average depth in the *low half* of the pattern. The average statistical relationship in percentages between *UC* and *DU* is shown in the following list:

UC	DU	UC	DU
98	97	80	69
96	94	76	62
92	87	72	55
88	81	68	49
84	76	64	43

To achieve high values of uniformity, close sprinkler spacings are usually required. In general, the closer the sprinkler spacings, the more expensive the system costs. For high value crops, especially those having shallow roots, the most economical systems usually operate at high uniformities, i.e., *DU* greater than 80% (or *UC* greater than 87%). For typical field crops having medium root depths in medium textured soils, the most economical uniformity normally ranges between a *DU* of 70 and 80% (a *UC* between 81 and 87%). For deep rooted orchard and forage crops growing where the quantity of supplemental rainfall is substantial, the most economic uniformity is often relatively low--in the range of *DU* between 55 and 75% (a *UC* between 72 and 83%).

Potential Application Efficiency

The *PELQ* should be determined in order to evaluate how effectively the system can utilize the water supply and what the total losses may be. Then the total amount of water required to irrigate the field fully can be estimated. Rates rather than depths should be used for computing *PELQ* of sprinkler systems to avoid confusion with *AELQ*.

The *PELQ* is always a little lower than the *DU* of a sprinkle irrigation system because the average water applied (which is the denominator for *PELQ*) is larger than the average water caught (which is the denominator for *DU*). (The numerator for both *PELQ* and *DU* is the average low quarter depth of catch, see Chapter I, pages 11 and 12.) The difference between the average water applied and the water caught or received is an approximation of losses due to evaporation and drift plus loss of water due to some of the area's being ungauged and some evaporation from the gauge cans. The *PELQ* indicates how well the tested sprinklers are able to operate if they are run the correct length of time to satisfy the *SMD* or *MAD*. It is therefore a measure of the best management can do and should be thought of as the potential of the system within the limit that the test represents the whole field.

The average rate of water application, *R*, in iph is computed from the sprinkler discharge in gpm and the sprinkler and lateral line spacings in feet. (See page 25.) From Form II-1 part 8, the average discharge of the sprinklers tested was 4.6 gpm, but the catalog rating on the sprinkler at the operating pressure of 40 psi is 4.4 gpm. Therefore, the average application rate for the 30- by 50-foot spacing that was being used was:

$$R = \frac{96.3 \text{ X } 4.6}{30 \text{ X } 50} = 0.30 \text{ iph}$$

For the area between sprinklers 5 and 6 and a 30- by 50-foot spacing, where the average catch in the low quarter of the cans was 0.22 iph:

$$PELQ = \frac{0.22}{0.30} \text{ X } 100 = 73\%$$

Table II-1 summarizes computations for *DU*, *UC*, and *PELQ* for four typical lateral spacings, for the area between sprinklers 5 and 6 and the area between sprinklers 4 and 5, computed as above from the data in Form II-1 parts 8 and 10.

Table II-1. *DU*, *UC* and *PELQ* of four standard sprinkler spacings for areas between sprinklers 5 and 6 and sprinklers 4 and 5.

Test area criteria	Sprinkler spacing (feet)			
	30 X 40	30 X 50	30 X 60	30 X 60 alt.
	Area between sprinklers 5 and 6			
DU	81	84	64	91
UC	87	87	75	93
PELQ	73	73	56	81
	Area between sprinklers 4 and 5			
DU	79	76	50	82
UC	86	88	70	91
PELQ	70	67	44	72

Comparison of percentage values in Table II-1 illustrates the problem of choosing a typical or minimum site. Some other sites in the field undoubtedly were poorer and some were better than the tested site; therefore, computed efficiencies are not universally applicable, but they are useful for evaluating the system.

Pressure variations throughout the system cause the overall efficiency of the system to be lower than the efficiency in the test area. An estimate of the efficiency reduction, *ER*, can be computed from the maximum, minimum, and average system pressures by:

$$ER = 0.2 \times \frac{\text{maximum pressure} - \text{minimum pressure}}{\text{average system pressure}}$$

The ratio of the average low quarter sprinkler discharges to the average sprinkler discharge in the system is approximately equal to $1.0 - ER$. Therefore, the system *PELQ* can be approximated by:

$$\text{System } PELQ = (1.0 - ER) \times \text{Test } PELQ$$

Using the data on Form II-1 part 12 and the test *PELQ* of 73%:

$$ER = 0.2 \times \frac{45 - 39}{40} = 0.03$$

and

$$System\ PELQ = (1.0 - 0.03) \times 73\% = 71\%$$

For this evaluation, the pressure variation is relatively small and only had a minor affect on the overall efficiency.

Application Efficiency

Effectiveness of use of a given sprinkler system can be determined from how much of the applied water is stored in the soil and available for consumptive use and how uniformly it is applied. Whenever the irrigation exactly satisfies the *SMD* in the least watered areas, *AELQ* = *PELQ*. But if excess water is applied, much of it may percolate too deeply and be lost; this would result in an *AELQ* considerably less than the *PELQ*. (The *DU* and *PELQ* values are not affected by the depth of water applied.)

The units for calculating *AELQ* are in terms of depths, not rates, because the maximum depth stored cannot exceed the *SMD*, which equals the depth of water that can be stored. (See Chapter I, pp. 11 and 12.) For the test used in the example above, the normal irrigation continued for 23.5 hours. With the 30- by 50-foot spacing the average application rate was 0.30 iph and the total average depth applied, *D*, was:

$$D = 0.30 \times 23.5 = 7.0\ in$$

The minimum rate caught was 0.22 iph, i.e., the application rate times *PELQ*, 0.30 iph X 73%/100. Therefore, the minimum depth infiltrated, D_n, was:

$$D_n = 0.22 \times 23.5 = 5.2\ in$$

It was determined that the soil holds about 2.2 inches of available moisture per foot of soil depth; depth of the root zone was 4.0 feet at that time, and a 50% *MAD*, which would not excessively stress the crop, was considered acceptable. (See Form II-1, parts 2 and 3.) At the time of irrigation, *SMD* was checked and found to be at the desired deficiency of 2.2 inches X 4.0 feet X 50% = 4.4 inches. The sprinklers as tested were applying 5.2 inches in 23.5 hours, which was more than enough since the amount stored cannot be greater than the existing *SMD*. This gave:

$$AELQ = \frac{4.4}{7.0} \times 100 = 63\%$$

which was considerably less than the *PELQ* of 73%; it could have been improved by shortening the application time so that *PELQ* would equal *AELQ*. However, if the roots continue to go deeper, *MAD* may increase to 5.2 inches and *AELQ* would then equal *PELQ*. For the true picture of water use efficiency as applied to the field, a further reduction from 2 to 5% should be allowed for line losses due to filling and draining the laterals and losses due to leakage from pipe couplers and sprinklers. For this test the system *ALEQ* would be about 60%. The same reduction should also be applied to the *PELQ*.

Analysis and recommendations

Several observations and recommendations can be based on the information recorded on the Sprinkler-Lateral Irrigation Evaluation Data Sheet, Form II-1, the computations summarized in Table II-1, and the value of *AELQ*.

The *pressures* along the lateral line are very uniform because the ground, which slopes down at 1 1/2% for 420 feet, drops 6 feet; this slope compensates for much of the loss of pressure due to friction. Therefore, the efficiency reduction due to pressure variation was also small, i.e., only 3%.

The typical sprinkler location on the lateral can be assumed to be between sprinklers 4, 5, and 6 because the pressure is very uniform. These sprinklers were not tested at other pressures although such tests might have shown a pressure change would be desirable. (see Figure II-7.) Since the test was brief and since longer tests usually produce higher *DU* and *PELQ* values, except when a sprinkler is defective, the higher values for the area between sprinklers 5 and 6 (Table II-1) were used.

Water losses. Water lost from causes other than deep percolation is indicated by the differences between the average rates applied and rates caught. The lost water includes drift and other losses in the air, water falling on ungauged areas, and evaporation and other losses from the containers. Evaporation losses from the droplets as they pass through the air are related to humidity, air and water temperature, wind speed, and size of drops. Such losses typically range between 2 and 15% and are less at night. Drift is related to wind velocity and drop size and normally range between zero and 5%. The fact that the wetted perimeter seldom coincides with the line midway between grid points typically results in an average can catch that is about 2% low.

Evaporation from the open catch containers can exceed 0.4 inches per day. It can be a greater percentage of the catch along the edge of the pattern than from near the sprinklers where the catch is deeper and the containers are also wet more on the outside. The volume of this evaporation loss can be approximated by the water loss from a container set adjacent to the test area as described earlier. Clouds, wind, humidity, container color and material, and time of day all have major effects on the direct evaporation losses from the containers.

When using the volumetric procedure to determine the depths of catch, as was done for the sample evaluation, some water clings to the can walls and remains unmeasured. The fact that some of the containers may be tipped and thus catch more or less than their share also adds to the inaccuracy of measurements.

Since it is impractical to try to measure precisely both the water applied and the water caught, the amount of water unaccounted for is only an approximation. For the 30- by 50-foot area between sprinklers 5 and 6, the average rate caught was 0.26 iph and the average rate applied was 0.30 iph. Therefore the rate unaccounted for was 0.04 iph or (0.04/0.30) X 100 = 13%. Accuracy of these measurements, as well as that from the evaporation container for the short test, i.e., 0.05 inch in 1.58 hours = 0.03 iph, was such that the evaporation from the container accounts for almost the entire computed loss. (See Form II-1, part 11.)

Improvements. Several improvements in operation of the system may be considered even though some may not be practical or economical. The move distance of 50 feet now being used achieves acceptably uniform distribution, since *DU* is more than 80%. (The corresponding value of *UC*, which is more than 87%, is also considered reasonable.)

1. The duration of irrigation can be reduced to less than 23.5 hours.

2. The rate of application can be reduced to obtain the desired duration and depth relation by either reducing pressure or using smaller nozzles. These changes affect *DU* and *PELQ* and would require further testing.

Pressures can be reduced by throttling, which may save water unless *DU* becomes much lower; but throttling usually does not reduce cost of power. However, changing the speed of the pump or the diameter of the impeller may save both water and power.

Use of smaller nozzles may require a change in pressure. For example: a 9/64-inch nozzle at 45 psi delivers 3.7 gpm and applies an average of 0.24 iph on a 30- by 50-foot spacing. With a *PELQ* of 77%, the system applies a minimum of 4.4 inches in 23.5 hours. However, a test would be needed to check the *PELQ*.

3. The *AELQ* could be improved by lengthening the interval between irrigations so that the *SMD* at which irrigation is applied is 5.2 inches. *MAD* would then be 60% instead of 50% as previously chosen. For many crops this would be the most practical answer; it would save both water and labor and would not result in a detrimental stress.

4. A 60-foot lateral move with alternate sets would be appreciably more efficient than the 30- by 50-foot spacing now used (i.e., from Table II-1, *PELQ* = 81% rather than 73%). The 60-foot move would also reduce labor by nearly 20%. Alternate set irrigation usually improves *DU* and *PELQ*, but unless the number of hours of operation is correspondingly reduced or *MAD* is increased, *AELQ* would not improve.[1/]

Adjusting the duration of irrigation. The optimum duration of irrigation, T_i, will just replace the *SMD* of 4.4 inches. Since the average low quarter application rate for the 50-foot lateral spacing is 0.22 iph; T_i would be 4.4/0.22 = 20 hours. The change to a 20-hour operation from 23.5 hours may be accomplished easily by turning

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[1/] By using the 60-foot move the average application rate would be reduced to 0.25 iph, and by alternate sets the *AELQ* would be increased to 81% giving a full irrigation of 4.4 inches in 22 hours, i.e., 0.25 X 22 X 81%/100 = 4.4 in. Although the original *MAD* could be increased to 5.2 inches only 4.8 inches could be applied in a maximum 2.35-hour set. Therefore, the irrigation interval could be increased only slightly to further reduce labor. Water would be saved by having the higher *PELQ* and irrigating to just replace the *SMD*.

the system off; however, it may be impractical if a constant flow is being delivered from a ditch and no reservoir is available. On some installations, an automatic time-activated cutoff may be installed. Where less than 24 hours per day operation is used it may be practical to schedule the shut-off time to avoid a windy period or high losses from evaporation during midday.

Summary of full evaluation

The test area was typical of the whole area irrigated by the lateral because pressures were very uniform along the line. Furthermore, the lateral on which the test was conducted was typical for the whole system. Tests at lower pressures or with 9/64-inch nozzles would be desirable for evaluating the second improvement described above.

Since duration of the test was only 1.58 hours, measurements of depth were calculated from volumetric data to obtain acceptable accuracy.

Two adjacent test areas gave significantly different values for *DU*, *UC*, and *PELQ*.

The *DU* and *PELQ* were reasonably high on the tested area and indicated that the system could provide efficient irrigation.

Water losses under the test condition were about as low as could be expected.

For the desired *MAD* of 4.4 inches, the designed 23.5-hour duration was too long and resulted in a low *AELQ*. This may be corrected by:

1. Operating only 20 hours.
2. Reducing nozzle size and rechecking *DU* and *PELQ* or operating at a lower pressure, which probably would result in a low *DU* and *PELQ* and certainly should be re-evaluated.
3. Increasing the *MAD* to 5.2 inches (60%), which should be acceptable for the mature tomato crop.
4. Using 60-foot alternate set moves, which would save both labor and water, should be the first choice if practical.

Field variations and inaccuracies in measurement, particularly of *SMD*, do not result in high accuracy. However, the field evaluation and analytical technique presented above are useful for revealing problems of system design and management.

Supplemental evaluation

In addition to checking the *AELQ* and ways for improving it, an economic study of the operation may also be valuable. Where pressure is created by pumping, the loss of pressure in the pipe lines and/or the cost of producing higher pressure to increase capacity may be uneconomical. A general rule of thumb that assures good uniformity but not necessarily good economics, requires that the loss of pressure due to friction and elevation in the lateral be less than 20% of the average design pressures. This results in about 10% range in sprinkler discharge rates and an average sprinkler discharge rate about 2 to 4% greater than the low quarter of the sprinkler discharge rates. For laterals having only one pipe size, the lateral inlet pressure should be the designed pressure plus three-fourths of the pressure difference due to friction loss (see Figure II-6) less one-half of the elevation difference for downhill or plus one-half for uphill laterals.

The following example illustrates the economics of considering a larger diameter lateral pipe. Data recorded in Form II-1 show the inlet pressure was 45 psi, and all other tested pressures were very close to the desired 40 psi for the 2-inch lateral line tested. A study comparing the pressure losses in a 3-inch pipe shows that the inlet pressure would be 39 psi, and the pressure along the line and at the end would average 40 psi because the downward slope more than compensates for friction losses. The economic value of the 45 - 39 = 6 psi savings in terms of reduced power costs should be compared with the increased annual cost for ownership of the larger pipe. Also the more uniform pressure would save a little water. The same principle can be applied to pressure loss along the main line.

The problem of achieving uniform watering along the boundaries of fields can often be solved by tipping sprinklers outward. Since a sprinkler system depends on overlap to apply an adequate depth of water between lines, the depth usually applied along the edge of fields, where there is no overlap, is inadequate. In established crops, the sprinkler range may be reduced and water concentrated along the edge of the field by tipping the risers to shorten the distance of throw. On the end of the lateral, the last sprinkler can be set back about one-fourth of its throw diameter from the downstream boundary, and the riser can be bent downstream. Along the edges of the field parallel to the laterals, the whole line must be tipped (or rolled) outward. This should be done only for fields where established crops are growing because the increased jet impact caused by the tipping could damage young seedlings.

Since differences in pressure exist throughout the pipeline network, adjustable valves should be provided at each lateral inlet, and the inlet pressure should be set to the desired value. Where maximum variations of pressure in a lateral are too large because of topography, flow or pressure regulators may be installed in the risers to establish a relatively uniform rate of flow for all sprinklers.

Maximum average rates of application usually occur close to the sprinklers, but the maximum combined depth may be elsewhere. The maximum rate, which does not vary with the move distance, should not exceed the rate of soil intake. Sometimes, where runoff is a problem, infiltration can be improved by increasing the operating pressure. This spreads and breaks up the jet and thus reduces the instantaneous application rate and drop size. The average application rate will be slightly increased but it will promote better infiltration. If increasing the operating pressure is impractical or unworkable, nozzle sizes must be reduced; otherwise, irrigations must be briefer and more frequent.

CHAPTER III
PERFORATED PIPE SPRINKLE IRRIGATION

Perforated pipe sprinkle irrigation almost became obsolete for agricultural irrigation but it continued to be widely used for home lawn systems. Because of the recent concerns about availability and cost of energy, interest in perforated pipe, overlapped hose-fed sprinkler grid, (see Chapter II), and orchard systems (see Chapter IV) has revived. They afford a means of very-low-pressure (5 to 20 psi) sprinkle irrigation. Often gravity pressure (produced by the difference in elevation between the water supply and irrigated area) is sufficient to operate the system without pumps. Furthermore, inexpensive low-pressure pipe (such as unreinforced concrete and thin-wall plastic or asbestos cement) can be used to distribute the water.

Perforated pipe systems spray water from 1/16-inch diameter or smaller holes drilled at uniform distances along the top and sides of a lateral pipe. The holes are sized and spaced so as to apply water reasonably uniformly between adjacent lines of perforated pipeline. The water issues from the holes and produces a rain-like application over a rectangular strip (see Figure III-1). Each hole emits a jet of water, which in rising and falling breaks up into small drops that are spread over the irrigated area by air turbulence. The spread, which ranges from 25 to 50 feet, increases as pressure increases. Such systems can operate effectively at pressures between 5 and 30 psi; they can be used only on soils having high capacities for infiltration such as loamy sands and coarser textured soils.

Full evaluation of perforated pipe systems requires elaborate catch containers which completely cover the soil surface across the wetted strip several feet along the perforated pipe line. (Representative samples cannot be obtained by using small containers.) Such catch containers must be of special construction and are too cumbersome for practical field use (although they can be inexpensively constructed of wood and plastic sheet).

Fortunately, simple evaluation techniques only slightly more complicated than those described for the overlapped sprinkler grid systems can identify fairly basic problems or errors in design, operation, and management of perforated pipe systems. This chapter on evaluating performance of perforated pipe systems assumes some understanding of Chapter II for "Sprinkler-Lateral Irrigation."

Figure III-1. Perforated pipe lateral in operation.

Evaluation

For the evaluation of a perforated pipe system, the following information is required at the inlet, middle, and end of a typical perforated pipeline:

1. Duration of normal irrigations.
2. Pressure at the pipeline perforations throughout the system.
3. Rate of unit length discharge.
4. Uniformity and width of the wetted strip of jet trajectory.
5. Hole size and extent of clogging.
6. *MAD* and *SMD*.
7. Uniformity of *SMD* between adjacent line settings.

8. Spacing between perforated pipeline sets and between hole pattern sequences along the pipeline.

9. Additional data required on Form III-1.

General study of the data obtained in the field enables estimation of uniformity, irrigation efficiency, and adequacy of duration of irrigation. Further study enables determination of the uniformity and economics of the pipeline spacings and/or alternate sets, the economics of pipe sizes used for mains and perforated laterals, the desirability of using other operating pressures and other durations of application, the effect of wind, and adequacy of screening.

Equipment needed

The equipment the evaluator needs is:

1. A pressure gauge (0-30 psi) with pitot attachment. (See Figure II-4.)

2. A bucket or 1-gallon jug.

3. A stopwatch or watch with an easily visible second hand.

4. A 500-ml graduated cylinder or a 16-ounce liquid measuring cup (with 1-ounce marks).

5. A tape measure to check the hole spacing and width of the wetted patterns.

6. A soil probe or soil auger.

7. A 2-foot square sheet of lightweight tin or aluminum and/or a 2- to 4-foot length of small diameter flexible hose (see Figure II-5) are optional but may be handy items when measuring discharge.

8. A shovel for digging a depression for the bucket when measuring discharge, or checking soil profiles, root, and water penetration.

9. Manufacturer's perforated pipe performance charts that show the relations between discharge, pressure, and width of wetted strip.

10. A set of 1/32-, 3/64- and 1/16-inch drill bits to use as feeler gauges.

Form III-1. PERFORATED PIPE SPRINKLE IRRIGATION EVALUATION

1. Location Florida Observer JK Date Oct 29, 75
2. Crop Citrus, Root zone depth 6 ft, MAD 75 %, MAD 4.0 in
3. Soil: Texture sandy, available moisture 1.0 in/ft, SMD 3.5in
4. Perforated pipe: make AMES, type C, hole diameter 3/64- in
5. Perforated lateral pipe spacing 40 ft, Irrigation duration 5½ hrs
6. Rated pipeline discharge 40 gpm/100 ft at 10 psi giving 0.96in/hr
7. Pipe: diameter 3.0in, material Aluminum, length 300 ft, slope 0 %
8. Holes per pattern sequence 7, Pattern sequence interval 2.5 ft
9. Wind: direction arrow relative
   to pipe flow direction ——► Initial ↓ Final ↓
   speed (mph) Initial 0-2 Final 2-5
10. Actual pipeline performance:
    Discharge estimates from 4 holes per pattern sequence and
    measured in oz (3785 ml = 1.0 gal, 128 oz = 1.0 gal)

		Position along perforated pipeline			
		Inlet	Middle	End	
11. Pressure (psi)		13	10	10	diff 3
12. Wetted width:	total (ft)	41	39	40	ave 40
	upwind (ft)	20	17	19	
	downwind (ft)	21	22	21	
13. Jet trajectory:	length (ft)	13	12	12	
	uniformity	good	good	good	
	alignment	good	pipe tipped	good	
Holes clogged or eroded		new pipe,	holes are	clean	and sharp
14. Catch:	volume (oz)	136	122	118	
	volume (gal)	1.06	0.95	0.92	
	time (seconds)	100	100	100	
Ave. discharge:	gpm/hole	0.16	0.14	0.14	
	gpm/ft	0.45	0.40	0.40	ave 0.42

15. Discharge pressures: max 14 psi, min 9 psi, ave 10 psi
16. Comments: No runoff after full irrigation. Checks with auger revealed a 2- to 3-foot wide dry strip midway between pipeline positions. There was much tree interference. The tree row spacing is 20 feet.

11. A rain suit or swimming suit (depending on temperature and personal preference) is recommended since it is difficult to keep clothing dry during the evaluation.

12. Form III-1 for recording data.

Field procedure

The information obtained from the following field procedure should be entered on a data sheet similar to Form III-1.

1. Choose a location at the middle of an average lateral for the test and fill in parts 1, 2, and 3 of Form III-1 concerning the crop and soil moisture characteristics of the field.

2. Determine and record the make and type of perforated pipe and the diameter of the holes in part 4. If the hole diameter is not given by the manufacturer, use the drill bits as feeler gauges to determine it.

3. Obtain the normal perforated lateral pipe spacing and duration of irrigation from the operator and record them in part 5.

4. Obtain the rated lateral discharge and pressure from the system design data and manufacturer's performance charts and compute the average design application rate and record them in part 6. To compute the average design application rate, R, in iph, use the discharge per 1-foot unit length of pipe, line spacing, and the following formula:

$$R = \frac{96.3 \text{ X unit length discharge (gpm/ft)}}{\text{line spacing (feet)}} = iph$$

5. Check and record (in part 7) the size, material, length, and slope of the perforated pipeline.

6. In perforated pipe irrigation laterals, the holes are drilled in a standard pattern, and the *pattern sequence* is repeated at precise intervals along the length of the pipeline. (Figure III-2 shows a typical hole layout using seven holes per pattern sequence.) Check and record (in part 8) the number of holes per pattern sequence and the spacing between pattern sequences along the pipeline.

7. Note the speed and direction of wind. Record the wind direction as shown in part 9 by drawing an arrow relative to the direction of water flow in the lateral. If an anemometer is not available, estimate the wind speed as 0-2 mph if almost calm, 2-5 mph if slightly breezy, 5-10 mph if breezy, and above 10 mph if windy.

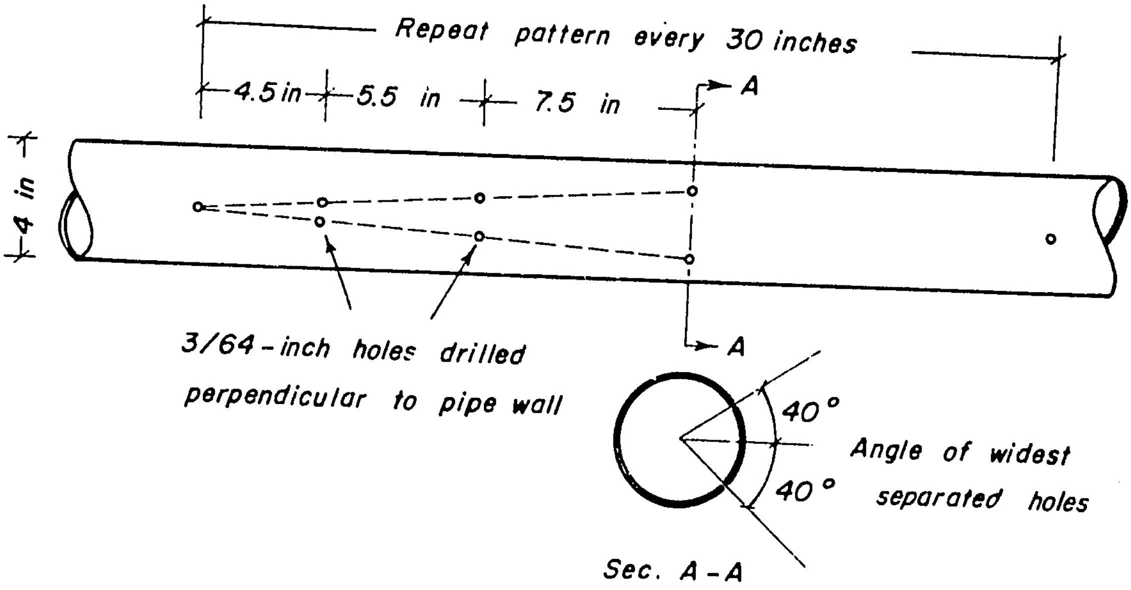


Figure III-2. Top view of typical perforated pipe having 7-hole pattern sequence every 30 inches.

8. Turn on the water to fill the lateral line. When the test lateral is full, turn the pressure up slowly to observe the trajectory, breakup of drops and the effect of wind at different pressures. Then set the pressure at the desired operating value. Operating characteristics of the perforated pipelines should be checked at the inlet, midpoint, and end of the line.

9. Use the pressure gauge with pitot tube attachment to check the pressure along the line and record in part 11. When measuring the pressure (Figure II-4), the pitot tube must be centered in the jet issuing from the pipe, which must impinge directly into its tip. The tip may be rocked slightly. Record the highest pressure reading shown while the pitot tube is being held directly against the pipe.

10. Measure and record in part 12 the width of the wetted strip and note the distances wetted upwind and downwind from the pipeline.

11. Estimate and record in part 13 the height of jet trajectory and compare the uniformity and precision of alignment of the jets between adjacent pattern sequences. Also note and comment on the degree of hole clogging and whether the holes seem to be eroded. (Hole erosion can also be checked with the feeler gauges after the water system has been turned off.)

12. Average discharge can be estimated by catching and averaging the discharge from several individual holes or by simultaneously catching water from a group of holes. (Typically, the discharge from a single hole ranges between 0.1 and 0.3 gpm.) The evaluator will need to devise his own methods for doing this; however, some useful suggestions are:

i. Turn the pipeline upside down to discharge directly into a bucket.

ii. Convey the discharge from several holes to the bucket by using a metal sheet.

iii. Using a flexible hose to convey the water from a single hole into a collection container. (See Figure II-5.)

iv. Rotate the pipe to direct individual jets directly into a gallon jug.

The volume of water discharged from a single hole or group of holes and the time required to collect it should be recorded in part 14; these data can be combined to compute the discharge rate per hole in gpm. To compute the unit length discharge in gpm per foot:

$$\textit{Unit length discharge} = \frac{\textit{gpm per hole X holes per pattern sequence}}{\textit{distance between pattern sequences (feet)}}$$

12. Check jet discharge pressures at 20 to 40 systematically selected locations throughout the system (for example, at the two ends and quarter points along each lateral) and record the maximum, minimum, and average pressures in part 15.

13. Near the end of a full irrigation, check for surface runoff and ponding. Also, use the probe, auger, or shovel to check the uniformity of wetting across the entire space between adjacent lateral settings from the previous lateral position. Give special attention to the area midway between line settings. Record any important comments in part 16.

Utilization of field data

Values for *DU*, *PELQ*, and *AELQ* cannot be computed because there is no grid of catch data to analyze mathematically. However, some valuable observations and recommendations can be based on evaluation of the field data from Form III-1.

Operating pressures. The observed operating pressure which was between 10 and 13 psi was well within the limits recommended in the manufacturer's equipment catalog. While carrying out step 8 in the field procedure, the ideal operating pressure appeared to be between 9 and 15 psi. Lower pressures produced insufficient jet breakup and pressures above 20 psi seemed to produce very small drops; this resulted in excessive wind drift.

The pressure difference of 3 psi between the inlet and end of the perforated pipeline and 5 psi through the system bordered on the high side, but it could be considered satisfactory, assuming measurements were not precise. (See Form III-1, parts 11 and 15.) The efficiency reduction, *ER*, caused by the variations in pressure throughout the systems (see Form III-1, part 15 and Chapter II, page 41), was:

$$ER = 0.2 \times \frac{14 - 9}{10} = 0.10 \text{ (or } 10\%)$$

Wetted width. The width of the wetted areas was uniformly between 39 and 41 feet along the entire line. There was only a slight shift in the pattern towards the downwind side of the pipeline.

The fact that the width of the wetted strip was so nearly uniform throughout the pipe length indicated that the pipe had been laid accurately, with the holes in all sections in a nearly upright position. However, one length of pipe at the middle was slightly tipped; this resulted in that section having the narrowest wetting pattern, only 39 feet. (See Form III-1, part 12.)

Jet characteristics. The height of the jets' trajectory was very uniform along the length of the pipe; it was approximately 1/3 of the width of coverage, which is typical for perforated pipe. The alignment and uniformity of the jets between adjacent pattern sequences were good.

Since the pipe was new the jets were clean (not diffused) as they left the pipe. This showed that the holes had been drilled with a sharp bit and were essentially free of burrs and/or irregular edges. Several holes were checked for size using the 3/64-inch drill bit as a feeler gauge and all were of the proper size as would be expected in new equipment.

Thorough inspection revealed only a few clogged holes. Clogging is a major problem in using perforated pipe irrigation and much care is necessary in order to minimize the problem. All water taken from surface sources must be thoroughly screened. Even when the water supply is clean, the pipe can be clogged by debris picked up while the pipe is being moved. Therefore, pipe movers must be cautioned to permit no soil or plant particles to enter the pipe. They should also be advised to let a small stream of water run through the pipes as they are being connected to flush out debris.

Flow rates. Flow rate was checked along the line by turning individual pipe lengths upside down at the test locations and simultaneously directing the jets of water issuing from four holes into a bucket. To simplify this operation, shallow depressions were dug into the ground to accommodate the bucket. Several sets of four holes were checked at the inlet, middle, and end of the pipeline; however, only the average volume of water caught at each test location is entered in part 14. The test time was 100 seconds. A sample calculation of average discharge at the inlet end is:

$$\text{Volume} = \frac{136 \text{ oz}}{128 \text{ oz/gal}} = 1.06 \text{ gal}$$

and

$$\text{Average discharge per hole} = \frac{1.06 \text{ gal} \times 60 \text{ sec/min}}{4 \text{ holes} \times 100 \text{ sec}} = 0.16 \text{ gpm}$$

therefore,

$$\text{Unit length discharge} = \frac{0.16 \text{ gpm} \times 7 \text{ holes/pattern}}{2.5 \text{ ft between patterns}} = 0.45 \text{ gpm/ft}$$

The difference in unit length discharge between the inlet and end of the line was 0.05 gpm/ft, i.e., 0.45-0.40 = 0.05. (See Form III-1 part 14.) This is slightly more than 10 percent of the 0.42 gpm per foot average unit length discharge. This difference in discharge is consistent with the pressure difference discussed above. Discharge varies as the square roots of the pressures; thus, variation in discharge is approximately half as great as the variation in pressure.

The average unit length discharge of 0.42 gpm per foot is very close to the manufacturer's catalog value, i.e., 40 gpm per 100 feet at 10 psi. This is further evidence that the pipeline was manufactured according to specifications and functioning properly.

Inspection of the pressures and discharges at the inlet, middle, and end of the pipe reveals that most of the loss of pressure occurs near the inlet. This is in accordance with the pressure loss diagram for a lateral having only one size of pipe (Figure II-6).

Uniformity. Uniformity of the sprinkler pattern and the resulting soil moisture distribution was estimated approximately by augering (probing did not work in the sandy soils). The soil moisture was estimated at numerous spots within the area irrigated a day earlier and bordered by adjacent line settings. Midway between the line settings was a 3- to 4-foot dry strip. This was to be expected because of the 40-foot settings between laterals and the fact that minimum width of the wetted pattern was only 39 feet.

Except for this dry strip, the moisture penetration in the rest of the irrigated area was quite uniform. Figure III-3 shows an actual average profile of water distribution that is typical of the performance expected from a properly functioning perforated pipeline. The wetting is remarkably uniform over most of the strip when winds are less than 5 mph. The patterns usually drop off very sharply near the outer edges; therefore, only a 3- to 5-foot overlap is recommended.

Two general criteria for perforated pipeline operation are:

i. Perforated pipelines should be laid out at right angles to prevailing winds where winds exceed 5 mph.

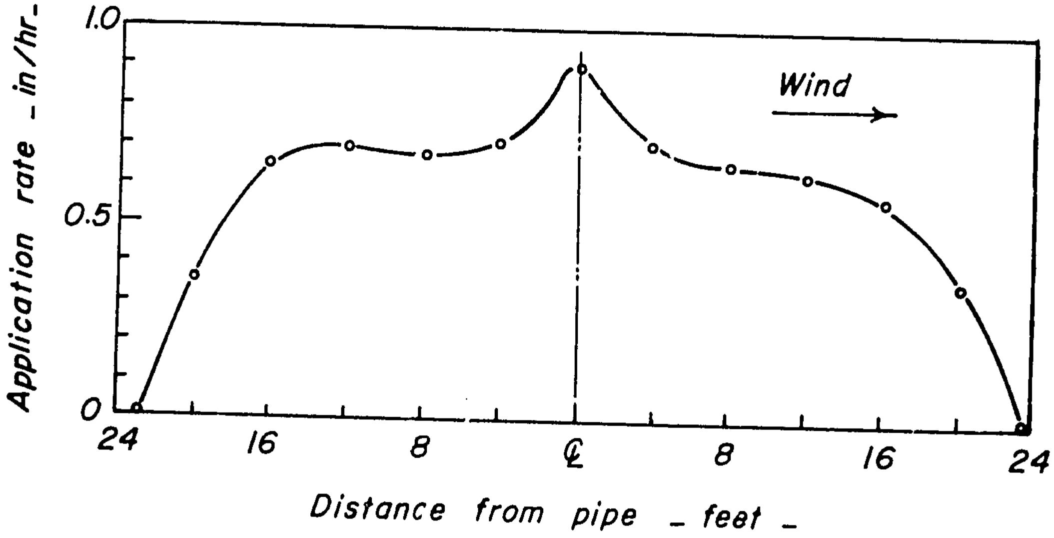


Figure III-3. Average profile of water distribution from 5 test runs for a typical perforated pipe at 22 psi in 0 to 3.3 mph winds.

ii. The spread or wetted width increases as pressure increases; practical minimum and maximum widths are approximately 25 feet at 5 psi and 50 feet at 20 psi.

Runoff. The minimum practical application rate that can be achieved with perforated pipe is approximately 0.75 inch per hour; however, even to achieve this application rate, very small (1/32-inch) holes and a relatively wide pattern sequence must be used. Clogging by debris or mineral deposits is a serious problem when very small holes are used.

Typical application rates for perforated pipe are approximately 1.0 iph. This is a major limitation to the use of perforated pipe because the infiltration capacity of most soils is considerably lower; therefore, use of perforated pipe irrigation is confined to sandy and porous soils. Runoff from higher to lower areas in a field not only reduces the uniformity of irrigation but also may cause waterlogging and crop loss in low areas. The first sign that runoff may be a problem is surface ponding in areas where the application rate exceeds the infiltration rate.

For the sample evaluation the soils had sufficient intake capacity and runoff was not observed to be a problem even after a full irrigation.

Analysis and recommendations

Several observations and recommendations for improving the system operation can be based on the information recorded on Form III-1 and the preceding comments.

Alternate setting is the practice of setting any lateral midway between previously used sets for every other cycle of irrigation. This would be desirable for use in the evaluated orchard. The system now used leaves a narrow dry strip between the parallel wetted areas; alternate wettings could compensate for this and satisfy the *SMD* in the presently unwetted strips.

The value of alternate settings can be readily visualized from Figure III-3, which shows a tendency to have some excess application along the pipeline; thus, the deficit due to the lack of pattern overlap would be greatly reduced. The dry strip is not very detrimental if moisture is periodically replenished because the tree roots are extensive and can absorb water from wherever it is available.

The trees, which were spaced in 20-foot rows, created considerable pattern interference. Alternative setting would somewhat compensate for this interference by providing water directly on both sides of each tree row.

Decreased spacing between the pipeline settings could eliminate the dry strip between settings; however, this would not be practical since the spacing between lateral sets must be a multiple of the tree row spacing of 20 feet.

Pressure could be increased to 15 psi to eliminate the dry strip. Either increasing the pressure or decreasing the pipeline spacing would be essential for the irrigation of small crops; however, for the trees and the system under study, alternate settings would be more practical.

Adjusting the duration of irrigation. Optimum duration can be calculated from the unit length discharge of the pipeline, the *SMD*, and an estimate of the *PELQ*. The first step is to find the average rate of water application, R, which for the unit length discharge of 0.42 gpm per foot and an assumed wetted width of 40 feet (less a 4-foot allowance for overlap) equals 36 feet.

$$R = \frac{96.3 \times 0.42}{36} = 1.12 \text{ iph}$$

Using an estimate of *PELQ*, which is usually between 70 and 80% for properly overlapped patterns, the assumed minimum application rate, R_n, at which water is infiltrated in the wetted area can be computed by:

$$R_n = R_a \frac{PELQ}{100}$$

which for this example using 70% because of the relatively large pressure variations throughout the system is:

$$R_n = 1.12 \times 70/100 = 0.78 \text{ iph}$$

Then the required duration of irrigation, T_i, to replace the *SMD* (3.5 inches) in the wetted area is:

$$T_i = \frac{3.5 \text{ in}}{0.78 \text{ iph}} = 4.5 \text{ hrs}$$

The proper duration of irrigation would be 4.5 hours for maximum efficiency. When the system is operated for 5.5 hours as scheduled, the last 1.0 hours of watering is wasted and unnecessarily reduces efficiency by almost 20%.

The *MAD* of 75%, which is equivalent to 4.0 inches for the sandy soil, allows little leeway for increase. Irrigation could be withheld until the *SMD* = *MAD* = 4.0 inches, and then a 5.1-hour application would maximize efficiency. An alternate procedure would be to irrigate at the existing *SMD* (3.5 in) and shorten the application time to 4.5 hours.

Summary

The system evaluated was a typical perforated pipe system. This individual system performed well, but a 2-foot wide dry strip lay midway between perforated pipeline settings, and tree branches interfered with some water jets. There were no other problems. Very few holes were clogged, the wetting pattern was uniform, and there was no sign of surface runoff.

Alternate settings were recommended as a simple and inexpensive solution to compensate for the dry strips and the pattern interference caused by tree branches.

Irrigation was applied somewhat sooner than the *MAD* required, i.e., the *SMD* was 3.5 inches but the *MAD* was 4.0 inches. Since the *MAD* of 4.0 inches tends to overly stress the crop, irrigating a little sooner than necessary may be advantageous.

Discharge along the pipeline ranged from 0.45 to 0.40 gpm per foot; this is a little more than the normally recommended 10% maximum variation but is not serious.

The duration of irrigation (5.5 hours) was too long and should be reduced to 4.5 hours for optimum efficiency when the *SMD* is 3.5 inches. This simple management correction would improve the irrigation efficiency by 20%.

CHAPTER IV
ORCHARD SPRINKLER IRRIGATION

This chapter describes and discusses procedures for evaluating under-tree sprinklers having nonoverlapping (or slightly overlapping) patterns of application.

The uniformity of the watering pattern produced by over-tree sprinklers, useful for frost protection and climate control as well as for irrigation, can be evaluated only at the top of the tree canopy level. Interference of the catch pattern by the trees makes soil surface measurements meaningless. However, ground level distribution is of most importance to irrigation. Observations give an indication of how much soil is dry, and probing can indicate uniformity of application. Under-tree systems requiring overlap from adjacent sprinklers to obtain uniformity can be evaluated by the standard technique for open field evaluation described in Chapter II.

The *orchard sprinkler* is a small spinner or impact sprinkler designed to cover the interspace between adjacent trees; there is little or no overlap between sprinklers. Orchard sprinklers are designed to be operated at pressures between 10 and 30 psi, and typically the diameter of coverage is between 15 and 30 feet. They are located under the tree canopies to provide approximately uniform volumes of water for each individual tree. Water should be applied fairly even to areas to be wetted even though some soil around each tree may receive little or no irrigation. (See Figure IV-1.) The individual sprinklers can be supplied by hoses and periodically moved to cover several positions or there can be a sprinkler provided for each position.

The following questions relative to use of orchard sprinklers should be considered before selecting equipment.

1. Is an under-tree sprinkler system the most practical irrigation system for the orchard?
2. Does wetting the soil around the tree trunk induce diseases, and would a shield give the trunk sufficient protection?
3. Will the irrigation spray damage the fruit?
4. Do low branches and props seriously interfere with the pattern's uniformity?

Figure IV-1. Orchard sprinkler operating from a hose line.

5. Would salinity of the irrigation water damage leaves which are wetted?
6. Is the water supply sometimes inadequate making it desirable to use sprinklers that can be adjusted to wet a smaller area when necessary?
7. Is a crop going to be raised between tree rows while trees are small? If so, what is the expected crop height.

Evaluation

The irrigation objectives must be known before the operation of the system can be evaluated intelligently. *Uniformity of application* and the *efficiency of storing* water for plant use are the two most important points to be considered. For evaluating orchard sprinkler systems, uniformity and efficiency must be qualified, for often it is not practical to try to have complete coverage. Fortunately, mature trees have such extensive root systems that they can extract soil moisture wherever it is available. Therefore, any available stored water may be absorbed by the roots.

The data needed for evaluating an existing under-tree nonoverlapping system are:

1. Depth (or volume) of water caught in a radial row (or rows) of catch containers.
2. Duration of test.
3. Duration and frequency of normal irrigations.
4. Flow rate from tested sprinkler.
5. Pressures throughout the system.
6. *MAD* and *SMD*.
7. Sprinkler locations relative to trees.
8. Spacing and arrangement of trees.
9. Interference of sprinkler jets by branches.
10. Sequence of operation.
11. Percent of ground area wetted.
12. Additional data indicated on Form IV-1.

Equipment needed

The equipment needed is essentially the same as for the full evaluation of sprinkler-lateral systems:

1. A pressure gauge (0-50 psi) with pitot attachment is useful but not essential. (See Figure II-4.)
2. A stopwatch or watch with an easily visible second hand.
3. A large (at least 1-gallon) container with volume clearly marked.
4. A bucket, funnel, 4-foot length of hose, and a tin sheet or other means for deflecting the sprinkler jets and any leakage into the container.
5. Approximately twenty catch containers such as 1-quart oil cans or plastic freezer cartons.

Form IV-1. ORCHARD SPRINKLER IRRIGATION EVALUATION

1. Location *California*, Observer *JLM*, Date *6/17/73*
2. Crop *apples*, Root zone depth *5.0* ft, MAD *50* %, MAD *4.0* in
3. Soil: texture *sandy loam*, available moisture *1.6* in/ft, SMD *4.0* in
4. Tree: pattern *square*, spacing *24-* by *24-* ft
5. Sprinkler: make *BR*, model *B-21*, nozzles *#1* by __ in
   spacing *24* by *24* ft, location to trees *center*
6. Irrigation: duration *24* hrs, frequency *21* days
7. Rated sprinkler discharge *1.1* gpm at *20* psi and diameter *26.6* ft
8. Sprinkler jet: height *3.3* ft, interference *negligible*
9. Actual sprinkler pressure and discharge (see back for location):

Sprinkler locations:	*test*	*2*	*3*	*4*
Pressure (psi)	*19*	*21*	*18*	*19*
Catch volume (gal)	*1.0*	*1.0*	*1.0*	*1.0*
Catch time (sec)	*54*	*52*	*55*	*54*
Discharge (gpm)	*1.1*	*1.2*	*1.1*	*1.1*
Wetted diameter (ft)	*26*	*27*	*26*	*26*

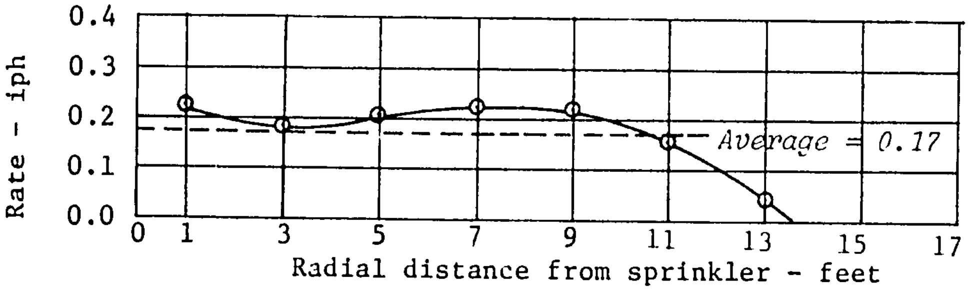
Comments: *Sprinkler performance good with smooth rotation*

10. Container row test data in units of *inch*, Volume/depth *--* ml/in

Test: start *7:20 pm*, stop *8:00 am*, duration *12* hr *40* min= *12.67* hr

Catch (*in.*): *2.8* *2.4* *2.5* *2.8* *2.8* *2.1* *0.5*

Rate (iph): *0.22* *0.19* *0.20* *0.22* *0.22* *0.16* *0.04*



11. Discharge pressures: max *21* psi, min *18* psi, ave *19* psi
12. Comments: *The apple tree branches did not obstruct the sprinkler jets and the sprinklers rotated smoothly and uniformly. The system is the portable hose-pull type.*

6. A measuring stick (or ruler) to measure depth or 500-ml graduated cylinder to measure volume of water caught in containers.

7. A soil probe or auger.

8. A tape for measuring distances in laying out the radial rows of catch containers.

9. A shovel for smoothing areas where containers are to be set and for checking profiles of soil, root, and water penetration.

10. Manufacturer's sprinkler performance charts.

11. Form IV-1 for recording data.

Field procedure

Information obtained from the following field procedure should be recorded on a data sheet similar to Form IV-1.

1. Choose radial row locations where water will be caught from only one sprinkler. It is best to test several sprinklers at several locations to check for system variations and improperly adjusted sprinklers. To save time it is practical to test the sprinklers simultaneously with different adjustments and pressures.

2. Fill in parts 1 and 2 of Form IV-1 concerning the crop, field, root depth and *MAD*.

3. Check and record in part 3 the *SMD* in the area of the pattern that will receive full irrigation. This area should represent half or more of the sprinkler pattern and should not be affected by overlap or tree drip. Also determine and record the soil texture, and estimate the available soil moisture capacity in the root zone.

4. Note the layout pattern of trees and the spacing between trees in part 4.

5. Check and record in part 5 the sprinkler make and model, size of nozzles, the normal sprinkler spacing, and the location of the sprinklers relative to the trees.

6. Obtain the normal duration and frequency of irrigation from the operator and record them in part 6.

7. Obtain and record in part 7 the rated sprinkler discharge and pressure from the design data and manufacturer's catalog.

8. Observe sprinkler operation at pressures higher and lower than normal; then set the pressure back to "normal" for the evaluation test. Note and record the height of jet trajectory, tree and wind interference, and characteristics of sprinkler rotation in parts 8 and 12.

9. Measure and record in part 9 the sprinkler pressure, wetted diameter, and total discharge including any leakage from the test sprinkler and from two or three other sprinklers spaced throughout the system. (See Figures II-4 and II-5.) Where the jet is *too* diffuse or small to use a pitot tube, the pressure gauge may need to be connected into the sprinkler riser. Overall uniformity of the system can be evaluated better by determination of flow rate than by pressure checks; however, a knowledge of pressures is useful.

10. Set out a radial row of catch containers along a radius of the sprinkler's wetted circle (as in Figure IV-2). If unusual conditions such as strong wind or a steep slope exist, four rows of containers should be used; however, if wind is negligible, as it often is in orchards, one row is adequate. Remove any potential interference of catchment caused by weeds, branches, props, or other objects. Be sure that all containers are empty. Space the first container 1.0 foot from the sprinkler, and align the rest 2.0 feet apart to cover the full range of the jet.

Note and record in part 10 the starting time of each test and continue the test until at least 1.0 inch is caught in some containers and note the time the test is stopped. If practical, continue each test for a full-length irrigation to obtain data that are representative of normal irrigation practice. Be careful that containers do not overflow.

Measure the depth or volume of water caught in each container. Record each measurement in the space above the corresponding radial distance of the container from the sprinkler in part 10.

11. Check the sprinkler pressure at 20 to 40 systematically selected locations throughout the system (for example at the two ends and at midpoints of each manifold) and record the maximum, minimum, and average pressures in part 11.

12. Note in part 12 the type of system operation and such operating conditions as speed of wind, impact on trees and resulting drip, overlap on adjacent sprinkler patterns if any, and uniformity of sprinkler rotation.

Check the general uniformity and the depth of wetting with the soil probe immediately following a normal irrigation. After one or

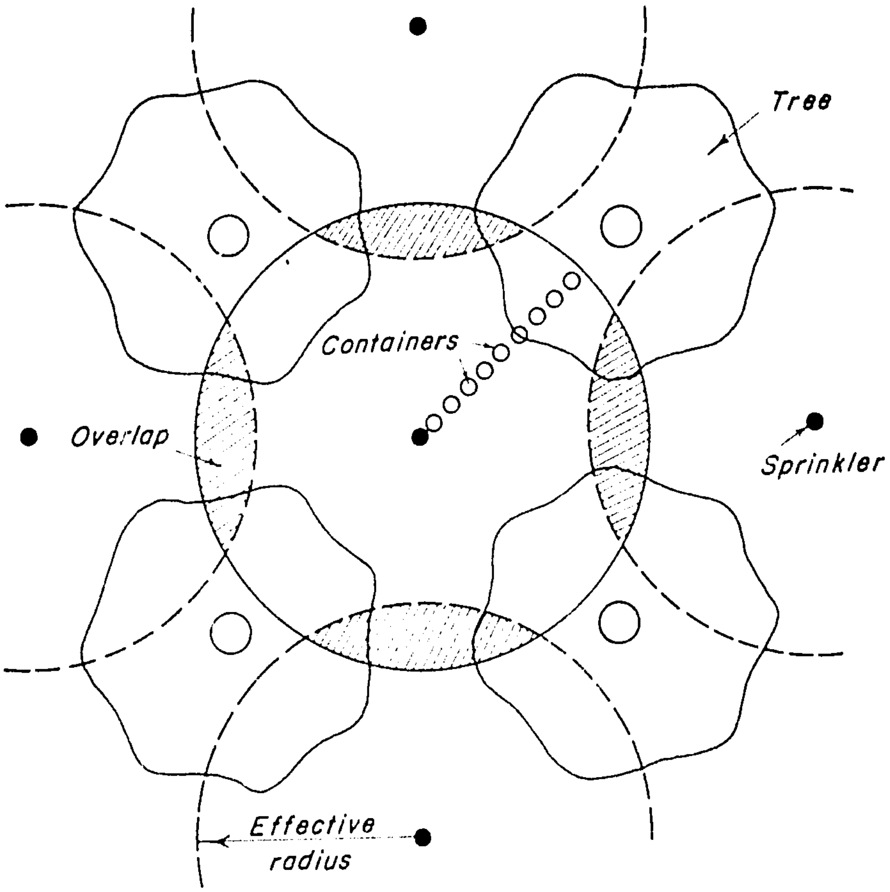


Figure IV-2. Layout for test of orchard sprinkler system in an orchard having a square pattern of trees.

two days check the depth again to determine whether the irrigation was adequate.

Utilization of field data

Information recorded in the field should be reduced to a form that can be conveniently studied and used. It is usually assumed that the water caught is equivalent to the water infiltrated. The depths or volumes of water caught should be converted to rates in inches per hour, iph; the rate profile should be plotted as shown on Form IV-1, part 10; and the effective radius, R_e, noted. R_e of the sprinkler in the reported test was 13.3 feet, which is the radius at which the rate profile plot crosses the zero line.

Average application rate

From the R_e of 13.3 feet, the radius at which the approximate average application rate occurs for each concentric quarter of the area can be computed by multiplying R_e by: 0.40 for the inner quarter, 0.60 for the second quarter, 0.78 for the third quarter, and 0.93 for the outer quarter.

For example, the radius at which the average rate occurs in the outer quarter is at 93% of the effective radius, i.e., 0.93 X 13.3 = 12.3 feet. The plot on Form IV-1 shows the application rate to be 0.08 iph at the radial distance of 12.3 feet from the sprinkler. An approximation of the average rate caught over the total wetted area is the sum of the rates at the quarter points divided by four. Computation of the average rate can be set up in the following tabular form.

Quarter of area	Radius where average rate occurs	Average rate from graph*
Inner	0.40 x 13.3 = 5.3 feet	0.20 iph
Second	0.60 x 13.3 = 8.0 feet	0.22 iph
Third	0.78 x 13.3 = 10.4 feet	0.18 iph
Outer	0.93 x 13.3 = 12.3 feet	0.08 iph
	Total	0.68 iph

Average application rate over wetted area $= \frac{0.68}{4} = 0.17$ iph

---

*See Form IV-1, part 10.

An alternate method for computing the *average rate* of application over the wetted area from the rates at each catch location is as follows:

Compute the *sum of the products* of all the catch rates times the respective radial distances to the container locations in feet, which for the sample evaluation is 7.59 from Form IV-1, part 10; then:

$$\text{Average rate} = \frac{2 \text{ X container spacing (feet) X sum of products}}{R_e \text{ (feet) X } R_e \text{ (feet)}}$$

Which for the sample data is:

$$\text{Average rate} = \frac{2 \text{ X } 2 \text{ X } 7.59}{13.3 \text{ X } 13.3} = 0.17 \text{ iph}$$

Distribution Characteristic

Since only part of the surface area may be wetted, the uniformity of irrigation should be evaluated by the *Distribution Characteristic, DC* instead of *DU*. Since only part of the area is left dry, the remaining smaller wetted area should be irrigated proportionally more often to supply the total water needed to balance evapotranspiration. For example, if only half of the area is wetted, the frequency of irrigation must be doubled. (See "Intentional Underirrigation" in Chapter I.)

For a single nonoverlapping sprinkler, *DC* is the percent of the total wetted area that has received and infiltrated more than the average depth.

$$DC = \frac{\text{Area that has received more than average depth}}{\text{total wetted area}} \times 100$$

The *DC* can be determined (see Form IV-1, part 10) by first drawing a line (see dotted line part 10) representing the average rate of 0.17 iph across the rate profile line and noting the radius of 10.8 feet where the two lines cross. Then, calculating the ratio of this radius to the total radius and multiplying the square of the ratio by 100 gives:

$$\text{Radius Ratio} = \frac{10.8 \text{ feet}}{13.3 \text{ feet}} = 0.81$$

and

$$DC = (\text{Radius Ratio})^2 \times 100$$

$$= (0.81)^2 \times 100 = 66\%$$

The *DC* relates to the uniformity of that portion of the central wetted area that may contribute to deep percolation losses even under good management. High *DC* values indicate that the adequately irrigated area may be relatively large while the potential losses from deep percolation are low. The *DC* can approach 100%; this would indicate an extremely uniform application provided there was very little overlap or tree interference. A *DC* greater than 50% is considered satisfactory, and the computed value of 66% for the example problem indicates a very good pattern.

Storage Efficiency

The most important objective of the field evaluation is to determine how effectively the water is being applied. Since orchard irrigation almost always leaves some areas and depths underirrigated but still results in a very satisfactory irrigation program, the term *Storage Efficiency, SE,* is used instead of *AELQ*.

In the area wetted the *SE* should be determined so that the effectiveness of the irrigation can be evaluated. Neither *PELQ* nor *AELQ* can be used to evaluate orchard systems, which wet only part of the area, since the average low quarter depth could be near zero.

$$SE = \frac{\textit{average depth stored under circular wetted area}}{\textit{average depth applied to circular wetted area}} \; X \; 100$$

In computing the *average depth stored* in the circular wetted area under each sprinkler, it is assumed that all the water that falls on each spot within the wetted area up to the *SMD* is stored. Water in excess of the *SMD* is lost by deep percolation. The following procedure will aid in calculating the average depth stored.

First determine what depth would be applied at each catch point by multiplying the rate values calculated in part 10 by the duration of a normal irrigation, which for this example was 24 hours. Then plot the depths of application at various radial distances from the sprinkler as shown in Figure IV-3 and draw a line across the depth profile representing the *SMD*. For this illustration the *SMD* was 4.0 inches and was assumed to be uniform (although it seldom is). All moisture above the *SMD* line would be stored in the soil. Overlap and/or distortions caused by the trees are not considered.

The *average depth of moisture stored* under the circular area represented by the area above the *SMD* line may be estimated by dividing the wetted area into subareas. The average depths applied to and stored in the various portions of the area can be multiplied by the percent of the area receiving that depth, and the sum of these products will equal the average depth stored. The entire area inside the radius at the intersection between the *SMD* line and the depth profile will store the *SMD*. If the profile is fairly uniform, one average value is adequate for the area beyond the *SMD* line intersection. However, if profiles are curved, computations of depth from two areas will give slightly more precise results. For Figure IV-3, one outer section would be adequate but two were used for demonstration. The steps used to calculate the average depth and the numerical values based on Figure IV-3 are:

1. Find the radius at the intersection of *SMD* with the depth profile (10.8 feet) and one other radius (12.0 feet); this divides the underwatered profile into two convenient subareas.

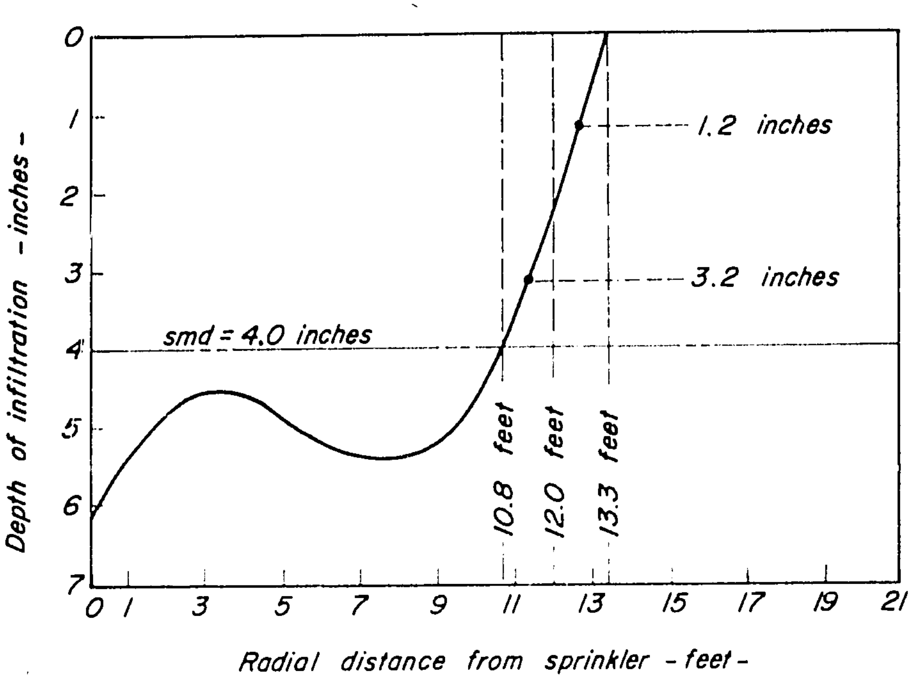


Figure IV-3. Profile of water application along the sprinkler radius for a 24-hour set.

2. Determine the ratio between these radii and the effective radius of 13.3 feet, (10.8/13.3 = 0.81, 12.0/13.3 = 0.90).

3. Square the radius ratios to find the corresponding portion of the area included inside each radius, [$(0.81)^2$ = 0.66, $(0.90)^2$ = 0.81].

4. Determine the portion of the total area included in each of the three subareas defined by the two intermediate radii. For this example, they are: 0.66, 0.81 - 0.66 = 0.15, and 100 - 0.81 = 0.19.

5. Estimate the average depth in each subarea from the depth profile (these can be taken at the middle of each subarea with adequate accuracy). From Figure IV-3, these are the *SMD* of 4.0 inches, 3.2 inches, and 1.2 inches.

6. Multiply each subarea portion by the corresponding average depth. The sum of the products equals the average depth of water stored in the root zone under the circular wetted area.

0.66 X 4.0 = 2.6 inches
0.15 x 3.2 = 0.5 inch
0.19 X 1.2 = 0.2 inch

Average depth = 3.3 inches stored under wetted circular area.

The *average depth of water applied* to the circular wetted area is computed by using the sprinkler discharge rate of 1.1 gpm (see Form IV-1, part 9, *test* column) and the wetted radius R_e, 13.3 feet, to obtain:

$$\text{Application Rate} = \frac{96.3}{\pi} \times \frac{\text{sprinkler discharge (gpm)}}{R_e\text{(feet)} \times R_e\text{(feet)}}$$

$$= 30.7 \times \frac{1.1}{13.3 \times 13.3} = 0.19 \text{ iph}$$

and for a 24-hour set

Average depth applied to wetted circular area = 0.19 X 24 = 4.6 inches

The *SE* can be computed (assuming negligible overlap and drip, which could cause some water to go too deep) by:

$$SE = \frac{3.3}{4.6} \times 100 = 72\%$$

Analysis and recommendations

Several observations and recommendations can be based on the information recorded on Form IV-1 and the preceding computations.

Uniformity on the tested area was good as indicated by the *DC* of 66%. If this percent had been much higher, it would have indicated that a greater depth had been infiltrated near the perimeter; this would result in a little water going too deep because of overlap unless the effective radius of 13.3 feet was reduced. If this were the condition, the wetted diameter should be reduced from 26.6 feet to nearly 24 feet, which is the tree spacing. (See shaded areas in Figure IV-2.)

The pressures, discharges, and wetted diameters of the sprinkler tested and other sprinklers checked were all reasonably close. (see sample Form IV-1, parts 9 and 11.) The efficiency reduction, *ER*, caused by the variations in pressure throughout the system in accordance with the formula presented in Chapter II page 41 was only:

$$ER = 0.2 \ X \ \frac{21 - 18}{19} = 0.03 \ (or \ 3\%)$$

This indicates that the general system uniformity was very good.

Water losses from causes other than deep percolation, such as loss from evaporation, are equal to the difference between the average application rate (0.19 iph) and the average catch rate (0.17 iph). This is equal to [(0.19 - 0.17)/0.19] X 100 = 10% of the water applied--a percentage that is too high for evaporation only. However, it is a reasonable figure because it includes any errors in measurement. These losses cannot be controlled by management practices.

Losses by deep percolation can be identified by the differences between the average depths infiltrated (0.17 iph X 24 hrs = 4.1 inches), and average depth stored,(3.3 inches). Thus, 0.8 inch or 18% of the applied water goes too deep; this is a large amount for a partial area irrigation program. Observing the depth profile and the 4.0 inches SMC line on Figure IV-3 shows that deep percolation is appreciable in the central portion of the pattern even though it is a nearly uniform pattern. A depth of 5.0 inches infiltrates near the sprinkler while only 4.0 inches can be stored. This excess depth occurred because the 24-hour set time is too long.

Improvements. A major improvement would be reduction of losses due to deep percolation. This could be accomplished by:

1. Reducing the duration of irrigation to less than 24 hours.
2. Lengthening the interval between irrigations by 1 or 2 days and increasing the MAD to near 5 inches.
3. Reducing the pressure or nozzle size to reduce the flow rate so the 24-hour duration could be continued.

The result of any of these changes would need to be re-evaluated to see whether it was better than the results achieved under the present system. The pattern could become worse or improve, as will be shown.

Alternate side irrigation is generally a good management practice. It is especially good when only a portion of the total area is wetted because it provides additional safety by reducing the average crop stress between irrigations.

Adjusting the duration of irrigation. The optimum duration of irrrigation T_i, to replace the *SMD*, can be found by trial. Figure IV-3 shows that 5.0 inches represents the approximate maximum infiltrated depth for a 24-hour set and that *SMD* is only 4.0 in. T_i can be estimated from:

$$T_i = \frac{4.0}{5.0} \text{ X } 24 = 19 \text{ hrs}$$

Storage efficiency, (72%) is a fairly low value particularly in view of the *DC* value of 66%. *SE* is low because the 24-hour irrigations being used are too long and cause excess deep percolation. Instead of using the original 24-hour set duration, 19 hours can be used and a new value of *SE* can be determined. This will require plotting a new profile of depth infiltrated similar to Figure IV-3 and proceeding with the evaluation outlined earlier to obtain:

$$SE = \frac{3.2}{3.6} \text{ X } 100 = 89\%$$

The analysis indicated the unmeasured losses remained at about 10%, but the losses to deep percolation were reduced to approximately 1%. Average depth stored in the wetted circular area was reduced from the initial 3.3 inches to 3.2 inches because less of the area received the full *SMD* of 4.0 inches. This will require reducing the irrigation interval to 3.2/3.3 = 97% of the initial interval, which is not very significant. However, the application time will be considerably reduced to 19/24 = 79% of the original. A 19-hour irrigation may be inconvenient, but it would be most efficient.

Average depth applied. The ratio of wetted area to actual tree-covered area must be determined before the average depth (or volume) of water to be applied to a field and the proper frequency of irrigation, based on anticipated evapotranspiration rates, can be computed. The circular wetted area provided by each sprinkler for each tree is:

$$\text{Wetted area} = \pi r^2 = 3.14 \text{ X } 13.3^2 = 556 \text{ sq. feet}$$

and the total area serviced by each sprinkler on a 24- by 24-foot spacing is 576 sq. feet.

Evapotranspiration and water applied are computed by assuming the entire soil area of the field is functioning. Therefore, for the 24-hour set where the average depth stored in the actual circular wetted area is 3.3 inches, the average depth of water stored over the whole orchard is:

$$\textit{Average depth stored} = \frac{556}{576} \text{ X } 3.3 = 3.2 \textit{ inches}$$

This value is to be used to compute the amount of water to be replaced and the irrigation interval.

Summary

Analysis of the field measurements recorded on Form IV-1 provided information about the sprinkler system and its operation. The *DC* of 66% indicated the pattern was uniform and that the dropoff in application rate at the outer perimeter was fairly rapid. A little higher value and steeper dropoff would be even better, since the overlap was small at the operating radius of 15.3 feet for the 24-foot tree and sprinkler spacing.

The current irrigation management program of 24-hour sets produced an *SE* of 72%. This is quite low for orchard sprinklers, since 28% of the applied water would not be available for the trees. Of this, approximately 10% was lost to evaporation and/or possible inaccuracies in measurements. Leakage from the sprinkler was not measured and is not included in the 10%. The remaining 18% went too deep. This loss to deep percolation was caused by running the sprinkler 24 hours, which was too long. The analysis showed that 19-hour sets would increase the *SE* to 89%.

For the *SMD* of 4.0 inches, an average of about 3.3 inches was stored under the circular wetted area by the 24-hour set, but only 3.2 inches would be stored during a 19-hour set. Changing to a 19-hour set would theoretically require slightly more frequent (3%) irrigation but would require only 79% as much water per irrigation.

For the presently used sprinkler pattern, which wets only part of the soil, the average depth of 3.2 inches stored over the whole orchard area should be used for computations of irrigation frequency based on the evapotranspiration rate. For determining the *SMD* at which to irrigate from field *SMD* checks, the *SMD* should be matched to the *MAD* in the central, uniformly irrigated area. Since at the time of this field study, *SMD* = *MAD* = 4.0 inches, it was the correct day for irrigating.

CHAPTER V
CENTER PIVOT SPRINKLE IRRIGATION

The center pivot system sprinkles water from a continuously moving lateral pipeline. The lateral is fixed at one end and rotates to irrigate a large circular area. The fixed end of the lateral is called the "pivot point" and it is connected to the water supply. The lateral consists of a series of spans ranging in length from 90 to 250 ft; it moves while irrigating and is carried above the crop by "drive units," which consist of an "A-frame" supported on wheels which are driven by motors. Devices are installed at each drive unit to keep the lateral in a line between the pivot and end drive unit; the end drive unit is set to control the speed of rotation. The most common total length of center pivot lateral is a quarter mile (1320 ft) to irrigate the circular portion (126 ac plus 2 to 10 ac more depending on the range of the end sprinklers) of a quarter section (160 ac). (See Figure V-1.)

The moving lateral pipeline is fitted with impact, spinner, or spray nozzle sprinklers to spread the water uniformly over the circular field. The area irrigated by each sprinkler (with a uniform sprinkler

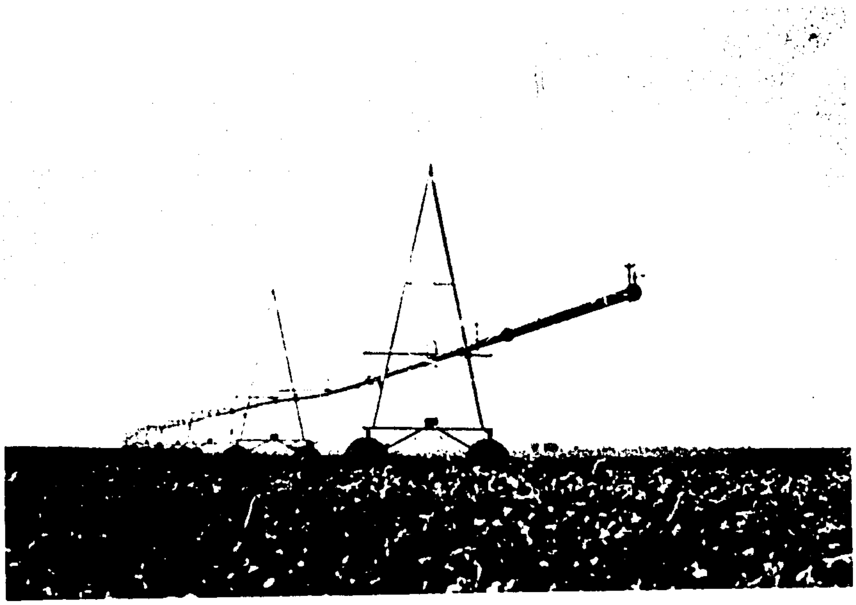


Figure V-1. Outer end of center pivot lateral in operation.

spacing) along the lateral grows progressively larger toward the moving end. Therefore, the sprinklers must be designed to have progressively greater discharges and/or closer spacings toward the moving end to achieve uniform application. Typically, the applicati rate near the moving end is in the vicinity of 1.0 inches per hour. This exceeds the intake rate of many soils except for the first few minutes at the beginning of each irrigation. To minimize surface ponding and/or runoff, the laterals are usually rotated every 10 to hours depending on the soil's infiltration characteristics, the syst capacity, and *MAD*.

Under such high frequency irrigation, *SMD* checks are useful mai for evaluating deep moisture conditions. This is especially true wh a field is intentionally underirrigated to utilize deep stored moist

Evaluation

Field evaluation of center pivot systems involves checking the *DU* along the lateral; the relative uniformity problems due to topography, infiltration and/or runoff along the outer end; crop condition; and the *SMD* in the lower half of the crop root zone.

Center pivot systems are propelled by using some of the water o by such independent power sources as electricity, oil hydraulics, or compressed air. Where water is used, it must be included as part of the total applied water; this somewhat lowers computed values of water use efficiency. When the water discharging from the pistons or turbines is distributed as an integral part of the irrigation pattern, its effectiveness should be included in *DU*; otherwise it should be ignored in the *DU* computations but should be included in computing *PELQ*.

There are similarities between the procedures and logic underlying the evaluation of all types of sprinkle systems. Effective us of procedures enumerated in this chapter will depend on a good under- standing of the procedures described in Chapter II, "Sprinkler-Later Irrigation."

The following information is required for evaluating center piv irrigation systems:

1. Rate of flow from the total system.

2. Rate of flow required to propel the system if water driven,

3. Depth of water caught in a radial row of catch containers.

4. Travel speed of end drive unit.

5. Lateral length to end drive unit and radius of the portion of the field irrigated by the center pivot.

6. Width of the wetted strip at end drive unit.

7. Operating pressure and diameter of largest sprinkler nozzles at the end of the lateral.

8. Approximate differences in elevation between the pivot and the high and/or low points in the field and along the lateral at the test position radius (taken to within plus or minus 5 feet).

9. Additional data indicated on Form V-1.

Accurate measurement of the flow rate into the system is needed for determining the *PELQ* of the system; however, if no accurate flow metering device is at the inlet, the *PELQ* can only be estimated. Under high frequency irrigation. it is difficult to evaluate the *AELQ* since the typical irrigation depth of 0.3 to 1.0 inch may be less than the probable error in the *SMD* estimate.

Equipment needed

The equipment needed is essentially the same as for the full evaluation of sprinkler-lateral systems:

1. A pressure gauge (0-100 psi) with pitot attachment. (see Figure II-4.)

2. A stopwatch or watch with an easily visible second hand.

3. From 60 to 100 (depending on the lateral length) catch containers such as 1-quart oil cans or plastic freezer cartons.

4. A 250-ml graduated cylinder to measure volume of water caught in the containers.

5. A tape for measuring distances in laying out the container row and estimating the machine's speed.

6. A soil probe or auger.

7. A hand level and level rod to check differences in elevation.

Form V-1. CENTER PIVOT SPRINKLE IRRIGATION EVALUATION

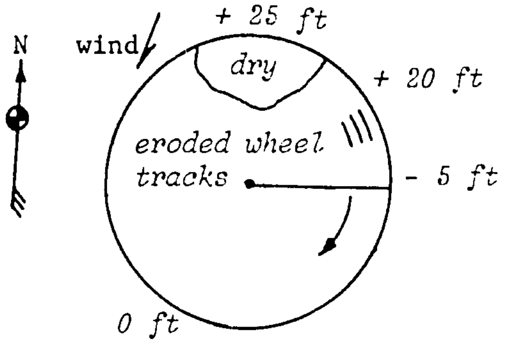
1. Location *Field F202*, Observer *JK*, Date & Time *8-18-71 p.m.*

2. Equipment: make *HG 100*, length *1375* ft, pipe diameter *6 5/8* in

3. Drive: type *water* speed setting *--* %, water distributed? *yes*

4. Irrigated area =

$$\frac{3.14\ (\text{wetted radius } 1450 \text{ ft})^2}{43{,}560} = 152 \text{ acres}$$

5. 

*Mark position of lateral, direction of travel, elevation differences, wet or dry spots and wind direction.

Wind *6* mph, Temperature *90* °F

Pressure: at pivot *86* psi

at nozzle end *60* psi

Diameter of largest nozzle *1/2* in

Comments: *Sprinklers operating OK but end part circle sprinklers out of adjustment*

6. Crop: condition *corn, good except north edge*, root depth *4* ft

7. Soil: texture *sandy loam*, tilth *poor*, avail. moisture *1.0* in/ft

8. SMD: near pivot *0.5* in, at 3/4 point *0.5* in, at end *3.0* in

9. Surface runoff conditions at 3/4 point *slight*, and at end *moderate*

10. Speed of outer drive unit *45* ft per *10* min = *4.5* ft/min

11. Time per revolution =

$$\frac{(\text{outer drive unit radius } 1350 \text{ ft})}{9.55\ (\text{speed } 4.5 \text{ ft/min})} = 31.4 \text{ hr}$$

12. Outer end: water pattern width *165* ft, watering time *39* min

13. Discharge from end drive motor *5.0* gal per *0.37* min = *13.5* gpm

14. System flow meter *115000* gallons per *10* min = *1150* gpm

15. Average weighted catches:

$$\text{System} = \frac{(\text{sum all weighted catches } 257{,}708)}{(\text{sum all used position numbers } 2044)} = 126 \text{ ml} = 0.50 \text{ in}$$

$$\text{Low } 1/4 = \frac{(\text{sum low } 1/4 \text{ weighted catches } 57{,}974)}{(\text{sum low } 1/4 \text{ position numbers } 518)} = 112 \text{ ml} = 0.45 \text{ in}$$

16. Minimum daily (average daily weighted low 1/4) catch:

$$\frac{(24 \text{ hrs operation/day}) \times (\text{low } 1/4 \text{ catch } 0.45 \text{ in})}{(31.4 \text{ hrs/revolution})} = 0.34 \text{ in/day}$$

Form V-1. CENTER PIVOT SPRINKLE IRRIGATION EVALUATION (Cont.)

17. Container catch data in units of *ml*, Volume/depth *250* ml/in

Span length *90* ft, Container spacing *22.5* ft

Evaporation: initial *150* ml *150* ml

final *-147* ml *-145* ml

loss *3* ml *5* ml, ave *4* ml = *0.016* in

Span no.	Container			Span No.	Container		
	Position Number	X Catch	= Weighted Catch		Position Number	X Catch	= Weighted Catch
1	1	*Start numbering at pivot end of inner span. Do not wait for completion of irrigation at first few containers.*		*10*	37	*118*	*4366*
1	2			*10*	38	*127*	*4816*
1	3			*10*	39	*115*	*4485*
1	4			*10*	40	*147*	*5880*
2	5			*11*	41	*127*	*5207*
2	6			*11*	42	*122*	*5124*
2	7			*11*	43	*118*	*5074*
2	8			*11*	44	*144*	*6336*
3	9	*141*	*1269*	*12*	45	*112*	*5040*
3	10	*160*	*1600*	*12*	46	*124*	*5704*
3	11	*122*	*1342*	*12*	47	*126*	*5922*
3	12	*130*	*1560*	*12*	48	*151*	*7097*
4	13	*143*	*1859*	*13*	49	*120*	*5880*
4	14	*150*	*2100*	*13*	50	*122*	*6100*
4	15	*134*	*2010*	*13*	51	*115*	*5865*
4	16	*123*	*1968*	*13*	52	*143*	*7436*
5	17	*144*	*2446*	*14*	53	*124*	*6572*
5	18	*138*	*2484*	*14*	54	*114*	*7776*
5	19	*135*	*1565*	*14*	55	*115*	*6325*
5	20	*207*	*4140*	*14*	56	*160*	*8960*
6	21	*122*	*2562*	*15*	57	*120*	*6840*
6	22	*114*	*2508*	*15*	58	*110*	*6380*
6	23	*115*	*2645*	*15*	59	*109*	*6431*
6	24	*138*	*3312*	*15*	60	*117*	*7020*
7	25	*109*	*2725*	*16*	61	*85*	*5185*
7	26	*113*	*2938*	*16*	62	*194*	*12028*
7	27	*114*	*3078*	*16*	63	*148*	*9324*
7	28	*126*	*3584*	*End*	64	*82*	*5248*
8	29	*116*	*3364*		65	*12*	*omit*
8	30	*107*	*3210*		66		
8	31	*122*	*3782*		67		
8	32	*140*	*4480*		68		
9	33	*117*	*3861*		69		
9	34	*105*	*3570*		70		
9	35	*111*	*3885*		71		
9	36	*125*	*4428*		72		

Sum all: used position numbers *2044*, weighted catches *257,708*

Sum low 1/4: position numbers *518*, weighted catches *57,974*

8. A shovel for smoothing areas to set catch containers and for checking profiles of soil, root, and water penetration.

9. Form V-1 for recording data.

10. Manufacturer's nozzling specifications giving discharge and pressure and the instructions for setting machine's speed.

11. For water-driven machines which do not incorporate the drive water into the sprinkler patterns, a 2- to 5-gallon bucket and possibly a short section of flexible hose to facilitate measuring the drive water discharge.

Field procedure

Fill in the data blanks of Form V-1 while conducting the field procedure. In a field having a low-growing crop or no crop, test the system when the lateral is in a position where differences in elevation are least. In tall-growing crops, such as corn, test the system where the lateral crosses the access road to the pivot point.

1. Set out the catch containers along a radial path beginning at the pivot with a convenient spacing no wider than 30 feet; a 15- or 20-foot spacing is preferable. The radial path does not need to be a straight line. A most convenient spacing can be obtained by dividing the span length by a whole number such as 3, 4, 5, 6, etc. For example, if the span length is 90 feet, use a 30-foot or 22.5-foot spacing. This simplifies the catchment layout since measurements can be made from each wheel track and the spacing related to the span, i.e., 4th span + 50 feet. Obviously, containers should not be placed in wheel tracks or where they would pick up waste exhaust water from water-driven systems (where the exhaust is not distributed). Where exhaust water is incorporated into the wetting pattern, lay out containers so they will catch representative samples of the drive water.

As an example, a typical layout between wheel tracks for 90-foot spans and any type of drive can be accomplished by:

a. Placing the first container position 5 feet downstream from the pivot.

b. Setting container positions 2, 3, and 4 at 22.5-foot intervals. The fourth container position is now 17.5 feet from the wheel track of the first span.

c. Repeat the above procedure to the end of the actual wetted circle placing a catch container at each container position along the way.

However, to save time it is most convenient to leave out the first few containers adjacent to the pivot since the watering cycle is so long in this area. Typically, the containers under the first one or two spans are omitted with little adverse effect on the evaluation. A number should be assigned to each container position with a sequential numbering system beginning with 1 at the container position nearest the pivot point. Even the locations not having containers under the first spans should be numbered.

2. Fill in the blanks in parts 1 through 9, dealing with climatic conditions, machine and test specifications, topography, general system, soil moisture, and crop performance. Determine the irrigated area, part 4, in acres by first estimating the wetted radius of the irrigated circle.

3. Determine the length of time required for the system to make a revolution by dividing the circumference of the outer wheel track by the speed of the end drive unit. (See parts 10 and 11 in which the conversion constant is 60/(2 x 3.14) = 9.55.)

a. Stake out a known length along the outer wheel track and determine the time required for a point on the drive unit to travel between the stakes. The speed of travel will be the distance divided by the number of minutes. An alternate method is to determine the distance traveled in a given time.

b. Since most machines have uniform span lengths except for perhaps the first span, the radius between the pivot and the outer wheel track can normally be determined by multiplying the span length by the number of spans.

4. Estimate the width of the wetted pattern (perpendicular to the lateral) and the duration of time water is received by the containers near the end drive unit. (See part 12.) The watering time is approximately equal to the pattern width divided by the speed of the end drive unit.

5. On water-driven systems, number each drive unit (span) beginning with the one next to the pivot. Time how long it takes to fill a container of known volume with the discharge from the water motor in the outer drive unit and record in part 13. The exact method for doing this depends on the water motor construction, and it may require using a short length of hose.

6. If the system is equipped with a flow meter, measure and record the rate of flow into the system in part 14 of Form V-1. Most standard flow meters indicate only the total volume of water that has passed. To determine the flow rate read the meter at the beginning

and end of a 10-minute period and calculate the rate per minute. To convert from cubic feet per second (or acre-inches per hour) to gpm, multiply by 450.

7. At the time the leading edge of the wetted patterns reaches the test area, set aside 2 containers with the anticipated catch to check the volume of evaporation losses. Measure and record in part 17 the depth of water in all the containers as soon as possible and observe whether they are still upright; note abnormally low or high catches. The best accuracy can be achieved by using a graduated cylinder to obtain volumetric measurements. These can be converted to depths if the area of the container opening is known. For 1-quart oil cans, 200 ml corresponds to a depth of 1.0 inches. Measure the catch of one of the evaporation check containers about midway during the catch reading period and the other one at the end.

Utilization of field data

The volumes caught in the containers must be weighted, since the catch points represent progressively larger areas as the distance from the pivot increases. To weight the catches according to their distance from the pivot, each catch value must be multiplied by a factor related to the distance from the pivot. This weighting operation is simplified by using the container layout procedure described earlier and Form V-1, part 17.

The average weighted system catch is found by dividing the sum of the weighted catches by the sum of the catch position numbers where containers were placed. Space for this computation is provided on Form V-1, parts 15 and 17.

For the average minimum weighted catch, an unknown number of containers that represents the low 1/4 of the irrigated area must be used. The low 1/4 is selected by picking progressively larger (unweighted) catches and keeping a running total of the associated position numbers until the subtotal approximates 1/4 of the sum of all the catch position numbers. The average weighted low 1/4 of the catch is then found by dividing the sum of the low 1/4 of the weighted catches by the sum of the associated catch position numbers. Space for this computation is also provided in parts 15 and 17.

Distribution Uniformity

In order to determine whether the system is operating at acceptable efficiency, the losses to deep percolation and *DU* should be evaluated by:

$$DU = \frac{\text{average weighted low quarter catch}}{\text{average weighted system catch}} \times 100$$

which for the example problem (Form V-1, part 15) is:

$$DU = \frac{112\ ml}{126\ ml} \times 100 = 89\%$$

This is a reasonable value and is independent of the speed of revolution. It is useful to plot the volume of catch against distance from the pivot (Figure V-2). Such a plot is useful for spotting problem areas and locating improperly nozzled or malfunctioning sprinklers. Usually there is excess water near each water-driven drive unit where the water is distributed as part of the pattern.

If the system is operating on an undulating or sloping field and is not equipped with pressure or flow regulators, *DU* will vary with the lateral postiion. The *DU* will remain nearly constant if the differences in elevation (in feet) multiplied by 0.43 (to convert to an equivalent psi) do not exceed 20% of the pressure at the end sprinkler. Thus, for the example test the line position would have minimal affect on the *DU* since the pressure at the end sprinkler was 60 psi and the maximum elevation differences were only 25 feet, equivalent to 11 psi which is only 18% of 60 psi.

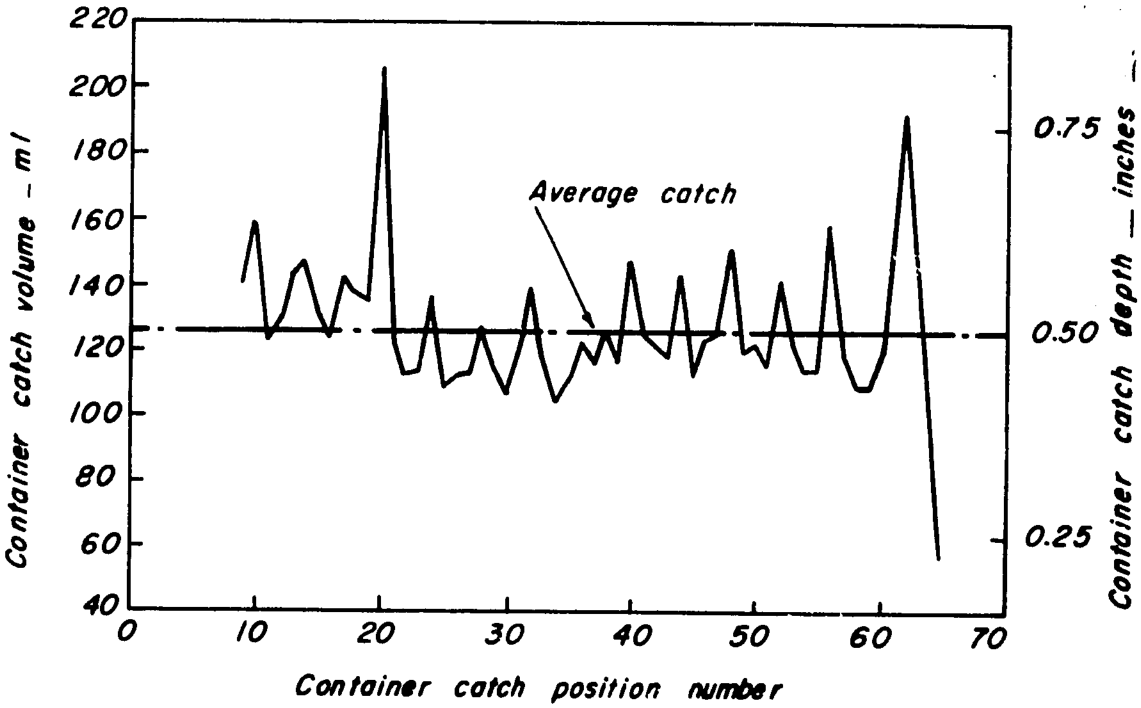


Figure V-2. Profile of container catch from center pivot sprinkler evaluation test.

Potential Application Efficiency

The *PELQ* can be determined if the pivot point is equipped with an accurate flow measuring device. (See Chapter I, page 12.) For the average low quarter rate caught use the average weighted low one-quarter of the catches expressed as a depth per revolution. The average rate in inches applied per revolution is calculated from the hours per revolution, system flow in gpm, and the wetted area in acres by:

$$\text{Average rate applied} = \frac{\text{time per revolution (hrs)} \times \text{system flow rate (gpm)}}{450 \times \text{(acres) irrigated}}$$

From the data computed on Form V-1 in parts 11, 14, and 4, the computations are:

$$\text{Average rate applied} = \frac{31.4 \times 1150}{450 \times 152} = 0.53 \text{ inches/revolution}$$

and with the average weighted low quarter catch of 0.45 inches/revolution from part 15:

$$PELQ = \frac{0.45}{0.53} \times 100 = 85\%$$

The small difference between *DU* of 89% and *PELQ* of 85% indicates that evaporation losses are quite small and within the limits of accuracy of measurement.

The system flow rate and *PELQ* can be estimated without a flow meter at the inlet. This is done by first estimating the gross application by adding the average depth caught and the estimated evaporation, which for the data recorded in Form V-1, parts 15 and 17, is 0.50 + .02 = 0.52 inch per revolution. The flow in gpm, which was distributed through the sprinkler, can be estimated by:

$$\text{Distributed flow} = \frac{450 \times \text{area (acres)} \times \text{gross application (in/rev.)}}{\text{time per revolution (hrs)}}$$

which for the recorded data is:

$$\text{Distributed flow} = \frac{450 \times 152 \times 0.52}{31.4} = 1133 \text{ gpm}$$

If water from the drive motor was not distributed, it must be added to the distributed flow to obtain the total system flow. The *PELQ* is then computed as before by using the computed system flow. For the recorded data the drive water was included in the distributed flow and need not be computed. However, if it had not been included in the distributed flow, it should be estimated by:

$$Drive\ flow = \frac{sum\ of\ drive\ unit\ numbers\ X\ gpm\ flow\ from\ end\ water\ motor}{number\ of\ drive\ units}$$

for the 15 drive motors and a flow rate of 13.5 gpm from the end water drive motor:

$$Drive\ flow = \frac{120\ X\ 13.5}{15} = 108\ gpm$$

Runoff. The above computation of *PELQ* is meaningful only if there is little or no runoff. Runoff and/or ponding may occur near the moving end of the system (Figure V-3). Increasing the system's speed will reduce the depth per application and often prevent runoff. However, on some clay type soils, decreasing the systems' speed and allowing the surface to become drier between irrigations will improve the

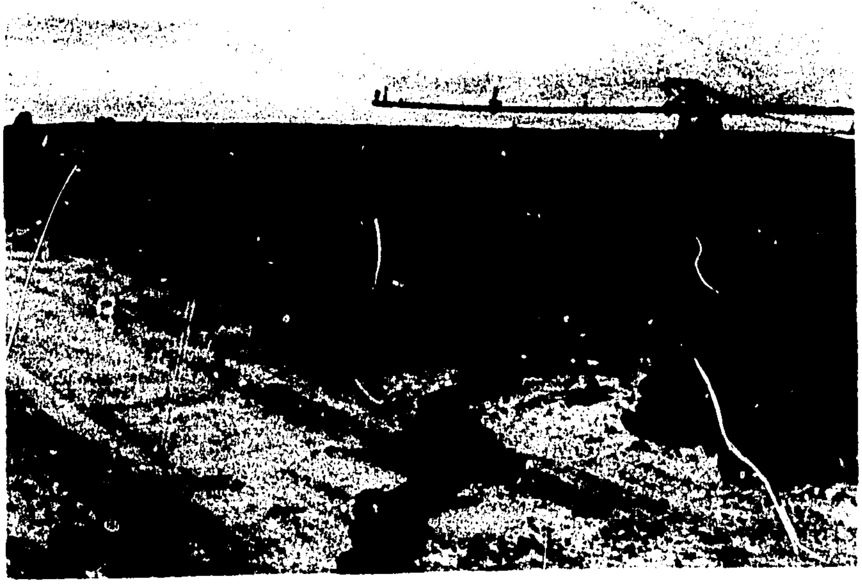


Figure V-3. Runoff near the moving end of a center pivot lateral.

soil infiltration characteristics and reduce runoff even though the depth per application is increased. Therefore, both increasing and decreasing the speed should be considered. Other methods for reducing runoff include:

1. Using an implement called a *pitter*, which scrapes indentations in the furrows followed by small dikes every 2 or 3 feet.

2. Reducing the total depth of water applied per week by turning the system off for a period after each revolution. (Automatic *stop devices* are available for many systems.) This allows the surface soil to become drier between irrigations and thus have a higher infiltration capacity. Careful planning is required in order to avoid extensive underirrigation which may reduce crop yields. (See Chapter I, "Intentional Underirrigation.")

3. Decreasing sprinkler nozzle diameters to decrease the system capacity and application rate. All the nozzles must be changed to maintain uniformity.

4. Increasing system pressure and reducing nozzle sizes throughout the system to maintain the same system flow rate. This decreases the average drop size and thereby drop impact which reduces the surface sealing that restricts infiltration.

5. Using special nozzles with *pins* to break up the jets and reduce drop sizes.

Application Efficiency

Since the depth of water applied per revolution is usually less than the normal inaccuracy of measuring the *SMD* it is impractical to try to compute *AELQ*.

Checks of the *SMD* in several places, especially near the outer end of the circle, are useful for spotting underirrigated areas; isolated areas may be underirrigated because of a low *DU* or a low *PELQ* due to runoff. Underirrigation due to runoff is most likely to occur at high spots in the outer fifth of the wetted circle where the application rates are highest.

Application rates

The maximum application rate near the moving end is normally quite high. It can be estimated in inches per hour, iph, from the average depth caught per revolution and the time water is being applied at the outer end by:

$$\text{Maximum application rate} = \frac{75 \times \text{average depth caught (inches)}}{\text{watering time (minutes)}}$$

in which 75 is a conversion factor to give iph assuming an elliptical water application profile. The maximum application rate for the example problem using the data from Form V-1, parts 12 and 15, is approximately:

$$\text{Maximum application rate} = \frac{75 \times 0.50}{39} \approx 1.0 \text{ iph}$$

Since the number of minutes the soil is receiving water each irrigation cycle increases toward the pivot end, the application rate decreases toward the center of the circle.

Analysis and recommendations

Several observations and some recommendations can be made from the additional data on Form V-1 and the computations of *DU* and *PELQ*.

Operational checks. Pressure at the large end sprinkler nozzle was too low for good jet breakup (1/2-inch at 60 psi). This produced large droplets, which tended to seal the soil surface and decrease the infiltration capacity. For good breakup from regular nozzles the largest nozzles for given pressures should be: for 55 psi, up to 1/4-inch; for 65 psi, up to 3/8-inch; for 75 psi, up to 1/2-inch; and for 85 psi, up to 3/4-inch. When breakup pins or orifice type nozzles are used, pressures can be reduced by 20%.

The time per revolution, estimated to be 31.4 hours (part 11), should be checked against the actual time required. Often the operator can give a good estimate of the actual time. Uniformity of the turn speed, which is essential to efficient watering, can be evaluated by comparing the computed with the actual time per revolution. Speed checks where the lateral is traveling up and down steep slopes may also be useful.

Runoff. Runoff was observed near the outer end of the system where the application rate reached 1.0 iph. This reduces the *PELQ* of 86% by an unknown amount. Further evidence that runoff occurred was noted in the outer wheel tracks; runoff traveled down furrows and collected in the wheel tracks, cutting the tracks 2 feet deep in some areas of the field. Thus, washing coupled with the digging action of the wheels can result in such deep erosion that the drive units scrape the ground and stop the system. Other evidences of runoff were the dry corn crop on a hill along the north edge of the field and the deep moisture deficit indicated by the *SMD* of 3.0 inches all around the outer edge of the irrigated circle. (See Form V-1, parts 5 through 9.)

Of the methods for decreasing runoff described earlier, reducing nozzles sizes and/or increasing pressures would probably produce the best results; however, accelerating the machine speed to approximately one revolution every 24 hours and then stopping the system for about 8 hours after each revolution would also be a simple but effective method. The time interval between revolutions should always be at least 2 hours more or less than 24, 48, or 72 so that the lateral will progressively change positions relative to the normal daily wind cycles.

Overirrigation. High frequency irrigation keeps the *SMD* near zero, and it is difficult to measure overirrigation. However, for the operation evaluated, the estimated peak daily water required for corn in that area was only about 0.25 inch per day. Since the operator was running the system almost continuously and applying a minimum daily 0.34 inch (part 16), he was obviously overirrigating. If he shut off the irrigation for 8 hours after every 24 hours, as suggested above for reducing runoff, the minimum daily application would be (24/32) X 0.34 = 0.25 inch.

Improvements. The operational changes described above not only would improve the efficiency of irrigation but would also reduce the operating problems that cause erosion in the wheel tracks. Under the current management the lateral often gets out of line in the eroded areas and the safety controls shut the system down. The operator must then pull the system into line and fill in the eroded tracks.

The plot of container catch data, Figure V-2, shows that a sprinkler in the vicinity of catch position number 20 either is stuck or has too large a nozzle. Also the ragged wetting pattern near the outer (moving) end indicates that the part-circle sprinklers on the end are either improperly designed or are set with the wrong arc. The sprinklers in these two areas should be checked and replaced or adjusted as needed.

When a system creates no runoff and its capacity is not sufficient to meet the crop's water requirements, slowing the operation usually improves yields. By slowing the system, the operation can apply deeper but less frequent irrigations. This reduces direct losses from evaporation and allows the crop to use the limited water supply more efficiently.

Summary

Both the *DU* of 89% and calculated *PELQ* of 85% of the center pivot system are very good. The main problems in operating this system are associated with runoff and overirrigation. Suggestions for reducing runoff included: reducing the system flow and increasing inlet pressures; changing the speed of rotation; and periodically turning the system off to reduce the total volume of water applied. The overirrigation could be eliminated by shutting off the system for 8 hours after every 24 hours of operation.

CHAPTER VI
TRAVELING SPRINKLER IRRIGATION

The traveling sprinkler (or traveler) is a high capacity sprinkler fed with water by a flexible hose; it is mounted on a 4-wheel self-powered chassis and travels along a straight line while watering. The most common type of traveler used in the USA for agriculture has a giant gun-type 500-gpm sprinkler that is mounted on a moving vehicle and wets a diameter of more than 400 feet. The vehicle is equipped with a water piston or turbine-powered winch that reels in the cable. The cable guides the unit along a path as it tows a high-pressure flexible lay-flat hose which is connected to the water supply pressure system. The typical hose is 4 inches in diameter and is 660 feet long; this allows the unit to travel 1320 feet unattended. (See Figure VI-1.) After use, the hose can be drained, flattened, and wound in a compact reel.

Some traveling sprinklers have a self-contained pumping plant mounted on the vehicle which pumps water directly from an open ditch while moving. The supply ditches replace the hose.

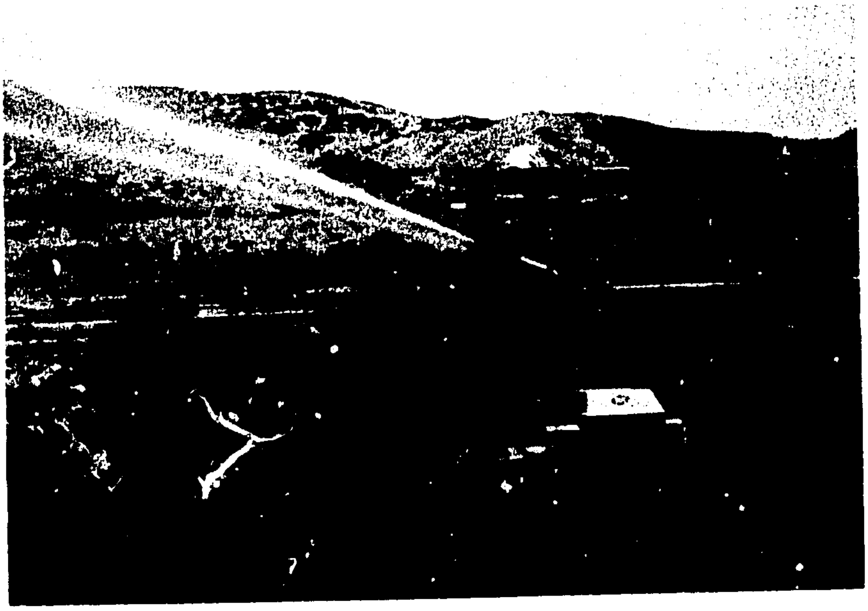


Figure VI-1. Hose fed traveling gun type sprinkler in operation.

Some travelers are equipped with boom (instead of gun) sprinklers. Boom sprinklers have long rotating arms (60 to 120 feet) from which water is discharged through nozzles as described in Chapter VII.

As the traveler moves along its path, the sprinkler wets a strip of land some 400 feet wide rather than the circular area wetted by a stationary sprinkler. After the unit reaches the end of a travel path, it is moved and set up to water an adjacent strip of land. The overlap of adjacent strips depends on the distance between travel paths and the diameter wetted by the sprinkler. Frequently a part-circle sprinkler is used; the dry part of the pattern is positioned over the towpath so the unit travels on dry ground. (See Figure VI-2.)

Figure VI-2 shows a typical traveling sprinkler layout for an 80 acre field. The entire field is irrigated for 8 towpaths each 1320 feet long and spaced 330 feet apart.

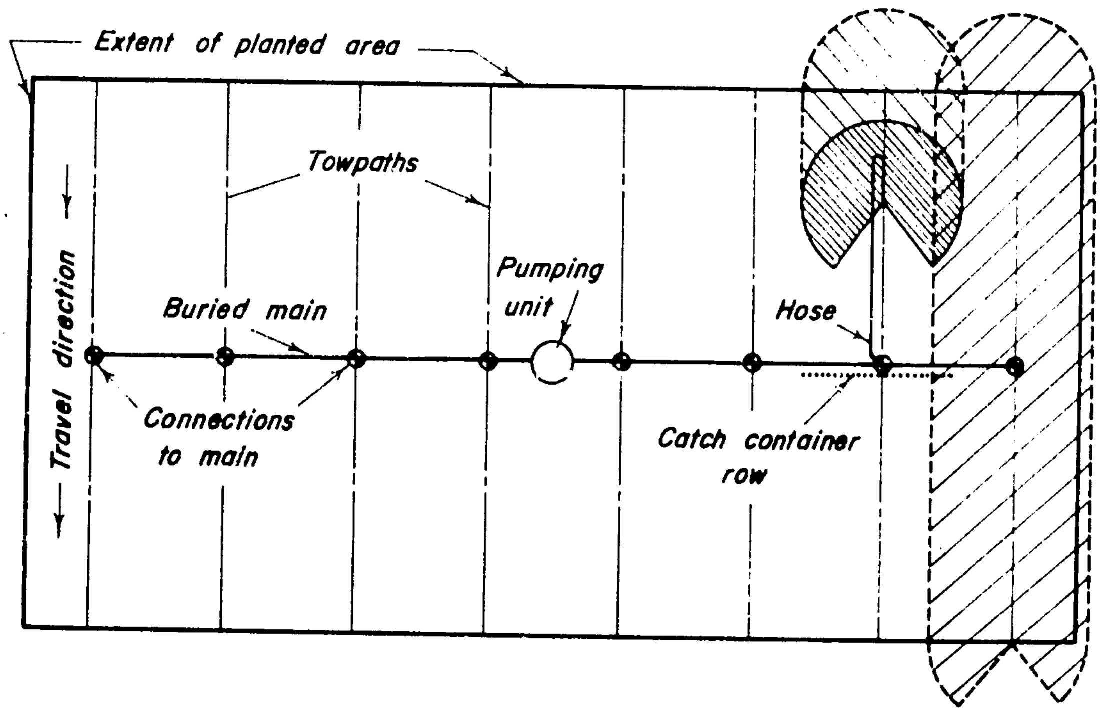


Figure VI-2. Typical layout for traveling sprinklers showing location of catch container line for evaluating the distribution uniformity.

The following procedures are designed mainly to check the uniformity and efficiency of irrigation across the travel paths. However, the nature of the operation and the large size of the sprinklers tend to reduce the quality of irrigation around field boundaries. It is particularly difficult to obtain high quality irrigation at the ends of the towpaths unless special control systems are used on the sprinkler, and on small fields this is an appreciable area--as much as 200 feet on each end.

If the traveling unit is powered by a water piston, the expelled water should not be included in evaluating the *DU* but should be included in computing the *AELQ* and *PELQ*.

Many procedures used in evaluating performance of traveling sprinklers are closely related to those used for evaluating the sprinkler-lateral and center pivot sprinkle systems. General knowledge of these evaluation techniques already presented for the sprinkler-lateral and center pivot systems is assumed (Chapters II and V).

Evaluation

The following information is required for evaluating traveling sprinkler irrigation systems:

1. Frequency of normal irrigations.
2. *MAD* and *SMD*.
3. Nozzle diameter and type for estimating system's flow rate.
4. Pressure at the nozzle.
5. Depth of water caught in catch containers.
6. Travel speed when the unit is at the test location and extreme ends of the towpaths.
7. Spacing between towpaths.
8. Rate of discharge from water piston (if applicable).
9. Additional data indicated on Form VI-1.

An accurate estimate of the flow rate from the nozzle is necessary for calculating the *PELQ* and *AELQ* of the system. A good way to estimate this flow is to use the sprinkler performance chart provided by the manufacturer. A typical performance chart gives the rate of

Form VI-1. TRAVELING SPRINKLER IRRIGATION EVALUATION

1. Location *Field 200*, Observer *JK*, Date *7/5/74*
2. Crop *Corn*, Root zone depth *4.0* ft, MAD *35* %, MAD *2.1* in
3. Soil: texture *fine sandy loam*, available moisture *1.5* in/ft
4. SMD: near tow path *2.1* in, at 1/4-point *2.2* in, at mid-point *3.7* in
5. Sprinkler/Traveler makes and models *Nelson 201* / *Heinzman 6645*
6. Nozzle: size *1.5* in, type *ring*, pressure *100* psi, discharge *500* gpm
7. Hose: length *660* ft, diameter *4* in, type *lay-flat*

   inlet pressure *137* psi, outlet pressure *110* psi
8. Drive: type *turbine*, discharge (if piston) *--* gal/ *--* min = *-* min
9. Towpath: spacing *330* ft, length *1320* ft, slope ± *0* %
10. Evaporation loss: (*200* ml catch = 1.0 in)

    cup #1 initial - final volume = *500* - *470* = *30* ml

    cup #2 initial - final volume = *500* - *482* = *18* ml

    average evaporation loss = *24* ml = *0.1* in
11. Traveler speed check at:

    beginning *9.5* ft/ *10* min = *0.95* ft/min

    at test site *10.0* ft/ *10* min = *1.0* ft/min

    terminal end *10.2* ft/ *10* min = *1.02* ft/min
12. Total: discharge *500* gpm, pressure loss *37* psi
13. Average application rate:

$$\frac{96.3 \times (\text{sprinkler discharge } 500 \text{ gpm}) \times 360}{(\text{towpath spacing } 330 \text{ ft})^2 \times (\text{wet sector } 345\,°)} = 0.46 \text{ in/hr}$$

14. Average depth applied:

$$\frac{96.3}{60} \times \frac{(\text{sprinkler plus piston discharge } 500 \text{ gpm})}{(\text{path spacing } 330 \text{ ft}) \times (\text{travel } 1.0 \text{ ft/min})} = 2.43 \text{ in}$$

15. Average overlapped catches:

$$\text{System} = \frac{(\text{sum all catch totals } 74.87 \text{ in})}{(\text{number of totals } 33)} = 2.27 \text{ in}$$

$$\text{Low } 1/4 = \frac{(\text{sum of low } 1/4 \text{ catch totals } 12.91 \text{ in})}{(\text{number of low } 1/4 \text{ totals } 8)} = 1.61 \text{ in}$$

16. Comments (wind drift, runoff etc.): *no evidence of serious wind drift or runoff; crop was stunted midway between paths*

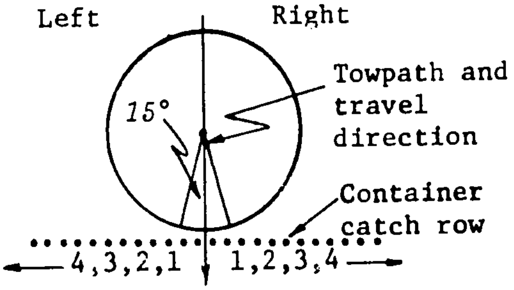
Form VI-1 TRAVELING SPRINKLER IRRIGATION EVALUATION (Cont.)

17. Container test data in units of ml, Volume/depth 200 ml/in

Wind: speed 5-10 mph

direction ↙

Note part circle operation and the dry wedge size in degrees



Start with number 1 opposite the towpath spacing and number down

Start with number 1 at bottom of column and number up

Path Spacing feet	Container Catch Volume				Right plus Left Side Catch Totals	
	Left side of path		Right side of path			
	Catch No.	Catch	Catch No.	Catch	ml	inches
330	1	560	33		560	2.80
320	2	540	32		540	2.70
310	3	510	31		510	2.55
300	4	490	30		490	2.45
290	5	505	29		505	2.53
280	6	475	28		475	2.38
270	7	480	27		480	2.40
260	8	460	26		460	2.30
250	9	430	25		430	2.15
240	10	410	24		410	2.05
230	11	370	23		370	1.85
220	12	325	22		325	1.63
210	13	305	21		305	1.53
200	14	345	20		345	1.73
190	15	335	19		335	1.68
180	16	310	18		310	1.55
170	17	305	17		305	1.53
160	18	290	16	35	325	1.62
150	19	250	15	75	325	1.62
140	20	230	14	120	350	1.75
130	21	215	13	215	430	2.15
120	22	165	12	365	530	2.65
110	23	95	11	410	505	2.52
100	24	65	10	515	580	2.90
90	25	25	9	540	565	2.82
80	26	--	8	525	525	2.62
70			7	500	500	2.50
60			6	490	490	2.45
50			5	470	470	2.35
40			4	490	490	2.45
30			3	540	540	2.70
20			2	605	605	3.02
10			1	625	625	3.12
			Sum of all catch totals			74.87
			Sum of low 1/4 catch totals			12.21

sprinkler discharge and diameter of coverage for various nozzle sizes at different pressures.

Equipment needed

The equipment the evaluator needs is:

1. A pressure gauge (0-150 psi) with pitot tube attachment (Figure II-4).
2. A stopwatch or watch with an easily visible second hand.
3. Approximately 60 catch containers such as 1-quart oil cans or plastic freezer cartons.
4. A 500-ml graduated cylinder to measure volume of water caught in the containers.
5. A 50- or 100-foot tape for measuring distances in laying out the lines of containers and estimating machine's speed.
6. A soil probe or auger.
7. Manufacturer's sprinkler performance chart giving the relationship between discharge, pressure, and wetted diameter plus recommended operating pressure range. Also speed specifications and setting instructions for the traveling vehicle.
8. A shovel for smoothing areas to set catch containers and for checking profiles of soil, root, and water penetration.
9. A hand level to check differences in elevation.
10. Form IV-1 for recording data.
11. For travelers powered by a water piston, a 2- to 5-gallon bucket and possibly a short length of flexible hose to facilitate measuring the piston discharge.

Field procedure

Fill in the data blanks of Form VI-1 as the field procedure progresses. Choose a test location about midway along the towpath where the traveler operates. The location should be far enough ahead of the sprinkler so no water reaches the test area before the catch containers are set up. It should be far enough from the outer end of the path so that the back (or trailing) edge of the sprinkler pattern passes completely over it before the sprinkler reaches the end of the towpath. A good location for the test area is along the main line where an access road is usually provided. In tall growing crops such as corn, an access road is the only practical location for the test.

1. Set out a row of catch containers 10 feet apart across the towpath (see Figure VI-2); the containers that are adjacent to the towpath should be set on both sides of the towpath about 5 feet from the center of the path. The outer containers should be at the edges of the wetted strip. It is good practice to provide at least two extra containers on both ends of the container row to allow for changes in wind direction or speed.

2. Fill in the data blanks about the crop and soil (parts 2 and 3 of Form VI-1).

3. Check the *SMD* at the following locations: 10 feet from the towpath; one-fourth of the distance to the next towpath; and midway between the towpath in use and the one to be used next. Enter these *SMD* data in part 4.

4. Note the make and model of the traveler, the sprinkler, type of nozzle (orifice ring or taper bore), and nozzle diameter. (It is also good practice to measure the nozzle size after the system is turned off. This is done to check for nozzle erosion so the estimated flow rate can be adjusted if necessary.) Enter this information in parts 5 and 6.

5. Check the hose length and diameter, also the inlet and outlet pressures of the hose, if feasible. Record in part 7.

6. Check and record in part 8 the type of drive used in the traveler. In evaluating water-piston powered travelers to estimate the drive flow, determine how long it takes the discharge from the piston to fill the bucket (or jug) of known volume.

7. Measure and record the spacing between towpaths and the towpath length and general slope in part 9.

8. Set out two containers with the anticipated catch to check the volume of evaporation losses. The first container should be set out when the wetted pattern first reaches the catch row and the second container when the sprinkler vehicle reaches the row. Record these catches in part 10 which is set up to record these data.

9. Determine the travel speed of the unit (ft/min) as it passes over the row of containers. This speed should also be checked

at the extreme ends (beginning and terminal on Figure VI-2) of the towpath and recorded in part 11. To do this, stake out a known length, say 10 feet, and determine the time required for a point on the vehicle to travel between the stakes. An alternate method is to determine the distance traveled in a given time, say 10 minutes.

10. Check and record in part 6 the pressure at the sprinkler nozzle when it is about directly over the catch row and estimate the sprinkler discharge from the manufacturer's performance chart. (See Figure II-4.)

11. Estimate and record in part 12 the total discharge from the traveler by adding the sprinkler nozzle and piston discharges. Also estimate and record the total pressure loss through the hose and sprinkler.

12. Note in part 17 the general test conditions including: wind speed and direction, angle degrees of the dry wedge of part-circle sprinkler operation, wet or dry spots, and runoff problems.

13. Measure and record in part 17 the depth of water in all the containers as soon as possible and observe whether they are still upright; note any abnormally low or high catches. Then measure and record in part 10 the catch in the two evaporation check containers after the last container in the row has been recorded.

14. Note any special comments such as runoff, test problems, and crop water stresses in part 16.

15. Do the computational work required in parts 17, and 13 through 15 of Form VI-1.

Part 17 of Form VI-1 is designed to simplify the procedure of overlapping the catches to simulate a complete irrigation between adjacent towpaths. To use the form, number the containers from the towpath outward beginning with 1, 2, 3, etc., to the right and to the left looking opposite to the direction of travel. Enter the container numbers and catch volumes as follows: for the left side data start numbering with container 1 opposite the actual towpath spacing (which for the example field evaluation is 330 feet) and number downward; and for the right side data start the numbering with container 1 opposite the towpath spacing of 10 feet and number upward.

Utilization of field data

Data used in computations in the following pages were recorded in evaluation of a traveling sprinkler system in a corn field (Form VI-1).

Assuming the test is representative and that the next run would give identical results, the left-hand side of the container catch volumes may be overlapped on (added to) the right-hand side. (See Figure VI-2.) Form VI-1 is designed to simplify this operation.

The overlapped data totals provide an estimate of the profile of the depth of irrigation water between adjacent towpaths. For computations of *DU*, *PELQ*, and *AELQ* (see Chapter I, pp. 11 and 12) that follow, it is assumed that this depth profile represents the distribution throughout the field. In other words, the assumption is that the depth profile across the strip between towpaths is the same along the entire strip. This is obviously subject to question because of discontinuities at the path ends, changes in travel speeds, variations in pressure due to elevation, and changes in wind speed and direction.

Distribution Uniformity

In order to determine whether the system is operating at an acceptable and economical efficiency, the *DU* should be evaluated. For the sample test using the average and low one-quarter catch data from part 15 of Form VI-1 is:

$$DU = \frac{1.61}{2.27} \times 100 = 71\%$$

This is a fair value for a traveler system with widely spaced towpaths and is generally independent of the speed of travel.

It is useful to plot the depth of catch along the distance between towpaths (see Figure VI-3) as a means for spotting problem areas. Note that the plotted points represent the depth of catch at the midpoint of each 10-foot interval between adjacent towpaths. Figure VI-3 shows that either the towpaths are too far apart, which results in a shallow wetted depth midway between towpaths, or that the angle of the part circle is set too narrow. The effect of narrowing the spacing between towpaths can be measured by using a blank copy of Form V-1, part 17 and repeating the above procedure with the same catch data and the new spacing. Widening this angle of the dry wedge would reduce the depth of water applied near the paths and would increase the depth of water applied midway between towpaths; but to measure the effect of widening the angle requires another catch test run.

The check of travel speed shows that the unit moves faster toward the terminal end of the towpath run. (See sample Form VI-1, part 11.) This change in speed is caused by the interaction of

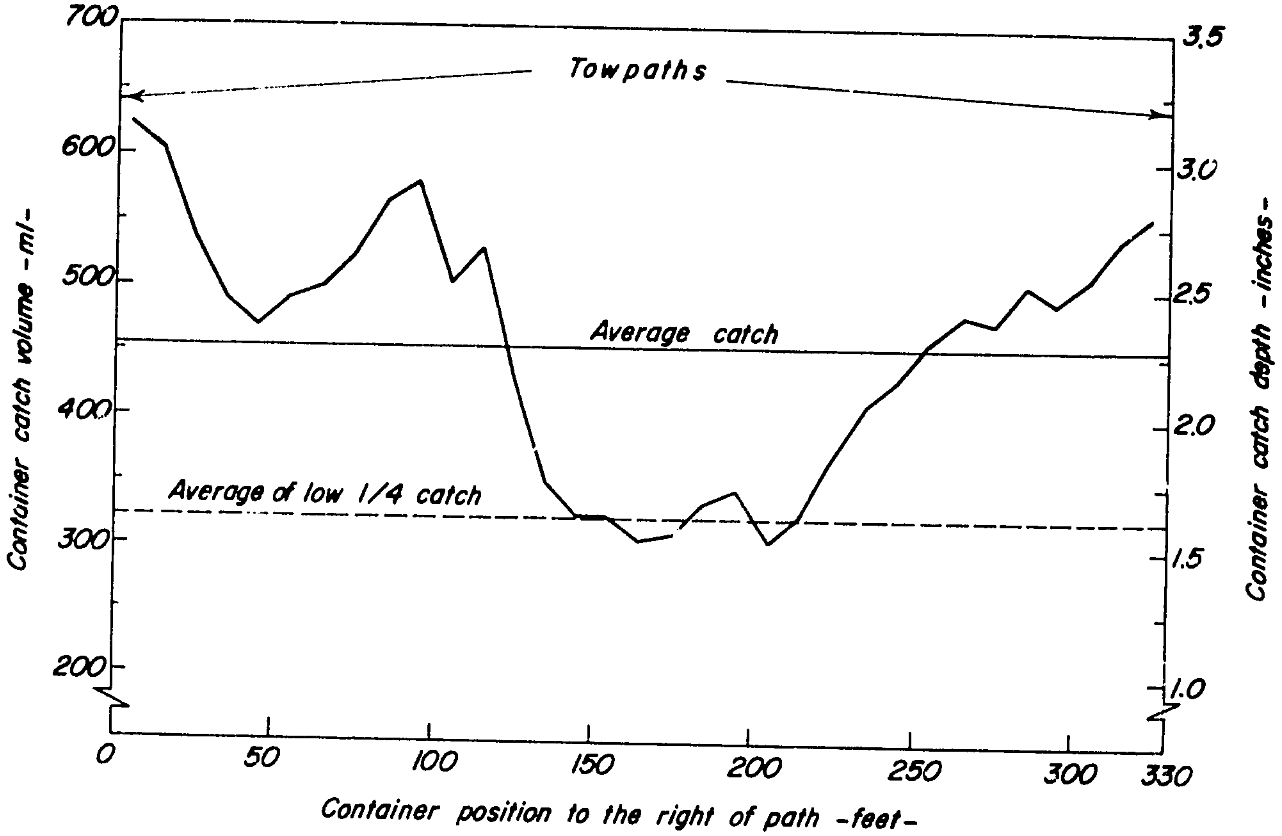


Figure VI-3. Profile of overlapped container catch data from traveling sprinkler evaluation.

the buildup of cable on the winch reel and the increased drag exerted by the hose as the unit moves from the beginning to the terminal end of the towpath. Fortunately, these two factors somewhat offset each other, and in the operation reported here the unit was traveling only 2% faster at the terminal end than in the test area and 5% slower at the beginning end. (See Figure VI-2.) These changes of speed would lower the *DU* over the entire strip by about three eighths of the total percent speed change, i.e., 3/8 X (2 + 5) or less than 2%.

Since the nozzle pressure is normally near 100 psi, differences in elevation are usually not great enough to affect *DU* appreciably. Only differences in elevation along the towpaths are of concern because valves can adjust hose inlet pressures. However, even with a difference of 40 to 50 feet in elevation along the towpath, the *DU* decreases by only about 4%.

Changes in wind speed and/or direction can greatly affect *DU*, especially if the wind direction changes appreciably during the operation in adjacent towpaths (blows from the left in Figure VI-2 one day and from the right the next day). However, if the system is managed to operate approximately 24 hours in each towpath, as in the example test, wind problems are minimized. The traveler is in about the same relative position along adjacent towpaths at a given time of day, when wind speed and direction are most likely to be similar.

Potential Application Efficiency

PELQ should be determined in order to evaluate how effectively the system can utilize the water supply and what the water losses may be, then the total amount of water required to irrigate the field can be estimated. *PELQ* is calculated from the ratio of the average low-quarter depth caught in the containers to the average depth applied (rather than rates as used in other sprinkler system evaluations).

The average depth applied, D, (in inches) is calculated from a constant times the total traveler discharge (the sprinkler discharge plus the piston discharge, if the traveler is driven by water piston) divided by the towpath spacing and the sprinkler's travel speed.

$$D = \frac{96.3}{60} \times \frac{\text{sprinkler plus piston discharge (gpm)}}{\text{path spacing (feet)} \times \text{travel (feet/min)}}$$

From the sample data given in parts 9, 10, and 11, and computed in Part 14 on Form VI-1, the average depth applied is 2.43 inches. The *PELQ* with a low one-quarter depth of 1.61 inches is:

$$PELQ = \frac{1.61}{2.43} \times 100 = 66\%$$

This is a reasonable value for the central portion of a traveler irrigated field with such wide towpath spacings; however, the *PELQ* around the boundaries will be much lower.

Application Efficiency

Effectiveness of the use of the traveler system can be estimated by how much of the applied water is stored in the soil and available for consumptive use and by comparing the *AELQ* and the *PELQ*.

The fine sandy loam soils in the area tested hold about 1.5 inches per foot available moisture. Depth of the root zone of the corn was 4.0 feet at that time, and a 35% *MAD* was considered ideal. This gives an *MAD* of 2.1 inches. The field checks (Form VI-1, part 4) showed that *SMD* near the towpath and at the 1/4 point were 2.1 inches and 2.2 inches, respectively, while in the middle of the strip it was 3.7 inches.

The minimum depth of 1.6 inches was applied in the middle of the strip where the *SMD* was 3.7 inches (Figures VI-2 and 3). Thus, the system did not apply a full irrigation; no water was lost to deep percolation in the low-quarter application area; and *AELQ* = *PELQ* = 66%.

Apparently much of the area had been receiving adequate irrigation because the *SMD* and *MAD* over much of the strip were less than or equal to the depth of application. However, underirrigation had created a cumulative deficit in the middle areas between towpaths. This deficit was beginning to affect the corn growth as evidenced by stunted plants midway between paths.

Application Rate

The gun sprinklers normally used on travelers produce a rather flat pattern of distribution. That is, if the traveler vehicle were standing still, the application depth or application rate over most of the wetted area would be fairly uniform. An estimate of the average application rate, R, in inches per hour can be obtained from a conversion constant times the flow (in gpm) from the sprinkler divided by the wetted area. The wetted area depends on the angle of the wet sector (for part-circle sprinklers).

$$R = \frac{96.3 \times \text{sprinkler discharge (gpm)} \times 360}{\text{towpath spacing (feet)}^2 \times \text{wet sector (degrees)}}$$

For the sample evaluation (Form VI-1, parts 6 and 9), the sprinkler discharges 500 gpm and the towpath spacing is 330 feet with the part-circle sprinklers set for a 15° dry sector i.e. 345° wet. The estimated average application rate computed in part 13 of Form VI-1 is R = 0.46 in/hr. This is a fairly high application rate for the fine sandy loam soils which could cause infiltration and runoff problems in steeper areas or where the soil is in poor condition (tilth).

Analysis and recommendations

Many of the observations and some recommendations that can be made from the additional data on Form VI-1, plus the *DU* and *PELQ* computations have already been referred to here and in other chapters about sprinkle evaluation.

Operational checks. The pressure of 100 psi at the nozzle is ideal for good breakup of drops. The total recorded losses of 37 psi (10 psi in the drive turbine and 27 psi in the 4-inch by 660-foot flexible hose) are reasonable. (See Form VI-1, parts 6, 7, and 12.)

Runoff. Infiltration did not appear to be a problem. The fine sandy loam soils could receive the light application at 0.46 iph with no runoff, and the towpath remained relatively dry.

Underirrigation. After reviewing the full value of the operation, it was concluded that the amount of underirrigation was reasonable. The area receives considerable summer rain which may offset the cumulative *SMD* along the center of the strips; furthermore, the large area of the field and the restricted supply of water made it impractical to increase the average depth of application very much Only improvements in *DU* and possibly slightly higher flow rates would be practical.

Improvements. The only major improvement necessary would be to increase the *DU*. However, it is not reasonable to narrow the towpath spacing during the growing season. If this spacing were reduced, the numbers of towpaths and consequently the number of days between irrigations would need to be increased.

Several practical possibilities for improving the *DU* might be tried in the following order:

1. Increase the angle of the dry area up to between 90° and 120°.

2. Try a taper bore nozzle, which would have a greater range for the same discharge and pressure.

3. Increase the nozzle size to the next larger sized ring nozzle.

Edge effects. The outside towpaths of the present system are placed 150 feet inside the field boundaries. The field was laid out similarly to what appears in Figure VI-2. There were 8 towpaths across the 2610-foot width of the field--2640 feet less a 30-foot road right-of-way. Data on Form VI-1, part 17, indicate this layout should give a reasonable application (1.7 inches) on the downwind side but a very light (0.4 inch) watering along the upwind side.

The traveler started at one edge of the field and stopped at the opposite edge. This resulted in considerable overthrow but watered the ends of the field (Figure VI-2) fairly well. The full length of the 660-foot hose was needed because it had to be dragged through the 1320-foot length of the towpaths.

The *PELQ* of 66% computed earlier was for the central portion of the field; however, because of poor uniformity along the boundaries where there is insufficient overlap, plus water that is thrown outside of the planted area (see Figure VI-2), the overall field efficiency is considerably lower. For the 80-acre field evaluated, the overall field *PELQ* was only estimated to be 52%. Much of this reduction in efficiency is due to poor uniformity along the edge of the field where the traveler is started and the edge where it stops. (See Figure IV-2.) To minimize the decrease in *PELQ* along the ends of the towpaths, the traveler would need to be started about 150 feet outside the edge of the field and allowed to travel 100 feet past the opposite edge of the field; these distances are unequal because of the wind. If the field were square (160-acre) with towpaths twice as long (2640 feet), the relative end effects would be half as great and the overall field *PELQ* would have been approximately 57%.

Summary

The *DU* of 71% and the *PELQ* of 66% found in the evaluation are typical for performance of supplemental irrigation systems used on corn. The main problems in this system are associated with a poor *DU*, in which the dryest part of the pattern occurred in the mid-portions of the strips between towpaths. Changing angle of the dry area of the sprinkler or the type or size of the sprinkler nozzle may improve the *DU*.

Special control systems which essentially eliminate the reduction in *PELQ* caused by the poor uniformity along towpath ends are in the pilot operation stage. These control systems change the angle of the part circle sprinkler and the speed of travel upon leaving and approaching the towpath ends. For the 80-acre field evaluated, such a control system could increase the overall field *PELQ* by about 10% or up to approximately 62%.

CHAPTER VII
GUN AND BOOM SPRINKLER IRRIGATION

Gun (or giant) sprinklers have 5/8-inch or larger range nozzles attached to long (12 or more inches) discharge tubes. Most gun sprinklers are rotated by means of a "rocker arm drive" and many can be set to irrigate a part circle. (See Figure VII-1.)

Boom sprinklers have a rotating 100- to 250-foot long boom supported in the middle by a tower mounted on a trailer. The tower serves as the pivot for the boom which is rotated once every 1 to 5 minutes by the reaction of jets of water discharged from nozzles. The nozzles are spaced and sized to apply a fairly uniform and gentle application of water to a circular area over 300 feet in diameter. (See Figure VII-2.)

Gun or boom sprinkler systems can be used in many similar situations and each has its comparative advantages and disadvantages. However, gun sprinklers are considerably less expensive and simpler to operate; consequently there are more gun than boom sprinklers in use. For convenience the word gun will also imply boom through the rest of this chapter, since both sprinklers can be evaluated by the same general technique.

Gun and boom sprinklers usually discharge more than 100 gpm and are operated individually rather than as sprinkler-laterals as discussed in Chapter II. (See Figures VII-1 and -2.) Gun sprinklers can be evaluated by the techniques described in Chapter II because they are a type of overlapped sprinkler-lateral system, but there are major difficulties in using these techniques because of the following:

1. Typical spacings range between 200 and 400 feet; thus, for a square grid catch container layout several hundred containers may be required.

2. Since the sprinklers normally run as individual units, the field test data need to be overlapped in two directions; first to represent the spacing between sprinklers on a lateral supply line and again to represent the spacing between lateral supply lines. With a large number of catch container data this overlapping process is both tedious and time consuming.

3. Often gun and boom sprinklers are used to irrigate tall growing crops, which complicate the catch container setup. The containers must either be mounted above the crop or a considerable

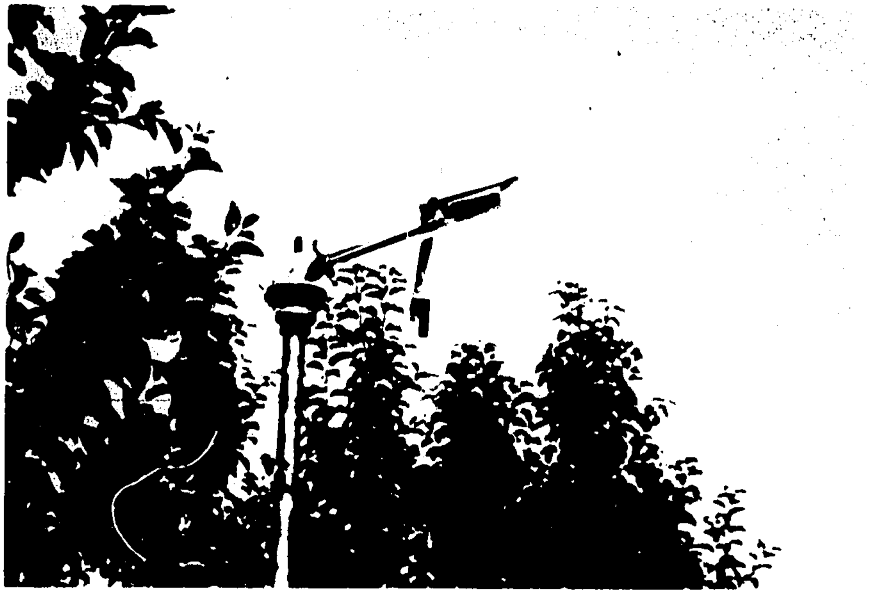


Figure VII-1. Part circle rocker arm drive gun sprinkler in operation.

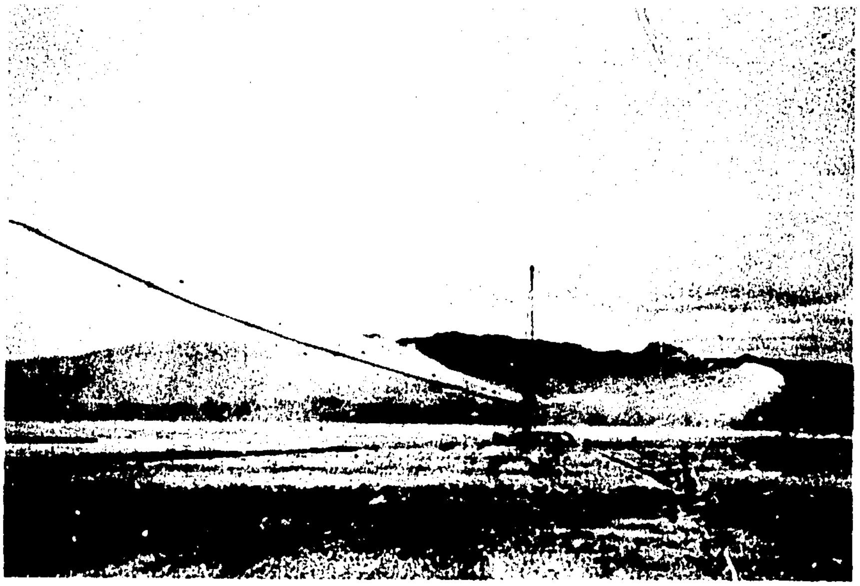


Figure VII-2. Boom sprinkler in operation.

amount of crop must be cleared from around each of them. (Since the wetted area around each sprinkler is quite large, it is difficult to find sufficiently large clear areas along the sides or ends of the fields to test the sprinklers outside of the cropped area.)

Because of the above considerations, a technique has been specifically developed for field evaluation of gun and boom sprinkler systems. This technique sacrifices some of the accuracy that could be obtained from a grid of several hundred catch containers, but it is less complex.

Many detailed procedures in evaluating gun sprinkler systems are similar to those used for evaluating traveling sprinklers. General knowledge of the techniques already described for evaluating the sprinkler-lateral and traveling sprinklers is assumed.

Evaluation

The following information is required:

1. Duration of normal irrigations.
2. *MAD* and *SMD*.
3. Nozzle(s) diameter and type for estimating system's flow rate.
4. Spacing of sprinklers along portable supply lines.
5. Spacing of supply lines along the main lines.
6. Pressure at the nozzle (or tower of a boom sprinkler).
7. Depth of water caught in catch containers.
8. Duration of test.
9. Additional data specified on Form VII-1.

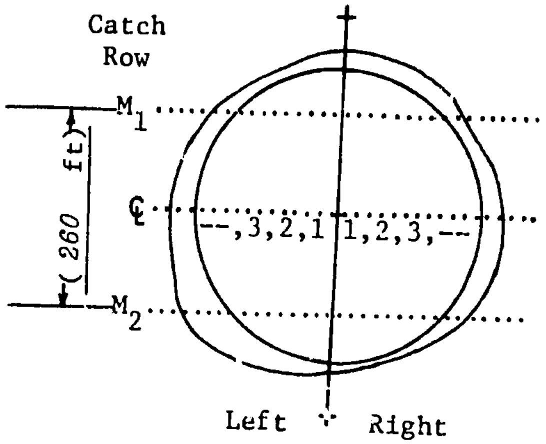
An accurate estimate of the flow rate from the nozzle is necessary for calculating the *PELQ* and *AELQ* of the system. A good way to estimate the flow is to use the manufacturer's sprinkler performance chart. A typical performance chart tells the sprinkler discharge and the diameter of coverage for various nozzles at different pressures.

Equipment needed

The equipment the evaluator needs is:

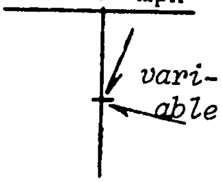
Form VII-1. GUN SPRINKLER OR BOOM IRRIGATION EVALUATION

1. Location *Florida*, Observer *JK*, Date *6/17/70*
2. Crop *Corn*, Root zone depth *4* ft, MAD *--* %, MAD *--* in
3. Soil: texture *medium*, tilth *good*, avail. moisture *2.0* in/ft
4. SMD ℄ : near lateral *3* in, at 1/4 point *4* in at mid-point *2* in
   SMD M : near lateral *2* in, at 1/4 point *2* in at mid-point *2* in
5. Sprinkler: make *Rain Bird*, model *204E*,
   nozzle (taper or ring) *1.3 taper* -inch
6. Sprinkler spacing *260* -ft by *330* -ft, Irrig. duration *4* hrs
7. Design sprinkler discharge *500* gpm at *105* psi giving *0.56* in/hr
8. Actual sprinkler pressure and estimated average discharge:
   initial *105* psi, final *105* psi, ave *105* psi estimated *500* gpm
9. Test layout.



Wind: speed *2 - 6* mph

direction



Note wet or dry areas and sketch the wetting pattern over the circle.

10. Evaporation: initial *100* ml, final *97* ml, loss *3* ml = *.015* in
11. Average catch rates for *2.1* hr test (*200* ml/hr = 1.0 in/hr):

System = (sum all catch totals *15,574* ml) / (number of totals *66*) X (*2.1* hrs) = *112* ml/hr = *0.56* in/hr

Low 1/4 = (sum of low 1/4 catch totals *2349* ml) / (number of low 1/4 totals *17*) X (*2.1* hrs) = *66* ml/hr

= *0.33* in/hr

12. Estimated average rate applied over area:

96.3 X (estimated sprinkler discharge *500* gpm) / sprinkler spacing (*260* ft) X (*330* ft) = *0.56* in/hr

13. Comments (wind drift, runoff, etc.) *no bad wind drift or runoff but some signs of ponding were evident--sprinkle jet did not break up too well!*

Form VII-1 GUN OR BOOM SPRINKLER IRRIGATION EVALUATION (Cont.)

14. Container row test data in units of ml, Volume/depth 200 ml/in

Container spacing: in rows 10 ft, between rows 130 ft

Start 9:30 am, Stop 11:36 am, Duration 2 hr 6 min = 2.10 hr

Lateral spac (ft)	Container Numbers and Catch Volumes								Right/Left Side Totals		M_1 + M_2 plus ℄
	Left side of lateral				Right side of lateral						
	Catch No. Start with number 1 opposite the lateral spacing and number down	M_1 Catch	M_2 Catch	℄ Catch	Catch No. Start with number 1 at bottom of column and number up	M_1 Catch	M_2 Catch	℄ Catch	M_1+M_2 Catch	℄ Catch	Totals
360											
350											
340											
330	1	124	152	230					276	230	506
320	2	135	153	228					288	228	516
310	3	140	157	273					297	273	570
300	4	149	156	317					309	317	626
290	5	153	160	252					313	252	565
280	6	154	165	188					319	188	507
270	7	143	173	191					316	191	507
260	8	133	180	197					313	197	510
250	9	112	192	201					304	201	505
240	10	97	197	207	24				294	207	501
230	11	81	198	237	23			0	279	237	514
220	12	64	193	265	22			10	257	275	532
210	13	52	201	272	21			33	253	305	558
200	14	45	202	279	20	0		64	247	343	590
190	15	36	177	270	19	8	0	92	221	362	583
180	16	23	144	251	18	11	9	105	187	356	543
170	17	11	96	191	17	25	17	112	149	303	452
160	18	5	50	128	16	45	25	123	123	251	374
150	19	0	17	97	15	90	20	132	127	229	356
140	20		9	53	14	125	69	145	203	198	401
130	21		5	14	13	129	116	153	250	167	417
120	22		0	0	12	128	136	144	264	144	408
110	23				11	127	152	135	279	135	414
100	24				10	127	164	116	291	116	407
90					9	125	169	101	294	101	395
80					8	119	167	99	286	99	385
70					7	115	167	100	282	100	382
60					6	112	168	137	280	137	417
50					5	115	161	167	277	167	444
40					4	115	156	153	271	153	424
30					3	117	157	138	274	138	412
20					2	120	153	137	273	137	410
10					1	120	152	169	272	169	441
Sum of all catch totals									15,574		
Sum of low 1/4 catch totals									2,349		3,108

1. A pressure gauge (0-150 psi) with pitot tube attachment (Figure II-4).
2. A stopwatch or watch with an easily visible second hand.
3. From 100 to 200 catch containers (depending on the diameter of coverage) such as 1-quart oil cans or plastic freezer cartons.
4. A 500-ml graduated cylinder to measure volume of water caught in individual containers.
5. A 50- or 100-foot tape for measuring distances in laying out the lines of containers.
6. A soil probe or auger.
7. Manufacturer's sprinkler performance chart that shows the relation between nozzle diameters, discharge, pressure, and wetted diameter plus recommended range of operating pressures.
8. A shovel for smoothing areas to set catch containers and for checking profiles of soil, root, and water penetration.
9. Form VII-1 for recording data.

Field procedure

Fill in the data blanks (Form VII-1) as the field procedure progresses. A good location for the test area is a sprinkler position adjacent to the mainline, where an access road is usually provided. For tall growing crops such as corn, an access road is the most practical location for setting out catch containers. However, since three rows of containers are required, some rows will need to be located directly in the crop.

1. Set out three rows of catch containers across the lateral supply line path. (See Figure VII-3.) One row should be located directly through the sprinkler test position; (the centerline row) the other two rows should cross the lateral supply line path at points midway between the sprinkler test location and the sprinkler locations at either side of it (the M_1 and M_2 rows).

Set the catch containers 10 feet apart in the rows. Containers adjacent to the lateral supply line should be set 5 feet from it on both sides. The outer containers should be at the edges of the anticipated wetted circle. This can be estimated from a sprinkler

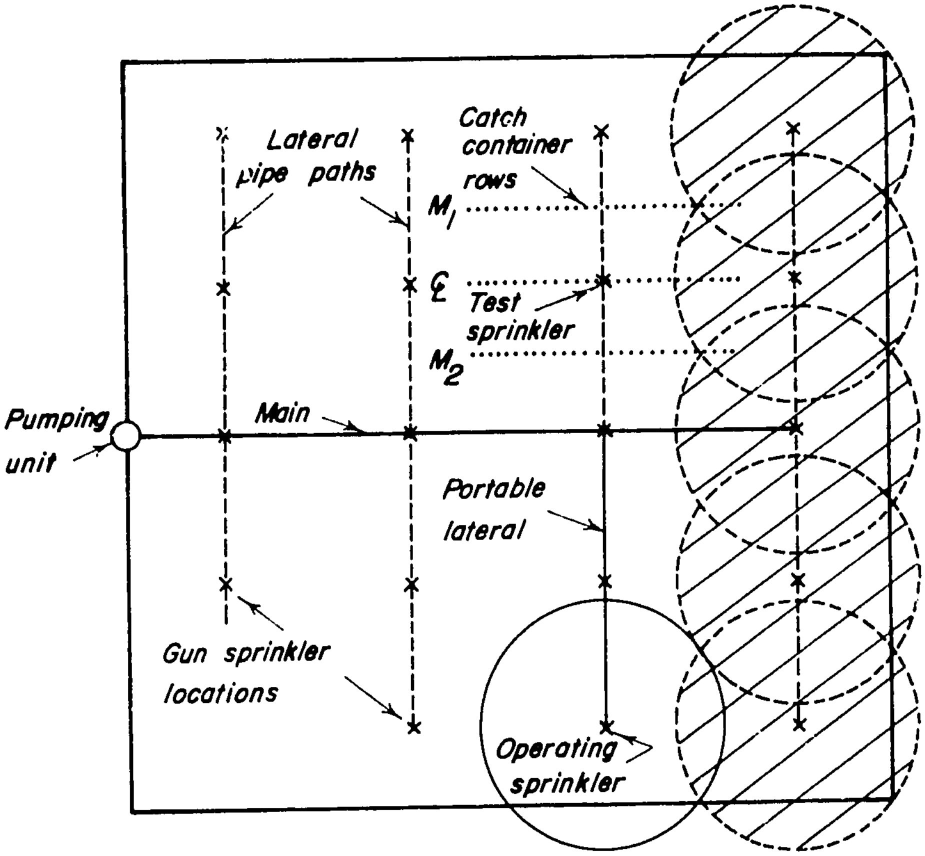


Figure VII-3. Typical gun sprinkler layout, showing location of catch container rows for distribution uniformity evaluations.

that is in operation or that has been in operation recently. It is good practice to provide at least two extra containers on both ends of the container rows to allow for changes in wind direction and speed.

2. Fill in the data blanks about the crop and soil (parts 2 and 3 of Form VII-1).

3. Check *SMD* along the centerline row and one other row of catch containers at the following locations: 10 feet from the lateral supply line; one-fourth of the distance to the next lateral; and midway between the lateral in use and the one to be used next. Enter these *SMD* data in part 4.

4. Note the sprinkler make, model, size, and type of nozzle(s) (orifice ring or taper bore for gun sprinklers). It is a good practice to check the nozzle for erosion or irregularities. Enter this information in part 5. (For boom sprinklers enter the nozzling designation in the blank after nozzle.)

5. Obtain the sprinkler spacing and duration of irrigation. Record these in part 6. Also obtain the design operating pressure and sprinkler discharge from the operator and compute the design application rate. Record this information in part 7.

6. Have the operator set up and turn on one sprinkler at the test location. While he is bringing the sprinkler up to the standard operating pressure, hold the drive mechanism (of gun sprinklers) out of the stream and direct the jet so that no water enters the catch containers. When the sprinkler reaches the normal operating pressure, release it and note the starting time in part 14.

7. Check and record (part 8) the initial and final pressure at the sprinkler nozzle (or tower of a boom sprinkler) and estimate the sprinkler discharge rate from the manufacturer's performance chart.

8. Check the wind direction and estimate wind speed occasionally during the test. Record as shown in part 9 of sample Form VII-1. Also note any irregularities in the wetting pattern.

9. Set outside the wetted area a container holding the anticipated amount of catch to check the volume of water lost by evaporation. (See part 10.)

10. Terminate the test by stopping the sprinkler from rotating when it is in a position where the jet (from gun sprinkler) does not fall into the containers. Note the time, check and record the pressure, and turn off the water. It is most desirable for the duration of the test to be equal to the duration of irrigation to get the full effects of wind and evaporation. Minimum duration tests should apply at least an average of 0.5 inch of water in the containers.

Measure the depth of water in all of the containers and observe whether they are still upright; note any abnormally low or high catches. Part 14 is designed to simplify the procedure of overlapping the catches to simulate a complete irrigation between two adjacent sprinklers along a lateral line and between two lateral lines. To use this form, number the containers from a lateral line outward beginning with 1, 2, 3, etc., to the right and to the left of the lateral supply line. (See Figure VII-3 and the Figure in part 9 of Form VII-1.) Enter the container numbers and catch volumes in part 14 as follows. For the left side data start numbering with container 1 opposite the actual lateral spacing (which for the example field evaluation is 330 feet) and number downward. For the right side data start the numbering with container 1 opposite the lateral spacing of 10 feet and number upward. There are three left-side and three right-side data columns to record the data from the three rows of catch containers.

Utilization of field data

Assuming the test is representative and that all adjacent sprinkler settings would give identical results, the right-hand side of the catch pattern may be overlapped on the left-hand side and the two mid-can (M_1 and M_2) rows overlapped. (See Figure VII-3.)

The overlapped data are an estimate of the profiles of the depth of irrigation water between two lateral pipe paths at two different locations. One is directly between two sprinklers on adjacent laterals and the other is halfway to the next two sprinklers. (See Figure VII-4.) For computations of *DU*, *PELQ*, and *AELQ* (see Chapter I, pp. 11 and 12) to follow, it is assumed that these profiles represent the distribution throughout the field. This assumption is obviously subject to question because of discontinuities at field boundaries, pressure variations, changes of wind direction and speed, and the fact that each data point must represent the uniform catch over a rather large area.

Distribution Uniformity

In order to determine whether a system is operating at acceptable and economic efficiency, the Distribution Uniformity in the central portion of the field should be evaluated. Using the system and low one-quarter average catch rates from the sample test (see Form VII-1, part 11):

$$DU = \frac{0.33}{0.56} X\ 100 = 59\%$$

This is a low but typical value for many supplemental irrigation systems with widely spaced gun sprinklers. It is useful to plot the depth of catch against the distance between supply laterals (Figure VII-4). Such a plot helps to spot problem areas. This plot shows that the mid-sprinkler catch ($M_1 + M_2$) row received more water on the average than the centerline (℄) row. It also indicates that the spacing between sprinklers on the lateral probably was too close and the spacing between laterals was too wide. Typically, the shallowest catch depths are in the areas where diagonal lines drawn between four

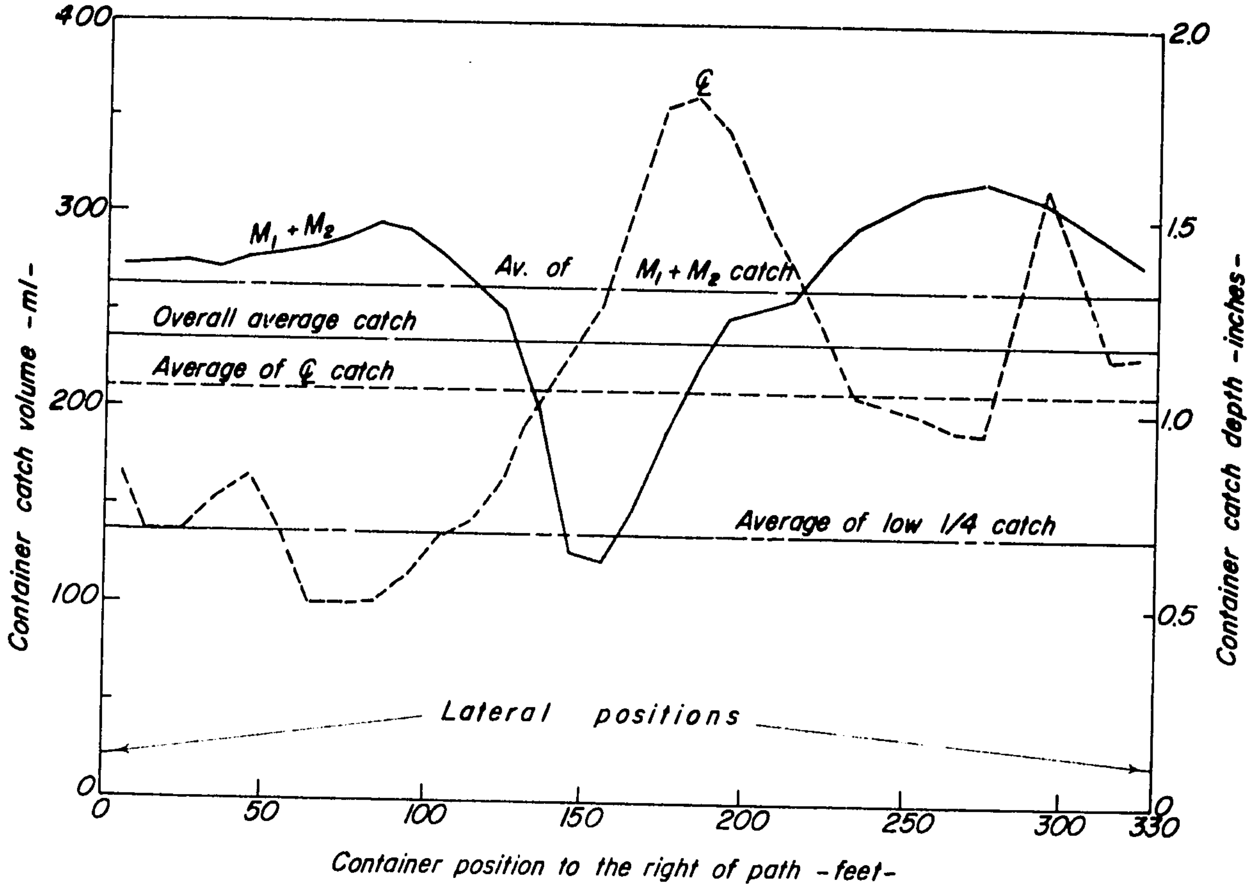


Figure VII-4. Profiles of overlapped catch data for gun sprinkler evaluation.

sprinklers cross. For the sample system the catch in this area fell in the low one-fourth range, as indicated by the dip (below the low quarter catch line) in the $M_1 + M_2$ profile, but other areas along sprinkler center line row were even dryer.

The sample catch data could be used to evaluate a wider spacing between lateral supply lines. Unfortunately a new set of data would need to be collected to represent a wider spacing between sprinklers on the lateral. This is because the mid-rows of containers must pass through the mid-points between sprinklers on the lateral line. (See Figure II-3.)

Alternate sets. It is often desirable to use alternate sets in which the sprinklers are always placed midway between the positions used at the preceeding irrigation. This does not solve the problem of how to water the ends of the field uniformly, in fact alternate setting may aggravate it; however, alternate setting results in a considerably higher *DU* for the complete cycle of two irrigations. This is the same as if all sprinkler positions along the lateral were one-half the normal distance, which for the system evaluated would be 130 feet apart.

To simulate the effect of alternate gun or boom sprinkler settings, the $M_1 + M_2$ and the ℄ total columns in part 14 of Form VII-1 can be added to make a single total column. When this was done for the sample test, the sum of the 8 lowest catch totals was 3108 ml. The sum of all the catch totals still equaled the previous value of 15,574 ml. This simple management program of alternate sets improved the *DU* in the interior of the field from a low of 59% for a single irrigation to:

$$DU' \ (alternate\ set) = \frac{3108/8}{15,574/33} \ X \ 100 = 82\%$$

The alternate set procedure does not compensate for an inadequate irrigation depth that would excessively stress the crop during the interval between the two full irrigations. However, moderate under-irrigation in the mid-area is not detrimental if adequate moisture is applied in the upper portion of the root zone and if irrigations are frequent.

Potential Application Efficiency

The *PELQ* must be determined in order to evaluate how efficiently the system can utilize the water supply and what the total losses may be, then the total amount of water required to irrigate the field can be estimated. The sample data recorded on Form VII-1 show that the average rate applied over the central portion of the field (part 12) was 0.56 iph, so:

$$PELQ = \frac{0.33}{0.56} \ X \ 100 = 59\%$$

This value of *PELQ* is the same as *DU* because the estimated average application rate applied over the area, based on a 260- by 300-foot sprinkler spacing and a 500 gpm discharge, was the same as the average catch rate. Since some water loss by wind drift and evaporation are inevitable (see Form VII-1, part 10), it would be impossible to achieve a catch rate equal to the application rate. The fact that *PELQ* and *DU* are equal results from unavoidable inaccuracy that is caused by having to estimate discharges and by having only a minimum number of catch containers.

Application Efficiency

Effectiveness of the use of the system can be estimated by measuring how much of the applied water is supplied to the soil and is available for consumptive use. The farmer applied weekly irrigations to the field which was studied in the sample evaluation (whenever it did not rain), and he had never thought about the concept of *MAD* for scheduling purposes. In checking the field, it was found the *SMD* ranged between 2 and 4 inches. (See Form VII-1, part 4.) With 4-hour irrigations, the minimum depth applied was 4 x 0.33 = 1.32 inches. Hence, no water was lost to deep percolation; in fact, areas that received the minimum depth were considerably underirrigated and *AELQ* = *PELQ* = 59%.

Analysis and recommendations

Observations and some recommendations that can be made from the additional data on Form VII-1 and the computations of *DU* and *PELQ* have already been reported here and in other sprinkler evaluation sections.

Operational checks. The pressure of 105 psi at the nozzle is ideal for good breakup of drops. The taper bore nozzle was smooth and produced a very clean stream of water.

Runoff. Some surface ponding began at the end of a 4-hour irrigation. This is quite typical for the high application rates associated with large gun sprinklers. Although there was no runoff, the ponding indicated that the length of set was about maximum for the soil infiltration conditions.

Underirrigation. This gun sprinkler system was designed to provide supplemental irrigation at an application rate of approximately 1.5 inches every week when there was no rain. Although underirrigation was considerable, there was a 90% probability of sufficient rain before the *SMD* became large enough over an area sufficient to create substantial crop loss. Furthermore, the system was being operated for only 16 hours a day for 5 days a week; if it did not rain, almost twice as much water could be applied by full-time operation of the system.

Improvements. Use of alternate sets would greatly improve *DU* and consequently *PELQ*. Because of considerable over-throw along the top and bottom ends of the field, the alternate sets would not create any more problem of end uniformity than already existed. Using alternate sets could raise the *PELQ* to 82% and would make the *SMD* more uniform throughout the field by filling in the low spots of the application. The uniformity along the boundaries of the field could be greatly improved by using half-circle sprinkler setting at the ends of the laterals in conjunction with alternate sets. This would require 6 settings along each lateral position for every other irrigation; but since the application rate would be double, the irrigation could be cut in half (to 2 hours) when the sprinkler was set to irrigate half-circles on the lateral ends. (See Figure VII-3.)

The application uniformity was poor along the sides of the field. The only way to improve the situation would be to use the half-circle sprinkler patterns on laterals laid along each side and full circle sprinklers along 3 laterals positions through the center of the field. (See Figure VII-3.)

Other possible improvements might be tried in the following order:

1. Change the taper bore nozzle to an orifice type nozzle. This would give better jet break up and would produce more fallout near the sprinkler where the deficits are now greatest.

2. The spacing between sprinkler settings on the supply lateral line could be increased to 330 feet to give four instead of five sprinkler wets in 1320 feet. (See Figure VII-1.)

Edge effects. The *PELQ* of 59% computed earlier was for the central portion of the field. However, there is no overlap from adjacent sprinklers around the boundaries of the field. Furthermore, the water which falls outside of the boundaries is lost. (See Figure VII-3.) These two boundary or edge effects reduce the overall *PELQ*. For the 40-acre field evaluated, the overall *PELQ* was only estimated to be 52%. By using alternate sets as described on page 115 the edge losses would only occur along the boundaries parallel to the lateral paths and the overall alternate set *PELQ* would be approximately 78%.

Summary

The *DU* and *PELQ* of 59% computed in the evaluation show typical performances of supplemental irrigation systems using widely spaced gun sprinklers on corn. The main problems of the system are associated with a poor *DU* in which the driest part of the wetting pattern is near the sprinkler. Using alternate sets improved the *DU* and *PELQ* to 82%, a very high value. However, the uniformity of wetting along the field boundaries would still be low. Using an orifice type nozzle and/or increasing the spacing between sprinklers along the supply lateral may increase the *DU* without using alternate sets and should be evaluated.

CHAPTER VIII
TRICKLE IRRIGATION

Trickle irrigation, sometimes called "drip" irrigation, is a system for supplying filtered water and sometimes fertilizer, directly onto or into the soil.

General operation

In trickle irrigation water is dissipated from a pipe distribution network under low pressure in a predetermined pattern. The outlet device that emits water to the soil is called an "emitter." Figure VIII-1 shows a typical lateral hose for supplying water to a row of trickle irrigation emitters; it is lying on the soil surface along a row of young trees. Emitters dissipate the pressure in the pipe distribution networks by means of a narrow nozzle or long flow path and thereby decrease the water pressure to allow discharge of only a few gallons per hour. After leaving the emitter at an emission point, water flows through the soil profile by capillarity and gravity; therefore, the area that can be watered from each emitter source point is limited by the constraints of the water's horizontal flow. Trickle systems can be operated daily, or less frequently, if desired.

For wide-spaced permanent crops such as trees and vines, emitters are individually manufactured units that are attached by a barb to a flexible supply line called the "emitter lateral," "lateral hose," or "lateral." Some emitters have more than one outlet to supply water through small diameter "spaghetti" tubing to two or more emission points. This is done to obtain a larger wetted area with a minimum increase in cost. For less permanent row crops such as tomatoes, sugar cane, and strawberries, the lateral with emitter outlets is manufactured as a disposable unit having either perforations spaced every 9 to 36 inches, as in bi-wall tubing, or having porous walls from which water oozes. For both types of trickle systems, the laterals are connected to supply lines called the "manifolds." Figure VIII-2 shows the layout of a typical trickle irrigation system.

Trickle irrigation is a most convenient means of supplying each plant, such as a tree or vine, with a low-tension supply of soil moisture that is sufficient to meet demands imposed by evapotranspiration. A trickle irrigation system offers unique agronomical, agrotechnical, and economical advantages for efficient use of water

Figure VIII-1. Trickle irrigation lateral hose in a young orchard.

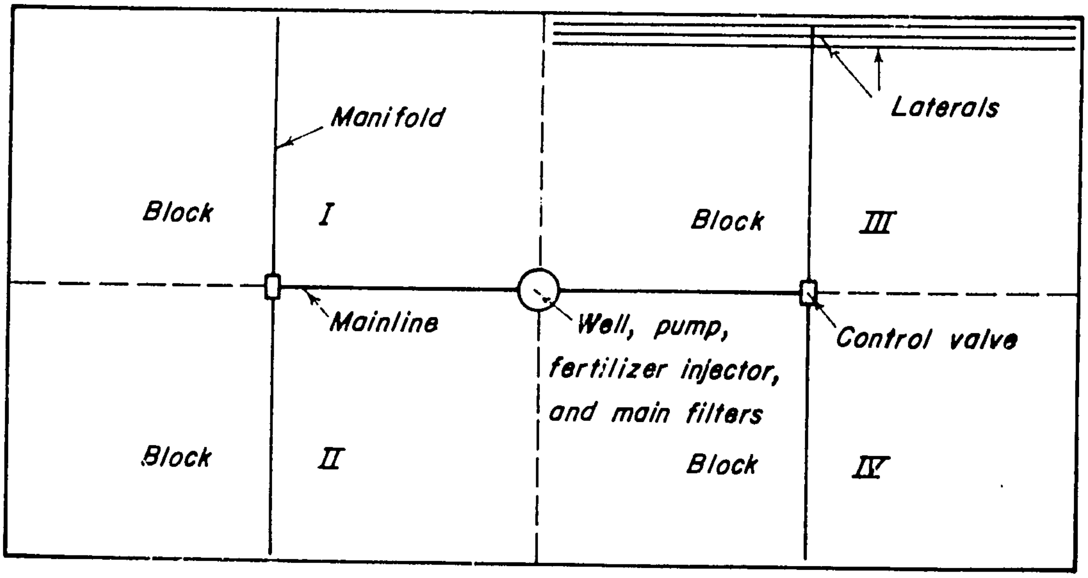


Figure VIII-2. Typical layout for trickle irrigation system.

and labor. The main disadvantages inherent in trickle irrigation systems are their comparatively high cost, their proneness to clogging, their tendency to build up local salinity, and where improperly designed, their too partial and spotty distribution of soil moisture.

Clogging. Clogging of emitters is the most difficult problem encountered in using trickle irrigation systems. The most common cause of clogging is presence of mineral and organic particles in the water supply. Filtration of the water and preventing contaminants from entering or forming within the system is the best defense against clogging for it is difficult to detect and expensive to clean or replace a clogged emitter. Figure VIII-3 shows a typical trickle irrigation filtration system of three sand filters followed by a bank of four screen filters.

Another common cause of clogging is the precipitation of calcium or the products of iron bacteria due to the presence of dissolved calcium and/or iron salts in the water supply. Periodic chemical treatment of the water supply is a good defense against slow clogging or plugging due to precipitates.

Figure VIII-3. Typical bank of sand filters followed by screen filters for a trickle irrigation system.

Clogging sometimes causes poor distribution along the laterals; this may damage a crop severely if emitters are clogged for a long time before they are discovered and cleaned or repaired. Normally the main bank of filtration and chemical injection equipment is located at the pumping plant. In addition, it is useful to include screens near the inlet of each hose as an additional safety factor. These screens stop any debris that entered the line during the cleaning of the main filters or during the repair of breaks in the mainline.

Fertilizer injection. Under trickle irrigation, the water does not leach the fertilizer spread or broadcast over the soil surface into the root zone; therefore, it is necessary to add much of the required fertilizer, especially nitrogen, directly to the irrigation water. Ordinarily, phosphorus fertilizers cannot be added to the water because they precipitate out in the top few inches of soil and are difficult to incorporate into the root zone except by mechanical means.

Application of potassium through the irrigation water causes no particular problems. Potassium oxide, the most common form, is very soluble and moves freely into the soil; the potassium molecules become exchanged on the soil complex and are not readily leached away.

Most nitrogen fertilizers are quite soluble, but applying nitrogen through the irrigation water requires some precautions. Ammonia fertilizers change the pH of the water and may cause precipitation of soluble calcium in the water. This precipitation coats the inside of pipes and plugs emitters. The safest nitrogen fertilizers to apply through a trickle system are ammonium sulfate, ammonium nitrate, or urea. These do not change the pH of the water and do not cause precipitation. All nitrogen fertilizers, however, are subject to being leached from the soil root zone; consequently, care must be taken to prevent them from being lost by overirrigation.

Irrigation depth and interval. Since trickle irrigation wets only part of the soil volume as orchard sprinkler systems do, the method for determining both the desirable depth or volume of application per cycle of trickle irrigation and the irrigation interval is unique.

The *MAD* at which irrigation should be started depends on the soil, the crop, and the water-yield-economic factor. Since this relationship cannot be expressed quantitatively, the *MAD* in most soils may be assumed as 30% for drought-sensitive crops and as much as 60% for nonsensitive crops.

The *percentage of wetted area (P)* as compared to the entire cropped area depends on discharge at each emission point, emission point spacing, and the type of soil being irrigated. (See Figure VIII-4.) The area wetted by each emission point is usually quite small at the soil surface; and *P* is determined from an estimate of the average area wetted at a depth of about 12 inches under the emitters divided by the cropped area served by the emitters.

No single right or proper minimum value for *P* has yet been established. However, one can conclude that systems having high *P* values provide more stored water (a valuable protection in case of system failure) should be easier to schedule and bring more of the soil system into action for storage and supply of nutrients. For the

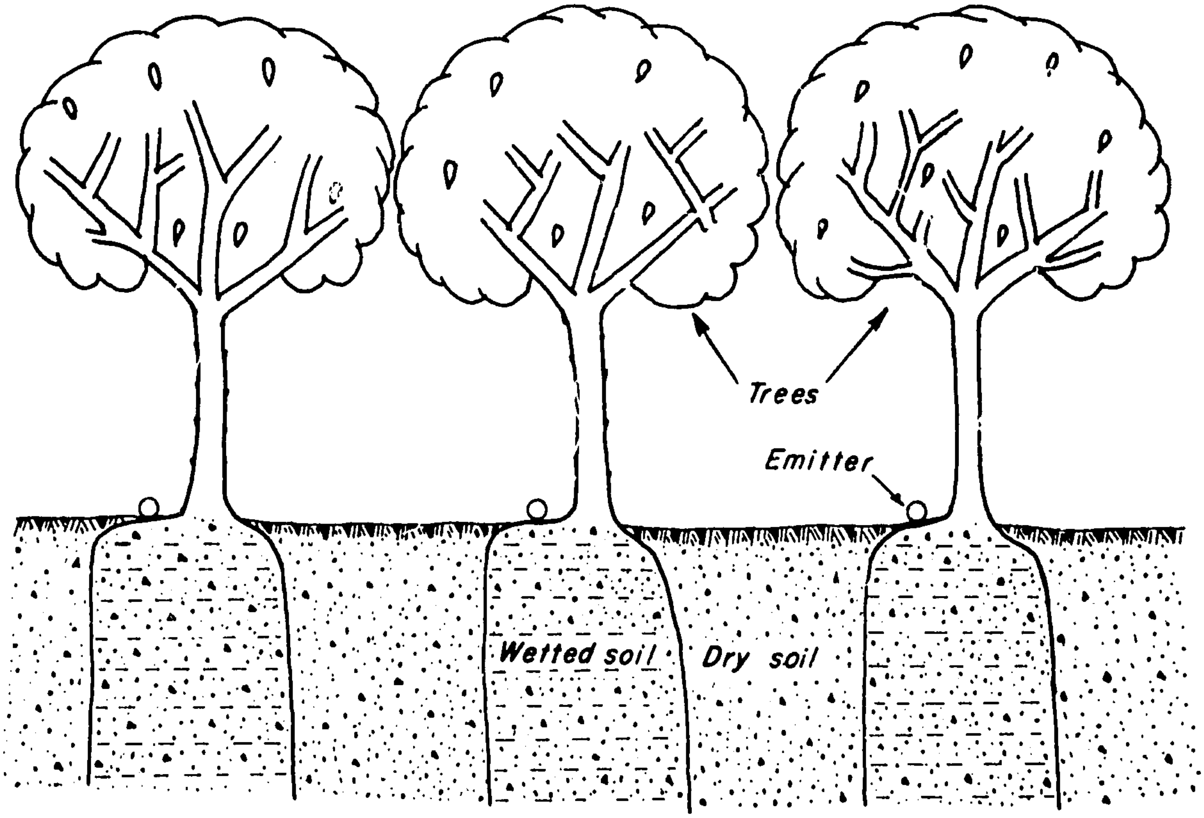


Figure VIII-4. Typical wetting pattern under trickle irrigation showing approximately 50 percent of the cross sectioned root area wetted.

current state of knowledge, a reasonable design objective for arid regions is to wet at least one-third ($P = 33\%$) and up to one-half of a cropped area. In regions that receive considerable supplemental rainfall, values in the neighborhood of $P = 20\%$ are acceptable. On the other hand, P should be held below 50 or 60% in widely spaced crops because one advantage of trickle irrigation is that it keeps the strips between rows of trees or vines relatively dry for cultural practices which also reduces water losses due to evaporation. Also capital costs increase with a larger coverage so economics favor the smaller percentage.

Evaluation

Use of much of the information that follows depends upon an understanding of the utilization of the field data and analysis that was presented on orchard sprinklers in Chapter IV. The data needed for evaluating a trickle irrigation system are available by determining:

1. Duration, frequency, and sequence of operation of normal irrigation cycle.
2. The *SMD* and *MAD* in the wetted volume.
3. Rate of discharge at the emission points and the pressure near several emitters spaced throughout the system.
4. Changes in rate of discharge from emitters after cleaning or other repair.
5. The percent of soil volume wetted.
6. Spacing and size of trees or other plants being irrigated.
7. Location of emission points relative to trees, vines, or other plants and uniformity of spacing of emission points.
8. Losses of pressure at the filters.
9. General topography.
10. Additional data indicated on Form VIII-1.

Equipment needed

The equipment needed for collecting the necessary field data is:

1. Pressure gauge (0-50 psi range) with "T" adapters for temporary installation at either end of the lateral hoses.

2. A stopwatch or watch with an easily visible second hand.

3. Graduated cylinder with 250 ml capacity.

4. Measuring tape 10 to 20 feet long.

5. Funnel with 3- to 6-inch diameter.

6. Shovel and soil auger or probe.

7. Manufacturer's emitter performance charts showing the relationships between discharge and pressure plus recommended operating pressures and filter requirements.

8. Sheet metal or plastic trough 3 feet long for measuring the discharge from several outlets in a perforated hose simultaneously or the discharge from a 3-foot length of porous tubing. (A piece of 1- or 2-inch PVC pipe cut in half lengthwise makes a good trough.)

9. Copies of Form VIII-1 for recording data.

Field procedure

The following field procedure is suitable for evaluating both systems with individually manufactured emitters and systems that use perforated or porous lateral hose. Fill in the data blanks of From VIII-1 while conducting field procedure.

1. Fill in parts 1, 2, and 3 of Form VIII-1 concerning the general soil and crop characteristics throughout the field.

2. Determine from the operator the duration and frequency of irrigation and his concept of the *MAD* to complete part 4.

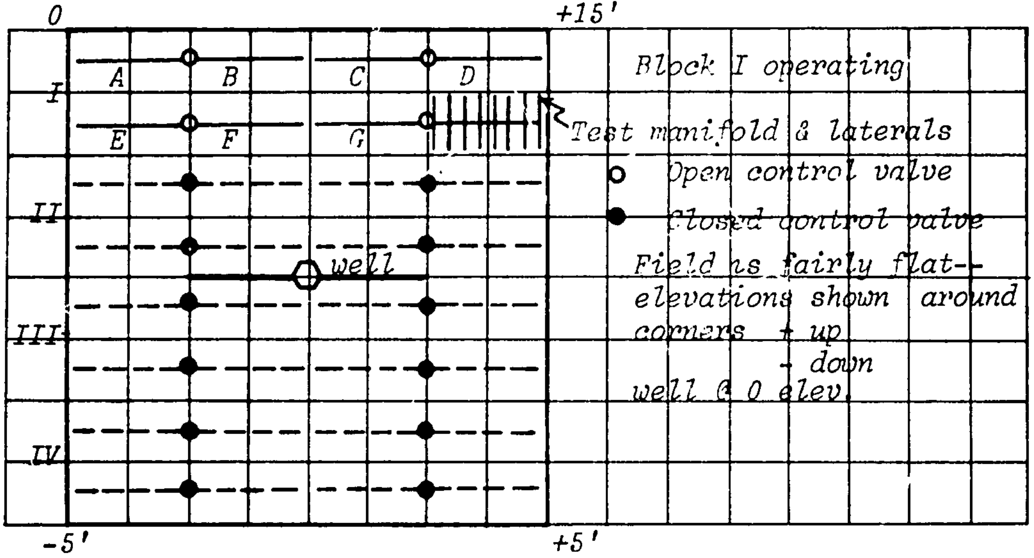
3. Check and note in part 5 the pressures at the inlet and outlet of the filter and, if practical, inspect the screens for breaks and any other possibility for contaminants to bypass the screens.

4. Fill in parts 6, 7, and 8 which deal with the emitter and lateral hose characteristics. (When testing perforated or porous tubing the discharge may be rated by the manufacturer in flow per unit length.)

5. Locate four emitter laterals along an operating manifold (see Figure VIII-2); one should be near the inlet and two near the

Form VIII-1. TRICKLE IRRIGATION EVALUATION

1. Location *Ranch 14*, Observer *JK*, Date *8-1-1971*
2. Crop: type *Citrus*, age *7* years, spacing *22*-by *22* -feet
   root depth *4* ft, percent area covered or shaded *70* %
3. Soil: texture *silt loam*, available moisture *2.0* in/ft
4. Irrig: duration *6* hrs, frequency *1* days, MAD *10%*, *.8* in
5. Filter pressure: inlet *60* psi, outlet *55* psi, loss *5* psi
6. Emitter: make *SP*, type *flushing* point spacing *5* ft
7. Rated discharge per emission point *3.0* gph at *30* psi
   Emission points per plant *4*, giving *72* gallon per plant per day
8. Hose: diameter *0.58* in, material *PVC*, length *150* ft, spacing *22* ft
9. System layout, general topography, and test locations:



10. System discharge *--* gpm, No. of manifolds *32* and blocks *4*
11. Average test manifold emission point discharges at *45* psi

$$\text{Manifold} = \frac{(\text{sum of all averages } 41.94 \text{ gph})}{(\text{number of averages } 16)} = 2.62 \text{ gph}$$

$$\text{Low } 1/4 = \frac{(\text{sum of low } 1/4 \text{ averages } 9.07 \text{ gph})}{(\text{number of low } 1/4 \text{ averages } 4)} = 2.27 \text{ gph}$$

12. Adjusted average emission point discharges at *46.1* psi
    System = (DCF *1.012*) X (manifold average *2.62* gph) = *2.65* gph
    Low 1/4 = (DCF *1.012*) X (manifold low 1/4 *2.27* gph) = *2.30* gph
13. Comments: *Trees looked as if they were not receiving enough water! Urea was being injected. Filter system seemed okay.*

Form VIII-1. TRICKLE IRRIGATION EVALUATION (Cont.)

14. Discharge test volume collected in 1.0 min (1.0 gph = 63 ml/min)

Outlet Location on Lateral		Lateral Location on the Manifold							
		inlet end		1/3 down		2/3 down		far end	
		ml	gph	ml	gph	ml	gph	ml	gph
inlet end	A	132	2.10	160	2.54	192	3.04	195	3.10
	B	160	2.54	188	2.99	140	2.23	205	3.26
	Ave		2.32		2.77		2.64		3.18
1/3 down	A	160	2.54	295	3.10	175	2.78	169	2.69
	B	168	2.66	158	2.50	170	2.70	180	2.86
	Ave		2.60		2.80		2.74		2.78
2/3 down	A	187	2.97	146	2.31	125	1.99	144	2.29
	B	175	2.78	155	2.46	155	2.46	175	2.78
	Ave		2.88		2.38		2.23		2.54
far end	A	170	2.70	190	3.02	210	3.34	151	2.39
	B	125	1.99	135	2.15	166	2.62	130	2.07
	Ave		2.34		2.58		2.98		2.18

15. Lateral inlet	47.5 psi	45.0 psi	45.5 psi	45.0 psi
closed end	46.0 psi	43.5 psi	45.0 psi	44.0 psi
16. Wetted area	150 ft^2	125 ft^2	140 ft^2	145 ft^2
per plant	31 %	26 %	29 %	30 %

17. Estimated average SMD in wetted soil volume -- in

18. Minimum lateral inlet pressures, MLIP, on all operating manifolds:

Manifold:	Test	A	B	C	D	E	F	G	Ave.
Pressure-psi:	45	49	47	43	42	50	48	45	46.1

19. Discharge correction factor, DCF, for the system is:

$$DCF = \frac{2.5 \times (\text{average MLIP } 46.1 \text{ psi})}{(\text{average MLIP } 46.1 \text{ psi}) + 1.5 \times (\text{test MLIP } 45 \text{ psi})} = 1.015$$

or if the emitter discharge exponent x = 0.5 is known

$$DCF = \left[\frac{(\text{average MLIP } 46.1 \text{ psi})}{(\text{test MLIP } 45 \text{ psi})} \right]^{x = 0.5} = 1.012$$

"third" points, and the fourth near the outer end. Sketch the system layout and note in part 9 the general topography, manifold in operation, and manifold where the discharge test will be conducted.

6. Record the system discharge rate (if the system is provided with a water meter) and the numbers of manifolds and blocks (or stations). The number of blocks is the total number of manifolds divided by the number of manifolds in operation at any one time.

7. For laterals having individual emitters, measure the discharge at two adjacent emission points (denoted as A and B in part 14) at each of four different tree or plant locations on each of the four selected test laterals. (See Figure VIII-5.) Collect the flow for a number of full minutes (1, 2, 3, etc.) to obtain a volume between 100 and 250 ml for each emission point tested. Convert each reading to ml per minute before entering the data in part 14 on Form VIII-1. To convert ml per minute to gallons per hour (gph), divide by 63.

These steps will produce eight pressure readings and 32 discharge volumes at 16 different plant locations for individual emission points used in wide-spaced crops with two or more emission points per plant.

For perforated hose or porous tubing, use the 3-foot trough and collect a discharge reading at each of the 16 locations described above. Since these are already averages from 2 or more outlets, only one reading is needed at each location.

For relatively wide-spaced crops such as grapes where one single outlet emitter may serve one or more plants, collect a discharge reading at each of the 16 locations described above. Since the plants are only served by a single emission point, only one reading should be made at each location.

8. Measure and record in part 15 the water pressures at the inlet and downstream ends of each lateral tested in part 14 under normal operation. On the inlet end, this requires disconnecting the lateral hose, installing the pressure gauge, and reconnecting the hose before reading the pressure. On the downstream end, the pressure can be read after connecting the pressure gauge the simplest way possible.

9. Check the percentage of the soil that is wetted at one of the tree locations on each test lateral and record in part 16. It is best to select a tree at a different relative location on each lateral. Use the probe, soil auger, or shovel--whichever seems to work best--for estimating the real extent of the wetted zone about 6 to 12 inches below the surface around each tree. Determine the percentage

Figure VIII-5. Field measurement of emitter discharge.

wetted by dividing the wetted area by the total surface area between four trees.

10. If an interval of several days between irrigations is being used, check the SMD in the wetted volume near a few representative trees in the next block to be irrigated and record it in part 17. This is difficult and requires averaging samples taken from several positions around each tree.

11. Determine the minimum lateral inlet pressure, MLIP along each of the operating manifolds and record in part 18. For level or uphill manifolds the MLIP will be at the far end of the manifold. For downhill manifolds it is often about two-thirds down the manifold. The manifolds on undulating terrain it is usually on a knoll or high point.

12. Determine the discharge correction factor, DCF, to adjust the average emission point discharges for the tested manifold. This adjustment is needed if the tested manifold happened to be operating with a higher or lower MLIP than the system average MLIP. If the emitter discharge exponent, x, is known, use the second formula presented in part 19.

13. Determine the average and adjusted average emission point discharges according to the equations in parts 11 and 12 of Form VIII-1.

Utilization of field data

In trickle irrigation all the system flow is delivered to individual trees, vines, shrubs, or other plants. Essentially there is no opportunity for loss of water except at the tree or plant locations. Therefore, uniformity of emission is of primary concern, assuming the crop is uniform. Locations of individual emission points, or the tree locations when several emitters are closely spaced, can be thought of in much the same manner as the container positions in tests of sprinkler performance.

There are four single emission point emitters per tree in the citrus grove where this test was conducted to obtain the data given in Form VIII-1. Therefore, the discharges from the two (A and B) emitters at each tree can be averaged. The minimum rate of discharge (or low 1/4) is then the adjusted average discharge of the lowest four of these (average) discharges per tree of 2.30 gph for the sample evaluation. The adjusted average rate of discharge per tree for the entire system was 2.65 gph. (See Form VIII-1, part 12.)

Average application depth. The average depth applied per irrigation to the wetted area, D_{aw}, is useful for estimating *MAD*. The D_{aw} in inches is computed from the average gph at each emission point, the number, N, of emission points per tree, the number of hours of operation per irrigation, and the area wetted per tree in feet^2:

$$D_{aw} = \frac{1.605 \times N \times gph \times hours}{feet^2}$$

which for the sample evaluation (Form VIII-1, parts 2, 4, 7, 12, and 14) is:

$$D_{aw} = \frac{1.605 \times 4 \times 2.65 \times 6}{140} = 0.73 \text{ inch}$$

The overall average depth applied, D_a, in inches can be found by substituting the tree spacing for the wetted area in the formula immediately preceding. Therefore:

$$D_a = \frac{1.605 \times 4 \times 2.65 \times 6}{22 \times 22} = 0.21 \text{ inch}$$

Volume per day per tree. The average number of gallons per day per tree or plant is computed from the average gph at each emission point, the number N of emission points per tree, the number of hours of operation per irrigation, and the irrigation interval in days:

$$\text{Average daily gallons per tree} = \frac{N \times gph \times hours}{days}$$

which for the sample evaluation (Form VIII-1, parts 4, 7, and 12) is:

$$\text{Average daily gallons per tree} = \frac{4 \times 2.65 \times 6}{1} = 63.6 \text{ gallons/day}$$

Emission Uniformity

In order to determine whether the system is operating at acceptable efficiency, evaluate the uniformity of emission by calculating EU by this formula:

$$EU = \frac{\text{minimum rate of discharge per plant}}{\text{average rate of discharge per plant}} \times 100$$

in which the average of the lowest quarter (Form VIII-1, part 12) is used as the minimum for each of the four emitters per plant:

$$EU = \frac{4 \times 2.30}{4 \times 2.65} \times 100 = 87\%$$

General criteria for EU values for systems which have been in operation for one or more seasons are: greater than 90%, excellent; between 80% and 90%, good; 70 to 80%, fair; and less than 70%, poor.

Potential Application Efficiency

The concept of *PELQ* used in other evaluation procedures must be modified when evaluating trickle irrigation systems, which wet only part of the area because the minimum depth would be zero. Since trickle irrigation wets only a small portion of the soil volume, the *SMD* must be replaced frequently. It is always difficult to estimate *SMD* because parts of the wetted portion of the root zone often remains near field capacity even when the interval between irrigation is several days.

For the sample evaluation where irrigations are applied every day, it is practically impossible to estimate *SMD*. For this reason, *SMD* must be estimated from weather data or information derived from evaporation devices. Such estimates are subject to error and since there is no practical way to check for slight underirrigation, some margin for safety should be allowed. As a general rule, about 10% more water than the estimated *SMD* or evapotranspiration should be applied to the least watered areas. Thus the *PELQ* under full trickle irrigation can be estimated by:

$$PELQ = 0.9 \times EU$$

which for the sample test data shown in Form VIII-1 is

$$PELQ = 0.9 \times 87\% = 78\%$$

In a trickle irrigation system, there are no field boundary effects or pressure variations along the manifold tested which are not taken into account in the field estimate of *EU*. Therefore, the estimated *PELQ* is an overall value for the manifold in sub-unit tested except for possible minor water losses due to leaks, draining of lines, and flushing (unless leaks are excessive).

Some trickle irrigation systems are fitted with pressure compensating emitters or have pressure (or flow) regulation at the inlet to each lateral. However, most systems are only provided with a means for pressure control or regulation at the inlets to the manifolds as was the case with the system evaluated. If the manifold inlet pressures are not properly set, the overall system *PELQ* will be lower than the *PELQ* of the tested manifold. An estimate of this efficiency reduction factor, *ERF*, can be computed from the minimum lateral inlet pressure, *MLIP*, along each manifold by:

$$ERF = \frac{\text{average MLIP} + 1.5 \text{ X minimum MLIP}}{2.5 \text{ X average MLIP}}$$

The ratio between the average emission point discharges in the manifold with the minimum pressure and the system is approximately equal to *ERF*. Therefore, the system *PELQ* can be approximated by:

$$\text{System PELQ} = \text{ERF X Test PELQ}$$

Using the data in Form VIII, part 18, and the test *PELQ* of 78%,

$$ERF = \frac{46.1 + (1.5 \text{ X } 42)}{2.5 \text{ X } 46.1} = 0.95$$

and

$$\text{System PELQ} = 0.95 \text{ X } 78\% = 74\%$$

A more precise method for estimating the *ERF* can be made if the emitter discharge exponent, x, is known by

$$ERF = \left(\frac{\text{minimum MILP}}{\text{average MILP}}\right)^{x}$$

For the tested system with orifice type emitters, which have an x of 0.5, this alternative calculation of *ERF* gives:

$$ERF = \left(\frac{42}{46.1}\right)^{0.5} = \sqrt{\frac{42}{46.1}} = .95$$

In this case the two methods for computing *ERF* give essentially equal results; however, for larger pressure variations or x values higher or lower than 0.5, the differences could be significant.

Application Efficiency

Like *PELQ*, the concept of *AELQ* must also be modified for trickle irrigation. Effectiveness of a trickle system can be estimated by how much of the applied water is stored in the root zone and is available for consumptive use by the plants. Since there are essentially no opportunities for losses due to evaporation and drift, for inadequate irrigation in which the least watered areas are underirrigated:

$$\text{System } AELQ = ERF \times \text{Test } EU$$

However, if excess water is applied in the least watered areas:

$$\text{System } AELQ = \frac{SMD \text{ in wetted area}}{\text{average depth applied to wetted area}} \times 100$$

for an ideal irrigation in which the *SMD* plus 10% extra water is applied to the least watered areas, *AELQ* = *PELQ*.

For the evaluation shown on Form VIII-1 where daily irrigations were being applied, it was impossible to estimate *SMD* in the wetted areas around each tree. Furthermore, the average depth applied to the total area, D_a, was only 0.21 inch per day which is hardly sufficient to meet the expected consumptive use requirements for mature citrus trees at the study location. Therefore, it is highly probable that the trees were being underirrigated, in which case for the test *EU* of 87%:

$$\text{System } AELQ = 0.95 \times 87 = 83\%$$

Overall minimum depth applied. The overall average depth applied to the total area, D_a, multiplied by *System PELQ (or AELQ)* is useful for managing the irrigation schedule because water requirements are expressed in similar units. (Multiply by the *System PELQ* except when there is underirrigation and *AELQ* is greater than *PELQ*.) For the sample evaluation the overall minimum depth applied to the total area, D_n, is:

$$D_n = D_a \times \text{System } PELQ \text{ (or } AELQ)/100$$

which for the sample evaluation which is underirrigated and has *System PELQ* and *AELQ* values of 74% and 83%, respectively, is:

$$D_n = 0.21 \times 83/100 = 0.17 \text{ inch}$$

Analysis and recommendations

Several observations and some recommendations can be based on the additional data on Form VIII-1 and the computations of *EU*, *PELQ*, and *AELQ*.

The *pressure* differences throughout the operating manifold studied were very small. (See Form VIII-1, part 15.) Pressure variations of 20% for orifice-type emitters and 10% for the long tube type result in flow differences of about 10%. Obviously it is important that each control valve be adjusted accurately to insure uniform pressures throughout the orchard. However, this was not the case as noted by the minimum lateral inlet pressure variations between manifolds as indicated in part 18 of Form VIII-1.

Uniformity of application throughout the operating manifold, expressed by the *EU* of 87%, was good. Since the pressures were very nearly constant, it appears that most of the lack of uniformity of application resulted from variations in operation of the individual emitters. This can be verified by studying the table on Form VIII-1, part 14. The discharges of emitters A and B at the same location, which would have almost identical pressures, often differed considerably.

Differences in *elevation* throughout the system were not extreme so the other manifolds should have produced similar uniformities. (See Form VIII-1, part 9.)

The *percentage of wetted area* ranged between 26% and 31% (Form VIII-1, part 12); this was less than the recommended minimum discussed in the introduction for arid areas.

For the *fertilizer application* program, urea was being injected into the irrigation water. Other fertilizers were being applied directly to the soil surface and incorporated by cultivation in the fall prior to the winter rainy season. This fertilizer program should prove satisfactory and cause no problem with the irrigation equipment.

Emitters. The emitters used in the recorded test were the automatic flushing type. The variations in discharge reported above probably were due to differences in manufacturing tolerance. These emitters, operating at pressures near 45 psi, averaged a discharge of 2.62 gph (Form VIII-1, parts 6, 11 and 15), which is considerably less than the rated 3.0 gph at 30 psi and indicates that the orifices may have been closing slowly or clogging after about one season's operation.

Variable clogging can cause large differences in flow from non-flushing emitters even though manufacturing tolerances may be very close. Some emitters can be flushed manually. Systems having manually flushed emitters should be checked monthly to determine the amount of change in flow before and after flushing.

Some multiple outlet emitters have a separate pressure dissipating channel for each outlet and thus the discharges at each emission point are independent. Other multiple outlet emitters have a single pressure dissipating channel discharging into the several outlets. With such emitters, the discharges through each outlet tube are usually erratic due to small elevation differences and blockage in the spaghetti tubes.

Filters. The filter system near the pumping plant seemed to be performing reasonably well. Apparently, it was not seriously clogged at the time of the check since the loss of pressure across it was only 5 psi (Form VIII-1, part 5). Small safety screen filters were installed at the inlet to each lateral hose. This precaution is recommended. Several of these screens were checked at random and all were reasonably clean; however, several screens had intercepted a considerable amount of coarse materail that would have clogged some emitters if it had passed through the laterals. The operator said he routinely cleans each safety screen after very 1000 hours of operation.

Improvements. A major improvement would be to increase the percent of wetted raea. This could be achieved by increasing the interval between irrigations to 2 days or by adding one or two emitters at each tree and decreasing the operating pressure accordingly.

Changing to a 12-hour irrigation on alternate days instead of continuing the present 6 hours per day could improve the percent of wetted area because longer applications wet more soil volume. No problems of infiltration were apparent, and the average depth applied to the wet area, D_{aw} of 0.73 inch, could easily be doubled without exceeding the *SMD* at an *MAD* of 30%. For example, for the 4-foot root depth and 2 inches per foot of available moisture, a total of 8 inches of moisture would be available. The depletion of 2 X 0.73 = 1.46 inch gives an *MAD* of less than 20% in the wetted area.

The manifold inlet valves should be adjusted to give the same minimum lateral inlet pressure on each manifold. This would increase the *System PELQ and AELQ* to the *PELQ* and *AELQ* of the tested manifold which is a 5% improvement.

It appears that emission from the lateral hoses had been gradually decreasing and that the system was designed to yield greater flow than was observed. Thus, adding emitters could restore the system's capacity to the original 12 gph per tree at an average operating pressure of 30 psi and increase the percentage wetted area to almost 40%.

The only way to improve *EU* would be to replace the emitters; this would be very expensive and is not now warranted.

The overall minimum depth applied to the total area, D_n, (only 0.17 inch per daily cycle) seems to be marginal for a mature orchard during the peak period of water demand. Although emitters were rated at 3.0 gph when operated at 30 psi, the test results in the field indicated that average rate of flow was only 2.62 gph at 45 psi; to meet the peak demands for water, the flow rate per tree would have to be restored to the original design of 12 gph (four emitters at 3 gph) by cleaning or otherwise repairing the emitters, by increasing the operating pressure, or by adding another emitter to the system at each tree.

Summary

The *EU* of 87% and estimated *PELQ* of 78% of the tested manifold are good. The main system problems are associated with a marginal amount of soil wetted (only about 30%), poor manifold control valve adjustment, and low rates of flow in the system. The operator was advised to try scheduling the irrigation to apply water for 12-hour periods on alternate days instead of continuing the current 6 hours per day cycling. He was also urged to (a) adjust the manifold control valves to obtain equal minimum lateral inlet pressures on all manifolds; and (b) to clean or repair the emitters or to add an extra emitter at each tree to restore flow rates to the designed volume and to increase the percent of wetted area.

CHAPTER IX
FURROW IRRIGATION

Furrow irrigation refers to water that is discharged into and runs down small sloping channels (called furrows, or corrugations which are cut or pressed into the soil. Water can be delivered to each furrow through syphon tubes from open ditches or directly from gated pipe (see Figure IX-1 and IX-2). The water infiltrates into the soil laterally as well as vertically from the wetted perimeter of the furrows. Infiltration rate and lateral spread at any point in a furrow are dependent upon soil infiltration characteristics as well as the time surface water is at that point (opportunity time) and is a relatively slow process.

Some important considerations and limitations of furrow irrigation are:

1. Furrow irrigation is applicable to row and tree crops and can be adapted to close-spaced crops placed in beds.

2. It is adaptable to all but very slow or very high intake rate soils. However, it can be efficiencly used on sandy high infiltration rate soils by employing short furrows and relatively large but non-erosive furrow streams requiring more labor unless automated.

3. Stream sizes should be nonerosive but large enough to reach the lower end of the furrows in a fraction of the time required to fill the root zone to assure uniform infiltration (Advance Ratio between 1:4 and 1:1).

4. Grading should be done to eliminate low spots which would trap water. Slopes generally are small, .1 to .3% where well graded, and should not exceed 2 to 3%. Contour planting should be used on steeper topography. Furrows with uniform slopes are usually preferred to achieve high distribution uniformities.

5. Furrow spacing and shape ("vee," parabolic, broad) can be varied to permit large variations in the duration of irrigation. They must be such that the lateral spread of water adequately irrigates the plants' root zone.

6. The soil along any furrow should be uniform.

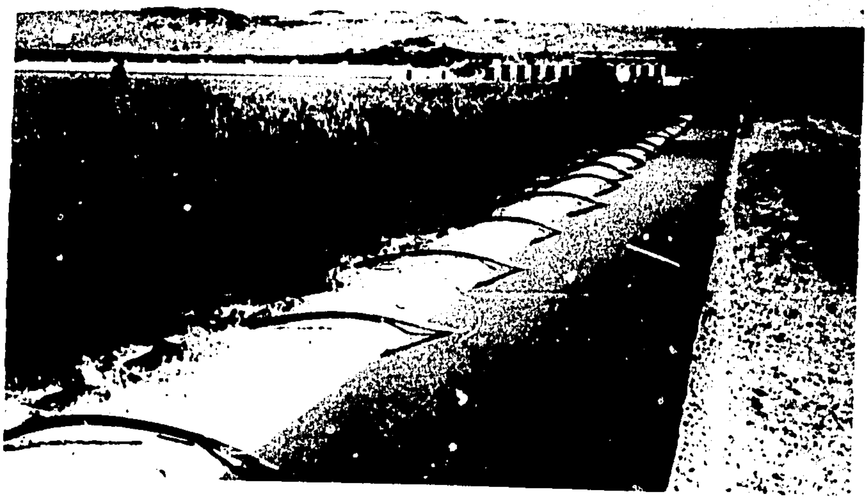


Figure IX-1. Furrow irrigation with syphon tubes in operation.

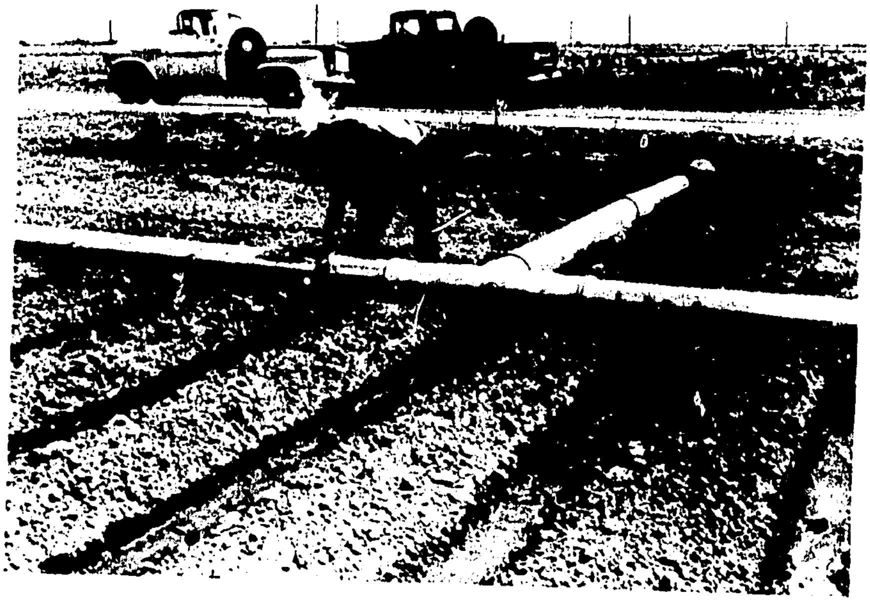


Figure IX-2. Furrow irrigation with gated pipe in operation.

Simple Evaluation

Simple techniques often provide information useful for identifying and correcting problems of operation. Most of the necessary data can be obtained by questioning the irrigator or by making simple observations and measurements.

Evaluation

For both simple and full evaluations, the following basic criteria of good irrigation should be considered:

1. Is the soil dry enough to start irrigating? Withholding water too long detrimentally stresses the crop. Irrigating too soon increases labor, often adds excess water to a high water table, and encourages pests and diseases.

2. Is the soil wet enough to stop irrigating? In other words, has an adequate but not excessive depth of water been infiltrated? Has the moisture spread far enough laterally?

3. Has water been distributed uniformly along the furrow? Excellent uniformity usually is achieved if the stream reaches the lower end of a furrow, without erosion, in about one-quarter to one-third of the time of irrigation. One-half the irrigation time is often economical.

4. Is there much runoff? A little water either ponded or running off at the lower end of a furrow is essential for practical operation. Runoff water can be saved by using a return flow system.

5. Is the water supply and system capable of delivering water for efficient and convenient use of both water and labor? Supplies should be large and flexible in both rate and duration. Furrow streams should be large enough to advance quickly, controlled in such a manner that they can be reduced in size for cutback, and be cut off as soon as the *SMD* is satisfied. Furrow streams should be convenient for the irrigator to handle, and the supply should be large enough to keep him busy for economy of labor.

Equipment needed

The equipment needed for the simple evaluation is:

1. A soil auger.

2. A soil probe.

Field procedure

The following illustration uses the simple part of the data obtained for the full evaluation of an irrigated corn field. (Data from a full evaluation are presented in Form IX-1 following this section of Simple Furrow Evaluation.)

Soil moisture deficiency, SMD, should always be the first concern. "Is it dry enough to irrigate?" is the critical question. Too often the answer is based on guesswork or rigid schedules that usually result in applying water too soon. For this sample study, in 660-foot long corn furrows spaced at 36 inches, *SMD* was checked and irrigation was needed because it was about 3.6 inches.

This information was obtained by using the Soil Moisture and Appearance Relationship Chart (see Table I-1). The soil auger was used in the sandy loam soil to obtain soil samples in 1-foot increments to a depth of 4 feet. The top foot was quite dry, and estimated *SMD* was high (1.6 inches per foot out of 1.8 inches per foot total available moisture). The second, third, and fourth foot samples appeared to have *SMD* values of 1.2, 0.6, and 0.2 inches per foot, respectively. This gave a total *SMD* of about 3.6 inches for the root zone.

The corn roots at that time had extended to approximately 3.5 feet and for the sandy loam soil, cool climate, and an expanding root zone, an *MAD* of 60% was acceptable. This gives an *MAD* of 1.8 inches per foot X 3.5 feet X 60% = 3.8 inches. The irrigator was applying water at about the proper time since the *SMD* of 3.6 inches nearly equaled the *MAD* of 3.8 inches.

Adequacy of irrigation is fairly accurately determined in the field during irrigation by using the probe as described in Appendix F. It can also be estimated analytically. Checking the adequacy of irrigation answers the second important question, "Is it wet enough to stop irrigating?"

At the upper and lower ends of several furrows, the probe was used to determine the depth of the wetting front. The probe penetrated easily where the soil was nearly saturated, but resistance to penetration increased noticeably at the wetting front.

When the field work for this evaluation was completed in about 2 hours, the probe penetrated only 1.5 feet at the upper ends of the furrows and a little less than 1.0 foot at the lower ends. Also, pushing the probe into the soil at an angle indicated that the lateral spread was not yet adequate.

To use the probe properly, checks should be made frequently to determine when to stop irrigating. For this field, water should have run until probing at the lower end of the furrow showed the wetting front had penetrated to about 2.5 feet. The following day, excess topsoil moisture would have drained down to satisfy the small deficiency at depths between 2.5 and 3.5 feet. After penetration is sufficient for a full irrigation, all water applied is lost; therefore, probing is recommended to determine when to stop irrigating. The irrigator made no check near the end of the 10 hour working time, but he should have and it could have been easily done.

Knowledge and figures gained from the full evaluation indicate that after 10 hours the probe would not have penetrated deeply enough to show adequate irrigation, since computations show it would require more than 14 hours. Also, the ground probably would not have been fully wet between rows. Both the vertical and lateral wetting should be checked at the end of irrigation. For implementing the learning process, a 2 foot deep trench dug across the furrow from ridge to ridge is sometimes helpful to show the vertical and lateral wetting patterns.

Uniformity of infiltration is important for efficient use of water. When furrow irrigating uniform soils, uniformity of infiltration is usually assured by quickly getting the water to the far end of the furrows. The Advance Ratio, *AR*, is expressed as a ratio between the Time of Advance, T_{adv}, needed to reach the lower end of the furrow and the Time or Duration of Irrigation, T_i, needed for the desired depth of water to be infiltrated at any point. If this ratio is about 1:4, excellent uniformity may be obtained. During this test the irrigation stream advanced the full 660 feet in about 1 hour, leaving 9 more hours for the water to run. The *AR* of 1:9 is lower than necessary for reasonable uniformity. For example, using information from the full evaluation with *AR* values of 1:5, 1:4, 1:3, and 1:2, the corresponding Distribution Uniformities would be: 0.94, 0.93, 0.91, and 0.87 for the test conditions and *MAD* (see Full Furrow Evaluation). This shows that for reasonable *AR* values smaller than 1:3, less than 10% of the water goes too deep.

Runoff streams 2 hours after the beginning of irrigation appeared to be about half the size of the inflow streams. The irrigator planned to run his irrigation about eight hours longer. Streams reached the ends of almost all furrows in less than 1 hour; therefore, runoff would continue for more than 9 hours. Since the intake rate decreases with increasing time, the runoff streams continually increase until the onflow stream is shut off. Runoff would be quite excessive in nine hours.

Furrow stream size can be estimated by dividing the system capacity by the number of furrows being irrigated simultaneously. In this field, the irrigator had a well that discharged 960 gpm, and he usually set

50 to 55 siphon tubes; consequently, each furrow stream flowed about 18 gpm. Since streams reached the ends of the furrows more quickly than was desirable, they should have been smaller. From the full evaluation, a stream of approximately 7 gpm would advance the full 660 foot furrow length in about 3 hours, which would be ideal; thus, 130 to 140 siphon tubes should be set to accommodate the well discharge of 960 gpm.

Utilization of field data

The observations and quick analysis reported above do not provide enough information to indicate the best modifications, but they provide a good start. The average depth, D, of water to be applied to the field can be calculated by:

$$D = \frac{96.3 \times \text{furrow stream (gpm)} \times \text{duration of irrigation (hrs)}}{\text{furrow spacing (feet)} \times \text{furrow length (feet)}}$$

in this field

$$D = \frac{96.3 \times 18 \text{ gpm} \times 10 \text{ hrs}}{3.0 \text{ feet} \times 660 \text{ feet}} = 8.7 \text{ inches}$$

The depth applied was 8.7 inches during the 10-hour irrigation, but the *SMD*, was only 3.6 inches. Very little water, if any, went too deep so there must have been an excess of runoff. This is consistent with the observation that runoff was about half of the inflow at the end of 2 hours. More than enough water had been applied, but probably not enough infiltrated.

Analysis and recommendations

The simple analysis showed the following:

1. The field was dry enough to be irrigated, since the *SMD* was 3.6 inches and the *MAD* was 3.8 inches.

2. Uniformity was far better than needed, since the furrow streams reached the ends of the furrows very quickly and the *AR* was very low (1:9).

3. Runoff was excessive because furrow streams were too large and reached the lower ends too quickly.

4. The water supply flow rate was not flexible, but adjustments could have been made by starting more furrows with smaller streams. Furthermore, additional furrows could have been started with water

saved by cutback irrigation, in which the inflow streams are reduced when the runoff has become large enough to warrant cutting back. However, this was not done because it was not convenient for labor.

To improve efficiency of the system, the following practices are recommended:

1. Check *SMD* to determine or confirm correct frequency and to avoid cumulative deficiencies in the lower part of the root zone. Even though the frequency of this irrigation was nearly correct, a cumulative *SMD* might occur.

2. Check depth and spread of infiltration during irrigation by using a probe to avoid over or underirrigation.

3. Use a smaller stream that would need about 3 hours to reach the end of the furrow. This would permit running more furrows at one time, or use a longer furrow with the same stream size. Either of these adjustments would save labor and still provide excellent uniformity as long as the *AR* is held to about 1:3 or faster.

To assure adequate infiltration, the smaller stream would have to be run for a longer time as the plants grow larger. Correct duration could be checked easily with the probe. If the longer duration is not practical because of increased labor, other changes could be made to shorten it. For example, the furrow could easily be made wider, *MAD* could be reduced to shorten the duration of irrigation, or an automatic pump shutoff could be installed. Reduction of *MAD* would require more frequent irrigations, possibly one more irrigation during the season which would require a little more labor.

4. Reduce runoff losses by doing the following: install a runoff recycling system or cut back the furrow stream about two hours after the flow reaches the lower end, and use a smaller initial furrow stream and/or use longer furrows.

A runoff return flow system that puts water into a reservoir at the upper end of the field is sometimes a very practical and economical way to save both water and labor. Just pumping the water back into the supply ditch is not good practice. It requires starting more furrows, each of which would have a different shutoff time and requires more labor if good efficiency is to be achieved.

The cutback stream procedure would not have been convenient in the operation described above. The farmer's ditch checks were solid earth embankments that had plastic covers for erosion control. These solid embankments could not be lowered easily to reduce head in order to change all the siphon flows simultaneously. Converting to adjustable checks would simplify cutback irrigation.

Another way to make cutback streams is to use two smaller siphons to start the initial streams and later remove one siphon to reduce flow. Also, one can raise the lower end of each single large siphon. However, when a supply ditch receives a constant inflow, any method of cutting back the streams flowing into the furrows leaves more water in the ditch. This water must be used to start streams in more furrows which increases labor because it requires different shutoff times for successive sets of furrows.

To reduce the waste from runoff, the most practical alternative to building a new distribution system would be to use longer furrows or streams small enough that they would reach the ends of furrows in one-third or even one-half the irrigation time. These streams would have little runoff even though the application time would be appreciably longer. A little more water would penetrate too deeply at the upper end of furrows which would result in a lower DU_a but would give more efficient use of labor and water. A full evaluation study would make it possible to anticipate effects of various possible changes.

5. Have the irrigator conduct the simple evaluations because some checks need to be made immediately after irrigation.

6. Conduct a full evaluation to provide answers to the following battery of questions the answers to which would give a detailed basis for making economic studies for improvement.

How much water is wasted to deep percolation and to runoff?

What is the DU_a?

What is the *AELA*?

What is the *PELA*?

(The Low Absolute *"LA"* values are more convenient for study, but the Low Quarter *"LQ"* values must be used when comparing methods or determining the correct depth of water to apply.)

What would be the cost of building a reservoir and installing a pumping system that would pump the well steadily at a lower rate? How much would this save?

How long should furrows be?

What is the best size of furrow stream?

Would a change in shape and/or spacing of furrows be useful?

Would a runoff return flow system be desirable?

Summary of simple evaluation

The *SMD* and the irrigation frequency in the operation described above were about right, but the correctness of the frequency should be periodically verified by checking the *SMD*. The *DU* was too high, so smaller furrow streams should be used. Runoff was so large that it wasted more than half of the water applied; it could best be reduced by using smaller streams in more furrows or by using the same sized stream in longer furrows. Flow from the well was at a usable rate, but a larger flow would reduce labor costs.

Full Evaluation

Detailed evaluations provide information needed for identifying existing problems, for making many possible changes to correct them, for making economic comparisons of procedures and methods, and for furnishing background for design of systems operating under similar conditions.

Evaluation

The techniques of evaluation consists of determining the following information at a typical location when the *SMD* is about equal to the *MAD*:

1. Rate at which the various streams ranging from too large to too small advance down the furrows.
2. Maximum desirable stream size as limited by erosion or furrow capacity.
3. Shape of existing furrows.
4. Intake rate in the furrows.
5. Furrow conditions such as new, used, firm, loose, and/or irregular.
6. The *SMD*.
7. Maximum furrow spacing that will allow adequate wetting of the soil between the furrows within the time of irrigation.
8. Adequacy of the depth and lateral spread of the irrigation water.

Additional desirable data are:

9. The wetted width and depth of the furrows.

10. Furrow gradient.

11. The water recession after the stream is shut off.

12. Rate of runoff from each furrow.

13. Rate of inflow and runoff for cutback streams.

14. Rate of advance beyond the normal furrow length into another field.

15. Soil texture and profile.

16. Maximum capacity of the water supply system.

17. Tests of furrows of various shapes such as "vee," parabolic, and broad.

18. Cylinder infiltrometer test adjacent to the furrows.

After the field data have been obtained and plotted, analysis will permit determination of the DU_a, *PELA*, and *AELA*. (The Low Quarter, *LQ*, are more valuable but are more involved to use.) A more detailed study would point out improvements that might be made, some of which might not be economical. Such a study could include the following options:

1. Changing stream size and rate of advance.

2. Changing the furrow length.

3. Changing the furrow spacing.

4. Changing the furrow shape.

5. Changing *SMD* at which irrigation is started.

6. Using alternate side irrigation.

7. Using continuous furrows with supplemental inflow.

8. Installing a reservoir that would provide for flexible delivery.

9. Adjusting factors so that duration of irrigation would match duration of water delivery for convenience of labor where a reservoir is not practical.

10. Installing a runoff return flow or some system which will save runoff and labor.

11. Revising the delivery system to give more flexible deliveries to save water and labor.

12. Using sprinkle irrigation in conjunction with furrows.

Equipment needed

The following equipment is needed for the evaluation:

1. A surveying tape to locate stations along the furrows.
2. Laths or stakes to mark stations and a hatchet to drive them.
3. A stop watch or watch with easily visible second hand.
4. Flow measuring devices such as small Parshall flumes with 1- or 2-inch throat, orifice plates, spiles, siphons, V-weirs, calibrated containers. The devices used should be provided with an instrument for measuring the head and be capable of measuring flow accurately when used to determine the rate of furrow intake (see Appendix B).
5. A shovel.
6. A soil auger and soil probe.
7. Forms IX-1 and IX-2 for recording data.

Additional equipment for more detailed work would include:

8. Surveying equipment to determine furrow gradient.
9. Cylinder infiltrometer equipment.
10. Soil moisture sampling equipment.

Field procedure

Choose a location in the field that is typical of conditions over the whole irrigated area. Soil should be uniform throughout. A steady source of water should be available from which streams (preferably of a constant size) can be turned into the furrows. (See Appendix A for detailed description of methods for stream control.)

Form IX-1. FURROW IRRIGATION WATER ADVANCE EVALUATION

1. Location *Santa Maria*, Observer *JLM*, Date *10 August 1976*
2. Crop *corn*, Age *mature*, Root depth *3.5* ft, Row: spacing *36* in, length *650* ft
3. Soil: texture *sandy loam*, available moisture *1.8* in/ft, SMD *3.6* in
4. Irrigation: duration *10* hrs, frequency *14* days, MAD *60* %, MAD *3.8* in
5. A: *Small #1* B: *Medium #3* C: *Large #5* D: ______

Stream: *4.0* gpm *9.2* gpm *17.5* gpm ______ gpm

Time – min.			Station	Time – min.			Station	Time – min.			Station	Time – min.			Station
Watch	Diff.	Cumu.	feet	Watch	Diff.	Cumu.	feet	Watch	Diff.	Cumu.	feet	Watch	Diff.	Cumu.	feet
8:22		0	0+00	8:24		0	0+00	8:27		5	0+00				
39	17	17	1+00	31	7	7	1+00	32	5	10	1+00				
9:05	26	43	2+00	39	8	15	2+00	37	5	17	2+00				
39	34	77	3+00	50	11	26	3+00	44	7	26	3+00				
10:22	43	120	4+00	9:03	13	39	4+00	53	9	36	4+00				
				22	19	58	5+00	9:03	10	48	5+00				
				46	24	82	6+00	15	12	55	6+00				
				10:03	17	99	6+50	22	7		6+50				

6. Comments: *Furrows were firm, reused, clean,* ‿ *shape, with 0.2% slope*

Form IX-2. FURROW INFILTRATION EVALUATION

1. Location Santa Maria, Observer JLM, Date Aug 1976

2. Furrow: Identity Q = 9.2, shape ◡, condition good

age reused, soil compact, moisture dry, slope 0.2%

a	b	c	d	e		f	g		h
Time			Station A — Flow Rate			Station B — Flow Rate			Intake
Watch	Diff. min.	Cum. min.	1-in Parshall	—	gpm	1-in Parshall	—	gpm	gpm/100ft
8:27		0	2"		9.4	☒	☒	☒	
33	6	6	1 15/16	used 9.2 as average	9.0	1 6/16"		5.2	4.0 2.0
38	5	11	2		9.4	1 8/16		6.0	3.2 1.6
49	11	22				1 9/16		6.4	2.8 1.4
9:03	14	36	1 15/16		9.0	1 10/16		6.8	2.4 1.2
20	17	53				1 11/16		7.2	2.0 1.0
47	27	80			9.4	1 11/16		7.2	2.0 1.0
10:24	37	117	2			1 12/16		7.6	1.6 0.8
Accuracy range					±0.2			±0.2	±0.2

2. Furrow: Identity Q = 17.5, shape ◡, condition good

Time			Station A — Flow Rate			Station B — Flow Rate			Intake
Watch	Diff. min.	Cum. min.	2-in Parshall	—	gpm	2-in Parshall	—	gpm	gpm/100ft
8:29		0	1 15/16		18.0	☒	☒	☒	☒
34	5	5	1 14/16	used 17.5 as average	17.1	2 8/16"		13.3	5.2 2.6
40	6	11	1 14/16		17.1	2 9/16		13.8	3.7 1.85
49	9	20				2 10/16		14.4	3.1 1.55
9:03	14	34	1 15/16		18.0	2 11/16		14.9	2.6 1.3
20	17	51				2 11/16		14.9	2.6 1.3
47	27	78				2 11/16		14.9	2.6 1.3
10:24	37	115	1 15/16		18.0	2 12/16		15.5	2.0 1.0
Accuracy range					±0.4			±0.3	±0.3

3. Comments: Stations A at 0+00 and B at 2+00

1. Select three or more test furrows. They may be alternate furrows to facilitate patrolling the streams without walking on wet soil. If the furrows are new with loose soil over a plow pan or other conditions in which water moves rapidly sideways, adjacent furrows should be run to prevent abnormal lateral flow.

2. Set stakes along one of the furrows, usually at 100-foot stations, but set a minimum of six (see Figure IX-3). The zero station may be set a short distance from the inlet end of the furrow to give flows a chance to stabilize before being measured. Elevations may be surveyed or gradient may be determined otherwise, but this is not essential for any specific evaluation.

3. Prepare flow measuring devices at station zero on all test furrows. (See Figure IX-4 and Appendix B for details of such devices.)

4. Set flow measuring devices for testing furrow intake rate in at least one furrow, but it is desirable to check intake at more than one location or furrow. They should be set in furrows carrying moderate streams; furrows having small or erosive streams should be avoided. The location is generally chosen at the inlet end of the furrow to provide longer duration of the test. For soils having rapid to moderate intake rates, the devices may be set 100 feet apart for inflow-outflow measurements. For soils having slower intakes, 200-foot intervals may be used, or several furrows may be combined. Flow measuring devices may also be set at the lower ends of the furrows to measure runoff.

5. Fill in parts 1 through 4 of Form IX-1 concerning the crop, soil, and irrigation. After determining the *SMD* (see Table I-1), note how closely it agrees with the desired *MAD*.

6. Set at least three, but preferably four, constant flow streams with different flow rates to bracket the possible range in stream sizes. If flow rates vary during the test, the change should be noted. One stream should be large enough to cause a little erosion unless limited by furrow capacity, and one should be so small as to barely reach the lower end. The larger of these should have a flow rate of about $10/s$ gpm, where s is the furrow slope in percent, but judgment will have to be used. For best results, two more intermediate stream sizes should be run. Where practical, a set of used and a set of new furrows should be tested. In cultivated orchards, furrows near the trees and in the middle space between the rows should both be tested since cultural compaction has appreciable effect. Also furrow use, soil structure, and moisture content importantly affect stream size, intake rate, and advance rate (see Figure IX-5). Furrows of other shapes may also be observed to broaden the irrigator's choice for possible revision.

Figure IX-3. Stakes set along furrow in preparation for water advance evaluation.

Figure IX-4. Small Parshall flume being used to measure furrow flow rate.

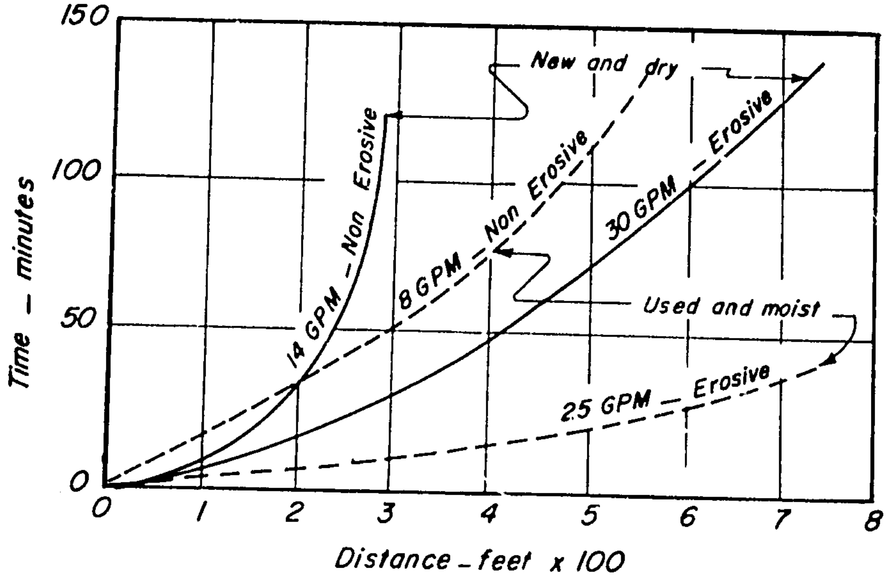


Figure IX-5. Effect of furrow condition, stream size, and soil moisture on advance rate.

7. Identify each tested furrow and record the size of stream flowing past station zero in each furrow on the advance form, Form IX-1 in part 5.

8. Record the time each stream reaches each station in the table provided on Form IX-1. These should be plotted in the field when they are recorded and observed for correctness. (Deviations from a smooth curve are important in diagnosis and should not be smoothed out.)

9. Fill in parts 2 on Form IX-2 identifying and describing the infiltration test furrows. (Note that zero time is not the same as used for the Advance Curve.)

10. Record the intake rate flow data in the columns a through f in the tables on Form IX-2 as follows:

a. Make the first entry when stream reaches midway between Stations A and B. Make second entry about a minute after the stream passes Station B. Make subsequent entries at increasingly longer intervals to obtain at least eight entries (more entries are even better).

b. Determine the difference or incremental time between successive watch (or clock) times entries.

c. Enter the summation of successive time increments.

d. Give the head on Parshall flume, orifice, or weir. Indicate device and units used. If a container is used, show size and time to fill.

e. Give conversion units if needed and corresponding flow rate in gpm passing stations A and B.

f. Determine the flow rate difference between station A and B and adjust to 100 feet if A and B are not 100 feet apart to give rate of intake in gpm/100 feet.

Preferably the test should be run for the duration of the irrigation but may be briefer. For soils having slow intake rates, tests may be shortened to 3 hours but not less than the times it would take a moderate stream to reach the lower end of the furrows.

11. Observe the furrow for erosion or overtopping. Estimate the maximum usable stream size. In new furrows, loose soil often muddies the water at first, but this is not considered to be erosion. Also, some erosion often occurs at the turnout, but the stream becomes stable after a short time.

12. Observe runoff at the end of each furrow. Under circumstances requiring a detailed evaluation, the rate of runoff should be measured several times; otherwise it may be estimated as a percent of the inflow stream and noted as such. Cutback streams are almost always desirable and practical in a properly designed system. One of the larger streams should be cut back after appreciable runoff is noted, and the runoff should be observed or measured. Where excessively long furrows can be tested, such as occur where supplemental lines are used, a long advance curve can be plotted without resorting to extrapolation. There is no runoff only continuous advance far past the end of a normal furrow length. This is a desirable condition for evaluations.

13. If water is present in the furrow for an appreciable time after the stream is turned off, it should be noted and a recession curve plotted, as it represents extra time water may be infiltering. It is negligible in most furrows since the intake rate is usually very slow at the end of irrigation.

14. Depth of water penetration and lateral spread should be checked during irrigation by using a probe or soil tube to follow the wetting front. Evidence of plow pans is readily observed when using the probe. Depth and width of penetration should be checked by using an auger or soil tube at several places along the furrow a day after irrigation is completed. More detailed information can be obtained by cutting a trench across the furrow for visual observations of the wetting pattern. This should be done at several locations in the furrow with the small stream to observe the wetting pattern for various durations of irrigation. This will show if the furrow spacing is too wide to adequately wet the area.

Utilization of field data

The field information is best presented by plotting. The *advance curves*, which show the time water arrives at each station, are usually plotted on rectangular coordinates and is best done in the field while taking the data. The characteristics (slope, shape, moisture condition, stream size, new or reused) of each furrow should also be noted on the graph. It is practical to extrapolate advance curves beyond actual field length by plotting the data on full logarithmic paper on which they will have only a slight curvature. This is often done on the same sheet as the intake curves or by finding the equation of the advance curve. The recession curve which relates the time and station location when water ceases to be on the surface may be plotted, but it is usually assumed to be on a horizontal straight line unless field data indicate a significant deviation.

The *intake rate curves*, which show the intake in gpm/100 feet at any given time, are usually plotted on 3-cycle logarithmic paper. The line of points for each test furrow should be plotted separately and the plus or minus accuracy range noted since the points themselves sometimes appear erratic. It is best to plot the data as soon as they are taken so if errors occur they may be noticed immediately and new readings taken. If the test results are similar, one line representing the typical condition may be added, but it should be used with the knowledge that it may be plus or minus the actual value. The depth applied should be computed and compared with a cumulative depth infiltrated plot and "adjusted" curves plotted if the two do not closely agree.

The full evaluation procedure is illustrated by records of a test in a corn field 1300 feet long but cut in half by a supplemental supply ditch (see Forms IX-1 and IX-2). The soil was a compact sandy loam and was estimated to have 1.8 inches/foot available moisture. The furrows were spaced at 36 inches, were clean, had a gradient of 0.2 percent, and had been used before. Alternate furrows were customarily irrigated at every other irrigation. Water was run in the furrows for 10 hours for convenience of labor. One siphon tube was used per furrow, and the flow was definitely nonerosive. Since a cutback flow was not convenient, appreciable runoff water was wasted in a ditch just above the supplemental supply ditch. For the evaluation, siphon tubes were set in three furrows using three different flow rates.

The *SMD* to a depth of 4 feet was found in each foot by using Table I-1 to be 1.6, 1.2, 0.6, and 0.2 inches. giving a total of 3.6 inches. The root zone at the time was 3.5 feet and would expand as the crop grew.

Intake rate data were found by setting 1-inch Parshall flumes at station 0+00 and station 2+00 in the furrows having the largest and the medium size streams. Flow rates into all three furrows were also measured by timing the flow from the siphon tube into a 1-gallon jug. Good correlation with the Parshall flume was obtained for the medium stream, but because the largest stream filled the jug too quickly, the correlation in that furrow was poor.

As shown by the data on Form IX-2, 200-foot sections of furrows were used making two entries in column h. The first represents total water intake, and the latter shows the intake in the desired units (gpm/100 feet).

The depth measurements in the Parshall flumes were made in a poor fashion with a ruler marked in 1/16 of an inch. These divisions were too large, and as shown on Form IX-2 for the 9.2-gpm furrow in column h, the resulting intake values could potentially vary by ± 0.4 gpm/200 feet or ± 0.2 gpm/100 feet. Finer divisions such as 0.01 inch or 0.001 foot should be used. Because of the crudeness of the measurements for this test, an average rate was presumed correct. If adequate accuracy is obtainable, the direct readings must be used rather than averages since they probably represent true flow variations. The accuracy of ranges given on the bottom lines of column h are important because in plotting each point, it must be appreciated that the ± values is a limit on the range anywhere within which the true value may occur. To clarify, such a range should be considered at each point when plotting, and the line should be drawn within the range as is the case for both intake curves (straight lines) on Figure IX-6. To increase accuracy of measurements, a point gauge should be used to measure from a datum to the water surface and to the bottom of the flume to obtain a zero reading. Such a point gauge may be improvised by fastening a wire to the end of a measuring scale.

Intake rate curves were developed by using the data in columns c and h on Form IX-2 and plotted on Figure IX-6. The cumulative intake was plotted following the procedure described in Appendix C as follows:

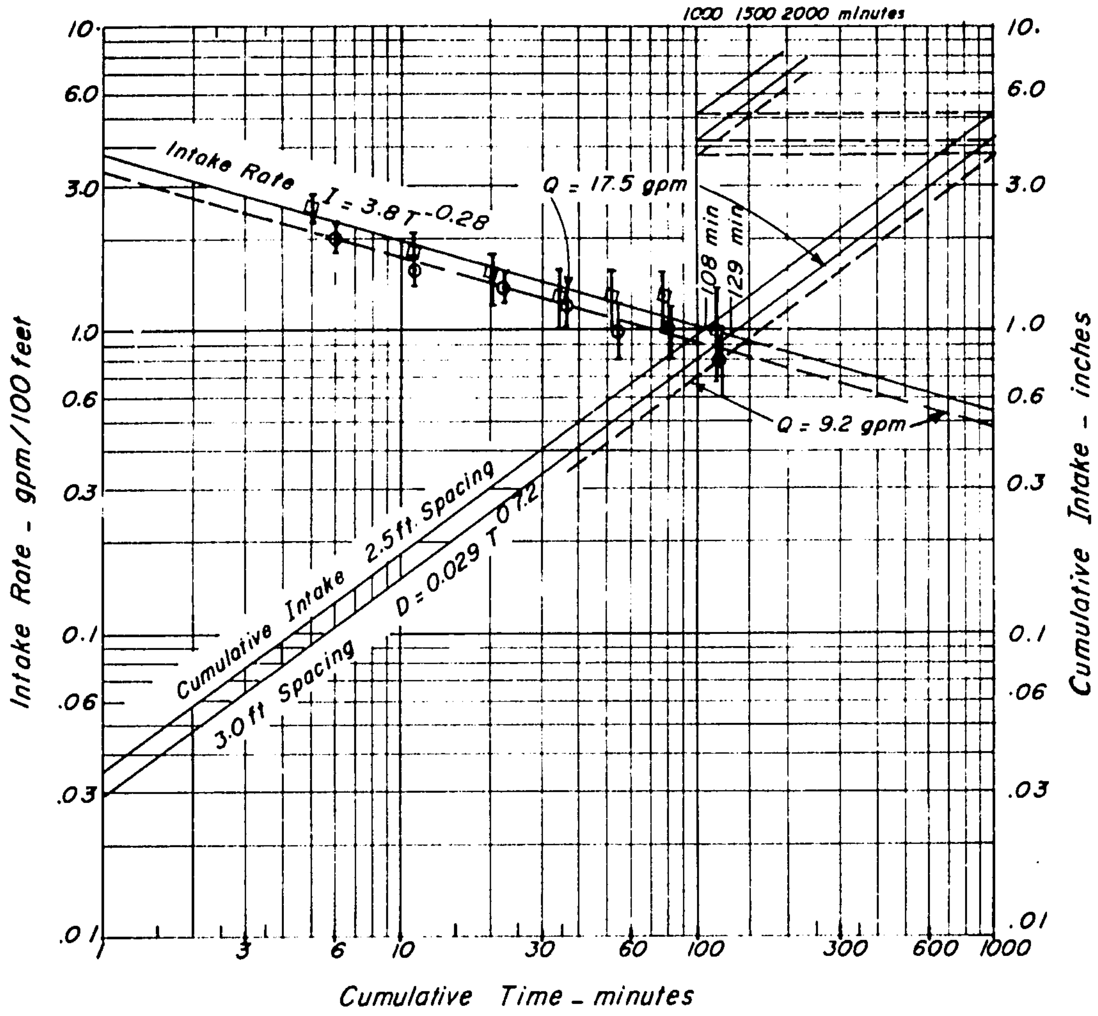


Figure IX-6. Furrow intake curves for the field test data given in Form IX-2.

1. Measure the vertical distance, v, between the two ends of the 17.5-gpm stream intake rate curve which in Figure IX-3 is $v = 1.31$ inches.

2. Measure the horizontal distance, h, between the two ends (the width of the graph) which is $h = 4.68$ inches.

3. Mark the time at which the intake rate curve crosses the cumulative intake curve, T', which for a furrow spacing of $S = 3.0$ feet is: $T' = 60\ (1-v/h)S$
$= (1-1.31/4.68)3.0 = 129$ *minutes*

4. Measure the horizontal distance between $T' = 129$ minutes and $T = 1.0$ minutes which is 3.25 inches.

5. Measure 3.25 inches vertically down from where the 17.5-gpm stream intake curve crosses the line $T = 1.0$ minute (at 3.8 gpm/100 feet) and mark it (at 0.029 inches). Note that there are two vertical scales on Figure IX-6, intake rate (gpm/100 feet) and cumulative intake (inches).

6. A line drawn through the two points plotted in steps 3 and 5 represents the accumulated intake after any time, T, for the 3.0-foot furrow spacing.

The two curves drawn for the two stream sizes are not averaged for this evaluation. They seem to have a relationship that may correctly be representing the slightly higher intake rate that a larger stream should have for this furrow shape. The cumulative intake curves were extrapolated past 2000 minutes on the 3-cycle logarithmic paper by setting back one log cycle. (See the upper right-hand corner of Figure IX-6.)

When desired, the mathematical representation of the curves may be found by the following procedure. The equation for the plotted intake curve, which is usually a straight line on logarithmic paper for short durations, is of the form:

$$I_{gpm/100\ ft} = KT^{n}$$

where $I_{gpm/100\ ft}$ is the intake rate in gpm/100 feet of furrow, T is the time of infiltration in minutes, K is the intercept when Time T is 1.0 minute, and n is the geometric slope of the line (vertical distance/horizontal distance). This slope is negative, so n has a minus sign. For long duration tests the equation is:

$$I = KT^{n} + c$$

where c is the final intake rate after a long time.

Converting from gpm/100 feet to inches/hour for a specific furrow spacing, S, may be closely approximated (4% too low) by dividing the above equation by S in feet:

$$I_{in/hr(S)} = \frac{I_{gpm/100\ feet}}{S\ feet}$$

Integrating the short duration rate equation produces the equation for cumulative depth of infiltration in inches for a furrow spacing, S in feet:

$$D_{(S)} = K'T^{(n+1)}$$

where

$$K' = \frac{K}{60(n+1)S}$$

K' is also the intercept of the cumulative curve on a logarithmic plot at T equals 1.0 minute.

For the long duration rate the equation for the cumulative depth of infiltration is:

$$D = K'T^{(n+1)} + CT$$

The n, K, and K' values for the above equations may be obtained from inspection of the plottings shown on Figure IX-6 as follows:

1. The slope, n of the 17.5-gpm stream intake rate curve is: $n = -v/h$

   which for v = 1.31 inches and h = 4.68 inches as determined earlier is:

   $$n = -\ 1.31/4.68 = -\ 0.28$$

2. The intercept of the 17.5-gpm stream intake rate curve with T = 1.0 minutes is K = 3.8.

3. The intercept of the cumulative intake curve with T = 1.0 minutes when S = 3.0 feet is:

   $$K' = \frac{3.8}{60\ (-0.28 + 1)\ 3.0} = 0.029$$

   which is the same as the value found graphically.

Using these values in the above formulas gives:

$$I_{gpm/100\ ft} = 3.8T^{-0.28}$$

and

$$D_{(3.0\ ft)} = 0.029\ T^{0.72}$$

As shown later, these curves almost always need to be "adjusted" to make them conform to the measured onflow depth.

Advance curves from data on Form IX-1 were plotted on Figure IX-7. Two of the curves were extrapolated to the full 1300 feet which may be approximated by any of three ways. A French curve may be used for lines without much curvature such as the 17.5-gpm stream or for short extrapolations such as for the 4.0-gpm stream. Also curves may be plotted on log-log paper and extrapolated using a French curve. This was done for the 9.2-gpm stream and transferred to the rectangular coordinates.

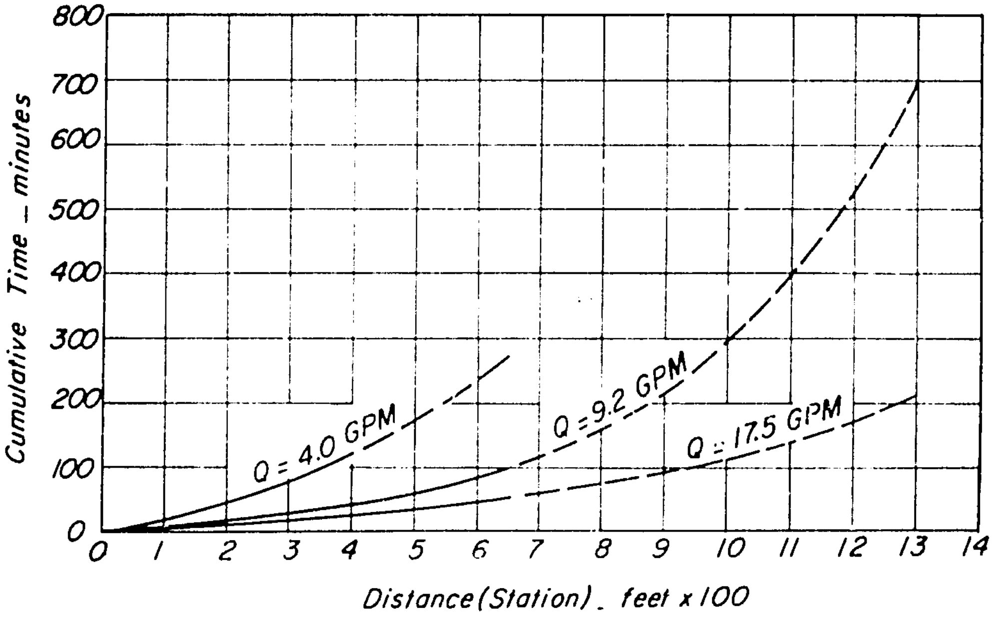


Figure IX-7. Furrow advance curves for field test data given in Form IX-1.

The third procedure involves finding the equation of the curve and using the equation to extrapolate. This is the most accurate one for very long extrapolations. An equation, $t_x = a(e^{cx} - 1)$ where t_x is the number of minutes to reach the distance x in feet, has been found to fit many advance curves. The constants a and c may be computed by obtaining the slope of (dt/dx) of the curve at two points with due care for scale distortion, putting the slope values into the differential equation of the form $dt/dx = ac + ct_x$ for the two locations, and solving the two equations simultaneously. The equation usually has to be slightly adjusted to match the original curve since the slope measurements seldom can be made precisely enough to determine the correct a and c values the first time.

An evaluation by a short analysis using "unadjusted" curves and absolute minimum values instead of the more correct but more involved Low Quarter *(LQ)* values will show:

1. How uniformly the water is distributed, DU_a.

2. The potential of the existing system if used to its best advantage, *PELA*. (This illustration shows the need to use an "adjusted" curve for intake to obtain correct values.)

3. How well the irrigator is using his system, *AELA*, i.e., whether the stream size and length of furrow are about correct, and whether the right amount of water is being applied.

Distribution Uniformity

The DU_a should be studied for several conditions, but for illustration only the 17.5-gpm stream and 3.0-foot furrow spacing are used here since this was what the irrigator was using. The ratio of the minimum depth infiltrated to the average depth infiltrated describes the uniformity of water intake without regard to the adequacy of irrigation. By utilizing the furrow intake and advance curves (Figures IX-6 and -7) and the time of application, T_a, of 10 hours (600 minutes), the following conditions were found: At the upper end the opportunity time, $T_{o(u)} = T_a = 600$ *minutes*; therefore, the depth infiltrated at the upper end, $D_{(u)}$, from Figure IX-6 was 2.9 inches. At the lower end of the furrow, the opportunity time, $T_{o(l)}$, would be $T_{o(u)}$, minus the time to advance 650 feet to the lower end, T_{adv}, of 52 minutes, so:

$$T_{o(l)} = T_{o(u)} - T_{adv} = 600 - 52 \approx 550 \text{ minutes}$$

Therefore, from Figure IX-6 the depth of infiltration at the lower end of the furrow, $D_{(l)}$, was 2.7 inches. These values are shown in

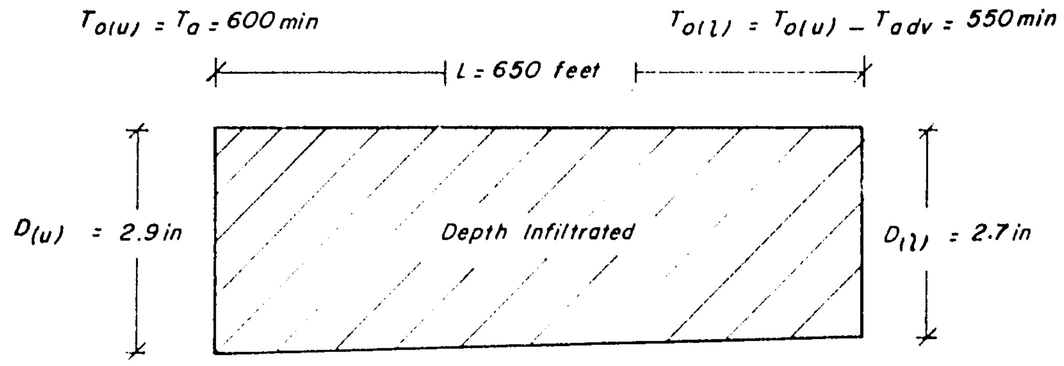


Figure IX-8. Relation of infiltrated depth along furrow with 17.5-gpm stream.

Figure IX-8. Numbers are rounded off since only reasonable accuracy can be expected. A uniform change in depth infiltrated is assumed for simplicity. This assumption is valid only for small advance ratios, AR_a, of about 1:3 or less. For much slower advances, the depth infiltrated is no longer approximated by a straight line as will be demonstrated later for the 9.2 gpm furrow stream. Using the above $D_{(u)}$ and $D_{(l)}$ values, the DU_a is:

$$DU_a = \frac{\text{minimum depth infiltrated (absolute)}}{\text{average depth infiltrated}} \times 100$$

$$DU_a = \frac{2.7 \text{ inches}}{(2.7 \text{ inches} + 2.9 \text{ inches})/2} \times 100 = \frac{2.7}{2.8} \times 100 \approx 95\%$$

Potential Application Efficiency

The $PELA$ is found when the "absolute" minimum depth of water infiltrated just satisfies the MAD. Since the irrigator was applying only about 2.7 inches when 3.6 inches were needed at that time, this efficiency must be found for the 3.6 inch condition.

From Figure IX-6, the "unadjusted" time of irrigation, T_i, to apply 3.6 inches is 800 minutes and $T_{o(l)}$ must be the same. At the upper end, the water will have been on longer by the length of time it took the stream to reach the lower end, T_{adv}, of about 52 minutes; therefore, $T_{o(u)} = 800 + 52 \approx 850$ minutes. The approximate average depth of water applied, D, by a furrow stream of 17.5 gpm flowing for 850 minutes (14.2 hours) to the 650 foot furrow with a 3.0-foot spacing is found by:

$$D = 96.3\ \frac{17.5\ gpm\ X\ 14.2\ hrs}{3.0\ feet\ X\ 650\ feet} = 12.3\ inches$$

and

$$AR_a = 50 : 800 = 1 : 16$$

D = 12.3 inches and is correct within the accuracy of the onflow measurement. However, the 2.7 and 3.6 inch minimum depths infiltrated and stored (used to compute *PELA* and *AELA*) were computed using the furrow intake curve which is independent of the onflow measurement. Figure IX-6 was developed from the "unadjusted" original set of data. The two depth values, onflow and infiltrated, are seldom consistent. They may be made consistent by using the technique described later under "Depth infiltrated and Adjusted intake curves."

The 17.5-gpm furrow stream was much greater than the intake capacity of the short furrow and caused a great deal of runoff, resulting in a very low *PELA* of:

$$PELA = \frac{3.6}{12.3}\ X\ 100 = 29\%\ (\text{"unadjusted"})$$

Application Efficiency

The *AELA* describes how much of the water applied is retained in the soil and is available for consumptive use at the point of "absolute" minimum application. As this field was irrigated, the maximum depth infiltrated, $D_{(u)}$, was 2.9 inches but it did not satisfy the *SMD*, i.e., all the area was underirrigated, however, there was heavy runoff. The minimum depth infiltrated at the lower end of the furrow, $D_{(l)}$, (all retained in the soil) was 2.7 inches. The average depth applied in T_a = 10.0 hours was:

$$D = 96.3\ \frac{17.5\ gpm\ X\ 10.0\ hrs}{3.0\ feet\ X\ 650\ feet} = 8.7\ inches$$

and

$AR_a = 50:550 = 1:11$

and

$$AELA = \frac{2.7}{8.7} X\ 100 \approx 31\%\ (Unadjusted)$$

The following conclusions can be drawn from the above short analysis computations and are useful for making recommendations for improvements:

1. DU_a of 95% shows that very little additional water infiltrates at the upper end relative to the lower end. This indicates that a slower rate of advance with a smaller stream would still do a satisfactory job. The water advanced down the furrow in about 1:11 the time it was at the lower end, i.e., $AR_a = 1:11$. An AR_a between 1:5 and 1:4 may be considered very satisfactory, and between 1:3 and 1:2 is often acceptable if a cutback is made or a return flow system is used.

2. $PELA$ and $AELA$ were both very low using "unadjusted" intake values. Since no water was lost to deep percolation, there must have been a great deal of runoff. For the system as used, runoff was 67%; and if the longer time required for a full irrigation of 3.6 inches was used, runoff would have been even greater.

From these conclusions the following recommendations can be made:

1. Use a smaller stream to reach the lower end of the furrow in about 1/4 or more of T_n; i.e., 13.3 hours/4 = 3.3 or more hours, which interpolated on Figure IX-7 would be done by a stream of about 6.0 gpm.

2. Run water longer to satisfy $T_n + T_{adv} = 13.3 + 3.3$, or approximately 17 hours. To further reduce runoff, cut back the stream or use a return flow system.

3. Increase the furrow length, if practical, by eliminating the supplemental supply ditch since it may be inferred that a much longer furrow could be used with the 17.5-gpm stream. Furthermore, an even larger stream could be used if desired and still not be erosive as the 0.2% slope since $10/S = 10/0.2 = 50$ *gpm*, which would permit an even longer furrow.

Further evaluation

By studying the curves further and "adjusting" the intake curves to find more precise values, some specific recommendations can be made relative to this system and its use. These recommendations can then be considered by management for their convenience, practicability and economics. The following illustrates what may be done.

Soil moisture deficiency at which to irrigate, *MAD*, must be chosen. For this soil, climate, and crop with an expanding root zone, *MAD* may reasonably be 60%. At the time of checking, the root zone was estimated to be 3.5 feet deep. *MAD* at 60% is then: 3.5 feet X (1.8 inches/foot) X 60% = 3.8 inches. Since estimated *SMD* was 3.6 inches, the time to irrigate was the test day or the day after. Subsequent irrigations when the root zone had expanded to 5 feet would then be applied when the *MAD* was about 5.0 feet X (1.8 inches/foot) X 60% = 5.4 inches. The operating procedures for these two (3.6 and 5.4 inches) and an earlier light application of about 2.5 inches, resulting in a range for *MAD* from 2.5 inches to 5.4 inches, requires flexibility in frequency, rate, and duration and will result in different efficiencies, desirable furrow lengths, and application durations. The system cannot easily be operated at the highest efficiency for all conditions, so compromising is inevitable.

Time of irrigation, or duration of irrigation, T_i, for the 3.8 inches *MAD* is about 860 minutes (see Figure IX-6).

Time of advance, T_{adv}, can be estimated by using one fourth of T_i as a "desirable" relationship which would result in a very high DU_a. This gives a T_{adv} of 860/4 = 215 minutes. (Using an AR_a as low as one-half of T_i (430 minutes) may be economical for no cutback, but will give a lower *PELA* if a cutback stream or reuse system is used.)

Furrow length to match this "desirable" T_{adv} using the 17.5-gpm stream is found on Figure IX-7 to be 1,320 feet, which is insignificantly longer than the 1300 foot field. (For a smaller stream, such as 9.2 gpm, the "desirable" length would be about 900 feet. For a furrow length of 650 feet, a "desirable" stream would be about 6.0 gpm.)

Time of application, T_a, would be $T_i + T_{adv} = 860 + 215 = 1075$ minutes (18 hours) giving:

$$T_a = T_{o(u)} = 1075 \text{ minutes; therefore } D_{(u)} = 4.5 \text{ inches}$$

$$T_i = T_{o(l)} = 860 \text{ minutes; therefore } D_{(l)} = 3.8 \text{ inches} = MAD$$

Using these values the DU_a becomes:

$$DU_a = \frac{3.8}{(3.8 + 4.5)/2} \text{ X } 100 = 91\%$$

and

$$AR_a = 215:860 = 1:4$$

Note that shortening the length from the "desirable" 1,300 feet (AR_a = 1:4) to 650 feet (AR_a = 1:16) only increased DU_a from 91 to 95%.

Potential Application Efficiency, PELA, when the minimum depth infiltrated equals *MAD*, and when the average depth applied, *D*, on an area 3.0 feet wide and 1300 feet long with no cutback stream is:

$$D = \frac{96.3 \text{ X } 17.5 \text{ gpm X } 18.0 \text{ hrs}}{3.0 \text{ feet X } 1300 \text{ feet}} = 7.6 \text{ inches}$$

then,

$$PELA = \frac{3.8}{7.6} \text{ X } 100 = 50\% \text{ (unadjusted)}$$

For ideal conditions of operation, *AELA* equals *PELA*.

Water losses are runoff and deep percolation. The amount of runoff equals the average depth applied minus the average depth infiltrated. The deep percolation loss is the infiltrated depth minus the stored depth. These values are drawn to scale on Figure IX-9. (For instructions to construct Figure IX-9, see the section Depth and Infiltration and "Adjusted Intake Curves" which follows.) The areas in each category are in proportion to the volumes of water involved in order that problems can be visually identified, efficiencies computed, and an "adjusted" cumulative intake curve drawn if refinement is desired.

From the depths shown in Figure IX-9 and their sum, which is 3.8 + 1.9 + 0.4 = 6.1 inches applied (assumed infiltrated on the extrapolated furrow length), the various losses and other terms can be computed as:

$$Runoff = \frac{1.9}{6.1} \text{ X } 100 = 31\%$$

$$Deep\ Percolation = \frac{0.4}{6.1} \text{ X } 100 = 7\%$$

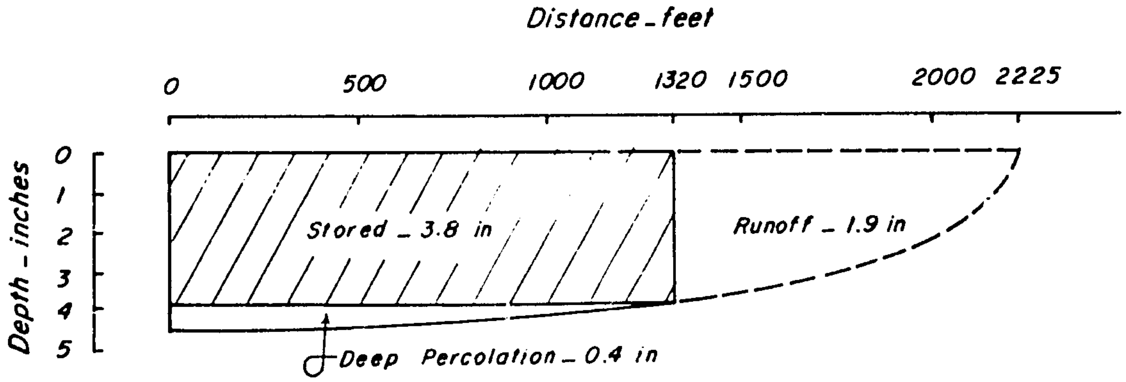


Figure IX-9. Distribution of depth infiltrated (stored plus deep percolation) and runoff for a 1320 foot furrow with a 17.5 gpm stream.

$$PELA = AELA = \frac{3.8}{6.1} \times 100 = 61\% \text{ (unadjusted)}$$

$$DU_a = \frac{3.8}{4.2} \times 100 = 91\%$$

The measured onflow depth of 7.6 inches and *PELA* of 50% computed earlier are different from the above values. This is usually true because of inconsistencies between the two techniques and the general assumption that the section of the furrow and the flow rates used for the infiltration test truly represent the whole furrow. Further error is introduced by using the approximation of dividing the intake rate in gpm/100 ft by the furrow spacing in feet to get the rate in inches/hour, when the precise value is actually obatined by using the intake rate in 96.3 feet of furrow rather than 100 feet of furrow.

The runoff loss can be reduced by cutting back the stream or by using a smaller stream, which would give a larger AR_a. Runoff can be eliminated by using a return flow system, which makes the runoff available for further use. If a return flow system is used, the *PELA* approaches the DU_a resulting in a very high efficiency. (For comparisons with other methods of irrigation, *PELQ* which is even higher than *PELA* should be used.)

Additional illustrations of water losses and efficiencies in dimensionless form using Advance Ratio, (AR_a), are included in Appendix G.

Depth infiltrated and adjusted intake curves

Because the 17.5-gpm stream was so much larger than is reasonable for the length of furrow used, having an AR_q of 1:11, the 9.2-gpm stream will be used to illustrate the "adjusted" intake curve development and other management practices.

Adjusted Intake Curves need to be developed to give more precision by reconciling the actual onflow depth with the calculated infiltrated depth. The frequent discrepancy occurring when the raw intake date is used, as previously illustrated, is caused by: (a) taking the difference (outflow minus inflow) of two numbers which are difficult to measure accurately, and (b) using a short sample length which may not be representative of the whole furrow. The onflow depth measurement is generally the more accurate; therefore, adjustments are normally made to the values of the "raw" intake curve.

To develop "raw" and "adjusted" intake curves, the furrow advance data must either be: (a) collected during the field test on furrows considerably longer than the normal length, or (b) extrapolated as previously discussed in connection with the advance curves presented in Figure IX-7. For this discussion an enlarged and lengthened plot of the 9.2-gpm stream advance curve was redrawn as Figure IX-10. The "raw" curve was terminated at 1750 minutes since this is when T_o = 1000 minutes which satisfies the *MAD* = 3.8 inches at a distance of 1320 feet, i.e., $T_{co} - T_{adv} = T_{o(L)} = T_o$ or 1750 - 750 = 1000 minutes. The recession curves are usually horizontal straight lines based on the assumption that the stream essentially recedes as soon as the onflow is terminated.

The "raw" depth of infiltration is tabulated in Table IX-1 using data from the "raw" cumulative intake curve (Figure IX-6) and the extrapolated advance curve (Figure IX-10). The table gives the depth infiltrated at several distances along the furrow corresponding to the T_o at those locations for the *MAD* = 3.8 inches at 1320 feet.

The "raw" depths infiltrated at the corresponding distances along the furrow are plotted in Figure IX-11 to show the distribution of infiltration plus runoff. For convenience, the "absolute" minimum is usually used for the depth stored (providing it is equal to or less than the *SMD*), which in this case is the *MAD* of 3.8 inches.

The equivalent depth on a furrow with 3.0-foot spacing and 1320 feet long represented by each portion above the "raw" curve in Figure IX-11 can then be determined. This may be done by counting grid squares on the graph paper used (or by planimetering the area or by visually estimating the positions of lines which represent the average depth of each area). From a square count the equivalent depths are:

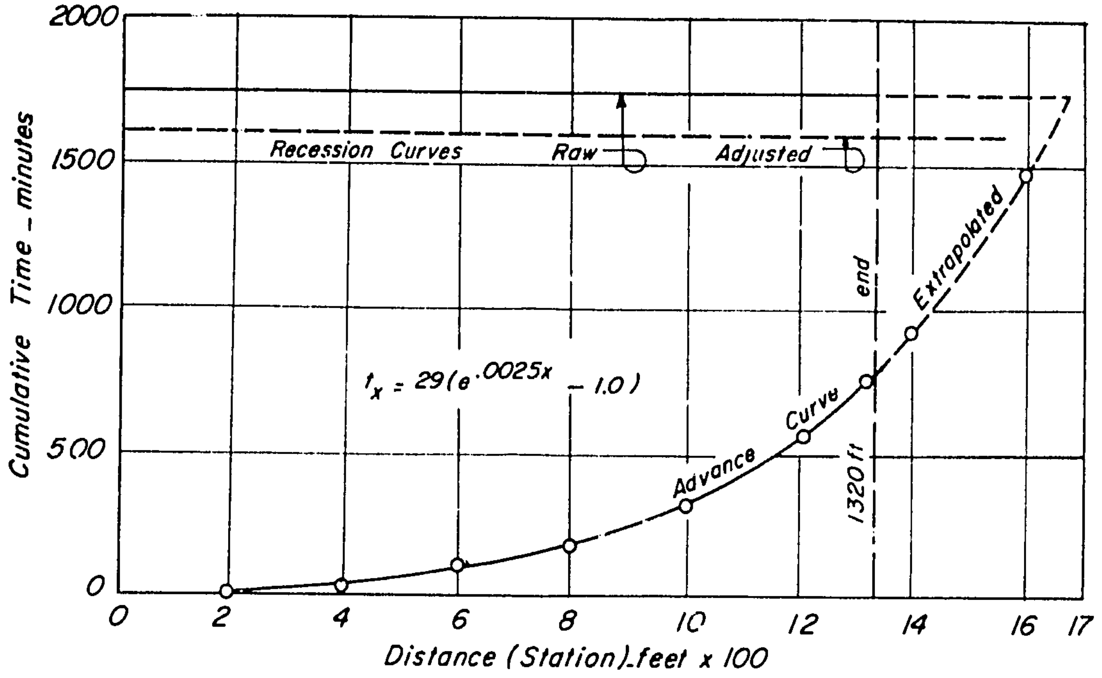


Figure IX-10. Extrapolated furrow advance and recession curves for 9.2-gpm stream in 1320-foot furrow.

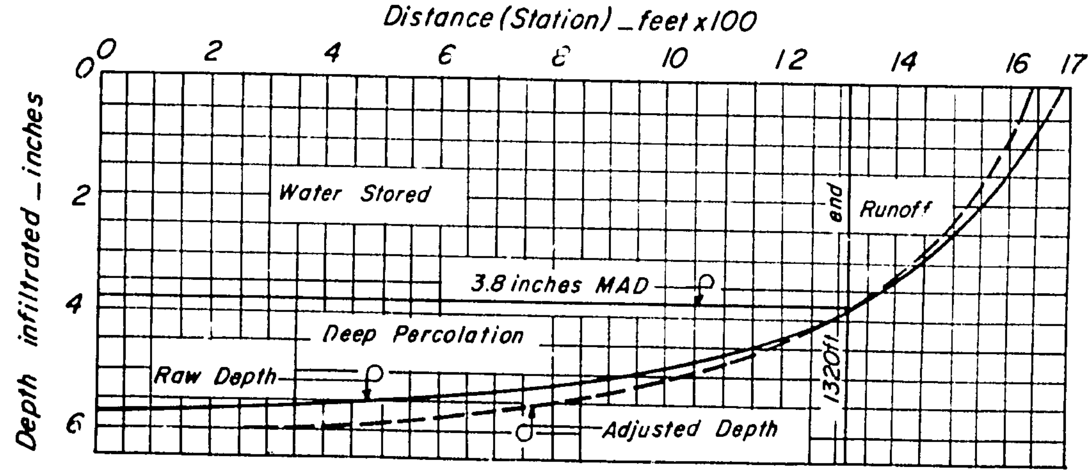


Figure IX-11. Distribution of infiltration plus runoff for 9.2-gpm stream 3.0-foot furrow spacing, and 1320 feet long.

Table IX-1. Raw depth of infiltration along furrow with 3.0-foot furrow spacing for 9.2-gpm stream (MAD = 3.8 inches, T_i = 1000 minutes; T_{adv} = 750 minutes; T_a = 1750 minutes, and extrapolated L = 1675 feet).

	Distance feet						
	0	400	800	1100	1320	1500	1675
T_{adv}	0	40	185	430	750	1190	1750
T_o	1750	1710	1565	1320	1000	560	0
D(raw)	5.7	5.6	5.2	4.6	3.8	2.5	0

Table IX-2. Adjusted depth of infiltration along furrow with 3.0 foot furrow spacing for 9.2-gpm stream (MAD = 3.8 inches), T_i = 850 minutes, T_{adv} = 750 minutes, T_a = 1600 minutes, and extraploated L = 1630 feet).

	Distance feet						
	0	400	800	1100	1320	1500	1630
T_{adv}	0	40	185	430	750	1190	1600
T_o	1600	15460	1315	1170	850	410	0
$D_{(adj)}$	6.0	5.9	5.3	4.8	3.8	2.2	0

Stored	201 squares	= 3.8 inches
Runoff	33 squares	= 0.6 inches
Deep Percolation	72 squares	= 1.4 inches
Total	306 squares	= 5.8 inches

The 201 squares in the stored area corresponds to 3.8 inches on an area 3.0 feet wide and 1320 feet long and establishes a ratio. The 33 squares then corresponds to 0.6 inches of runoff, 72 squares to 1.4 inches of deep percolation and 306 squares corresponds to the total application of 5.8 inches on the 1320-foot length.

The calculated average onflow depth based on a 9.2 gpm stream flowing for 1750 minutes (29.2 hours) is:

$$D = 96.3 \frac{9.2 \text{ gpm} \times 29.2 \text{ hours}}{3.0 \text{ feet} \times 1320 \text{ feet}} = 6.5 \text{ inches}$$

which is considerably greater than the estimated 5.8 inches from the infiltration analysis. The adjusting procedure must reconcile the discrepancy between the 5.8 inches of infiltration while utilizing the 6.5 inches measured onflow as the more probable correct value. To do this, a new "adjusted" cumulative intake curve for the 9.2-gpm stream must be drawn on Figure IX-6. This "adjusted" curve should pass through 6.5 inches of cumulative intake at the same time that the "raw" curve passes through 5.8 inches of cumulative intake and have the same slope as the "raw" curve. On Figure IX-6, the "raw" 9.2-gpm curve passes through 5.8 inches at approximately 1800 minutes. For this illustration the "adjusted" 9.2-gpm curve just happens to coincide with the 17.5-gpm stream "raw" curve.

The "adjusted" depth of infiltration is tabulated in Table IX-2 using Figure IX-6 and IX-10. It is also plotted on Figure IX-11 and the corresponding equivalent depths on a furrow with 3.0-foot spacing and 1320 feet long represented by a square count in each portion above the "adjusted depth curve are:

Stored	201 squares	= 3.8 inches	= 63%
Runoff	29 squares	= 0.6 inches	= 9%
Deep Percolation	87 squares	= 1.6 inches	= 28%
Total	317 squares	= 6.0 inches	= 100%

The calcualted average onflow depth based on the 9.2 gpm stream flowing for 1600 minutes (26.8 hours) is:

$$D = 96.3\ \frac{9.2\ gpm\ X\ 26.8\ hours}{3.0\ feet\ X\ 1320\ feet} = 6.0\ inches$$

which is now identical to the "adjusted" estimated application based on the infiltration analysis.

Evaluation. The DU_a and $PELA$ for this very slow advance can be computed from the "adjusted" estimates of the stored (3.8 inches), runoff (0.6 inch), deep percolation (1.6 inches), and total (6.0 inches) depths of water applied as:

$$AR_a = 750:850 = 1:1.1$$

$$DU_a = \frac{3.8}{3.8 + 1.6}\ X\ 100 = 70\%$$

and

$$PELA = \frac{3.8}{3.8 + 1.6 + 0.6}\ X\ 100 = 63\%$$

to obtain comparable values with other methods and to allow for economically under irrigating a small area, the absolute minimum must be replaced by the average depth in the low quarter. This is emphasized by the following calculations. From the adjusted depth curve in Figure IX-11, the average depth in the low quarter (by visual estimation) is approximately 4.7 inches. The runoff remains the same 0.6 inch or 10%, but the deep percolation is reduced to only 0.7 inch or 12%, and evaluation terms for this slow AR_a are improved to:

$$AR_a = 750:1200 = 1:1.6$$

$$DU = \frac{4.7}{5.4}\ X\ 100 = 87\%$$

and

$$PELQ = \frac{4.7}{5.4}\ X\ 100 = 78\%$$

For small AR values, 1:4, the difference between absolute and Low Quarter values are not as great. This illustration emphasizes the necessity of using only LQ minimums when comparing various evaluations.

Additional studies

Some additional studies using the "unadjusted" infiltration data for ease of illustration rather than the "adjusted," are presented below to demonstrate procedures and possibilities for further manipulation of the test data.

Size of cutback furrow stream and whether only one or several cutbacks are made, depend on the economics of labor and costs of water. The secondary effects of the results of runoff, such as crop damage, breeding of mosquitoes, high water table, etc., will also enter into the management decision on how many cutbacks should be made or whether a return flow system should be installed.

The size of the infiltrated stream at any moment may be found by summing the flow in gpm infiltration in each section at that particular moment. The rate of runoff is then equal to the rate of inflow minus the summation of the average rates of infiltration. The length of the furrow sections chosen for the following procedure must be short enough so that rates at each end do not vary greatly and their average is representative within the section. Sections other than 100 feet in length must be "weighted" since the infiltration rate is expressed in units of gpm/100 feet.

Table IX-3 is set up to estimate the proper size of the cutback stream for the 17.5-gpm furrow stream after 5 hours (300 minutes) of operation. This is about 1.5 hours after water reaches the end and is running off. Sections 200 feet long are used except for the 100-foot end section. The T_{adv} and unadjusted $I_{gpm/100\ feet}$ are taken from the plotted curves on Figures IX-6 and -7.

The total intake along the 1300 – foot furrow presented in Table IX-3 show that the stream should be cut back from 17.5 gpm to approximately 10.6 gpm after about 5 hours. At this time the runoff would be 17.5 - 10.6 ≈ 7.0 gpm. By a similar process for when the irrigation is completed after 18 hours (using cutback streams and the whole furrow as one section since intake rate is very uniform after this long time), the total intake was estimated as 7.2 gpm giving about 3.4 gpm of runoff. This indicates that the first cutback was made a little too late to have a constant rate of runoff for the most effective use of a return flow system.

The average depth applied with the single cutback would be :

$$D = 96.3\ \frac{(17.3\ gpm\ X\ 5.0\ hrs + 10.6\ gpm\ X\ 13.0\ hrs)}{3\ feet\ X\ 1300\ feet}$$

Therefore, the efficiency would be improved to:

Table IX-3. Total rate of unadjusted infiltration after 300 minutes of application with the 17.5-gpm furrow stream.

					Between Station Averages	
Station	T_{adv}	T_o	$I_{gpm/100\ ft}$		$I_{gpm/100\ ft}$	$I_{gpm/200\ ft}$
0+00	0	300	0.75			
					0.75	1.5
2+00	12	288	0.76			
					0.77	1.5
4+00	26	274	0.78			
					0.79	1.6
6+00	49	251	0.80			
					0.81	1.6
8+00	77	223	0.82			
					0.84	1.6
10+00	120	180	0.87			
					0.91	1.8
12+00	170	130	0.95			
					1.00	1.0/100
13+00	210	90	1.05			
				Totals		10.6 gpm

$$PELA = \frac{3.8}{5.4} \times 100 = 71\%$$

For the above analyses, adjusted intakes would give different and more precise values but would complicate the illustration.

For comparative purposes (to the 17.5-gpm stream), the 9.2-gpm *medium sized furrow stream* using "raw" data can be studied. This unadjusted 9.2-gpm stream had a 15% slower intake rate than the 17.5-gpm stream as shown on Figure IX-6. (This may well be an unnecessary refinement since intake rates often vary much more between furrows because of cultural operations that cause differing compaction of the soil.) When:

$D_{(l)}$ = 3.8 inches $\qquad$ L = 1320 feet

Therefore,

$T_i = T_{o(l)} = 1000$ *minutes* $\qquad T_{adv} = 750$ *minutes*

$T_a = T_{o(u)} = T_i + T_{adv} = 1000 + 750 = 1750$ *minutes*

$D_{(u)} = 5.6$ *inches* $\qquad AR_a = 750:1000 = 1:1.3$

Using a linear interpretation(which is not precise for this slow an advance to estimate the average depth of infiltration):

$$DU_a = \frac{3.8}{(3.8 + 5.6)/2} \times 100 = 81\%$$

This is a 10% reduction from the 91% given by the larger stream and shows the effect of the slower advance.

The slowing of the Advance Time from 25% to 75% of T_i is less important than reducing waste from running water after the *SMD* has been satisfied and 100% of the onflow is wasted. Creation and continuance of both of these wastes, deep percolation and runoff, are the responsibility of the irrigator and are not the fault of the method.

If the 9.2-gpm stream which has a slow AR_a = 1:1.3 were run without any cutback for 1750 minutes (29.2 hours), the evaluation terms are:

$$D = 96.3 \frac{9.2 \text{ gpm} \times 29.2 \text{ hrs}}{3 \text{ feet} \times 1320 \text{ feet}} = 6.5 \text{ inches}$$

$$PELA = \frac{3.8}{6.5} \times 100 = 58\% \text{ ("unadjusted")}$$

This is considerably better than the *PELA* = 50% computed for the 17.5-gpm stream with no cutback and AR_a = 1:4.

A single cutback would increase the *PELA* of the 9.2-gpm stream to about 70% even though the furrow is 470 longer than the "desirable" length of 850 feet which would give $AR_a = 1:4$ (see Figure IX-10). Small *AR* values (1:4) result in high uniformities but much runoff and low *PELQ* values unless cutback streams or return flow systems are used; whereas, large *AR* (1:1) are the more efficient when these practices are not used.

A 24-hour application could be obtained for convenience of operation by choosing a stream size of about 12.0 gpm that would take 440 minutes to advance the 1320 feet. This, plus the 1000-minute T_i, would give the desirable duration of 1440 minutes (24 hours) and an *AR* of 1:23. This combination with no cutback would give acceptable distribution (DU_a = 87%) but inefficient irrigation (*PELA* = 54%). However, a 24-hour application is most convenient for labor and continuous water deliveries. With a cutback after 10 hours, this alternative would have a reasonable *PELA* of about 67% (*PELQ* = 74%) and would require very little additional labor. Another alternative is to use a return flow system which could increase the *PELA* to about 87% (*PELQ* ≈ 95%) and require minimum labor and only a medium capacity return flow capacity.

The 17.5-gpm stream would give a *PELA* of 91% (*PELQ* = 96%) and utilize the same labor but would require a larger irrigation and return flow system and should be cut off after 17 hours instead of 24 hours. Management must decide whether the 4% increase in *PELA* is economical or not.

Continuous furrows save water and labor. An alternate method would be to replace the supplemental supply ditch (in the middle of the field) with gated pipe. In this practice, smaller streams are started more or less simultaneously at the upper end and at the intermediate line or lines. Runoff from the upper portion mingles with the streams at the intermediate locations and thereby the upper runoff is utilized. Since the upper line may supply all the flow needed after cutting back or completely turning off the water at the intermediate line, total runoff is reduced with a minimum of labor. With the portable gated pipe, lengths of run in long fields may be varied as the *MAD* of crop changes.

Furrow spacing and shape are important management tools. Spacing is often related to crop row spacing, but usually a limited variation is reasonable. For example, the effect of a change from a 2.5-foot to a 3.0-foot furrow spacing for a *MAD* of 3.0 inches can be seen on Figure IX-6. This increases the T_i from 480 minutes to 600 minutes which also permits increasing the "desirable length" for the same *AR* and *DU*.

If it is not practical to change spacing, the furrow could be widened by about 6 inches. This would enable use of a larger stream with little change in T_i.

The maximum spacing for a specific furrow shape is related to:

1. The soil texture as it affects lateral capillary movement.

2. The *SMD* as it affects how long water flows in the furrow.

The general wetting patterns related to texture in dry soils are shown in Figure IX-12.

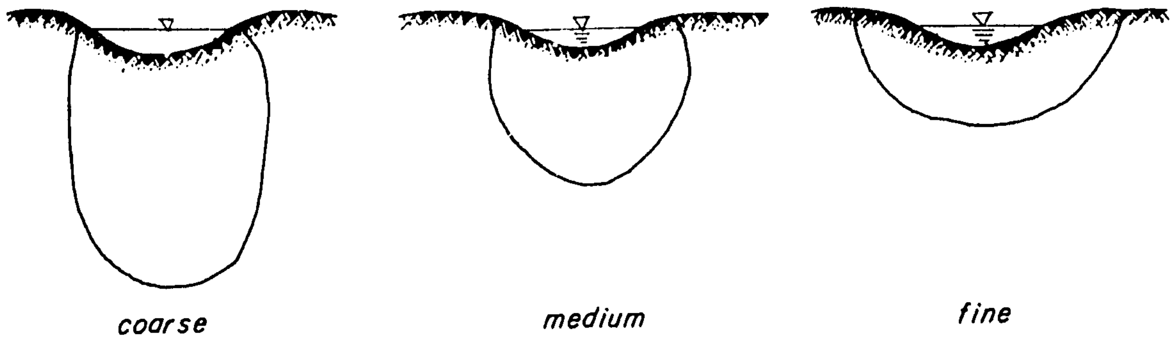


Figure IX-12. Wetting patterns under furrows in various textured dry soils.

A dry fine-textured soil conducts water laterally and downward at about the same rate and permits a wide furrow spacing. The downward speed of the moving water decreases as the wetting front penetrates deeper and encounters moister soil. In coarse textured soil, the lateral capillary flow does not move very far, while the downward flow moves easily through the coarse soil by gravity.

Generalized furrow shapes are shown in Figure IX-13. In the "vee" furrow, wetted width and depth decrease as streamflow decreases downslope. This will moderately decrease the intake rate along the furrow. In parabolic and broad furrows, a decrease in flow causes a small corresponding decrease in water depth but causes very little change in wetted width so intake rate is quite uniform along the furrow length. Parabolic and broad furrows can handle larger flows without erosion than the "vee" shape. Also, they can easily be made different widths, therefore, they are more desirable shapes.

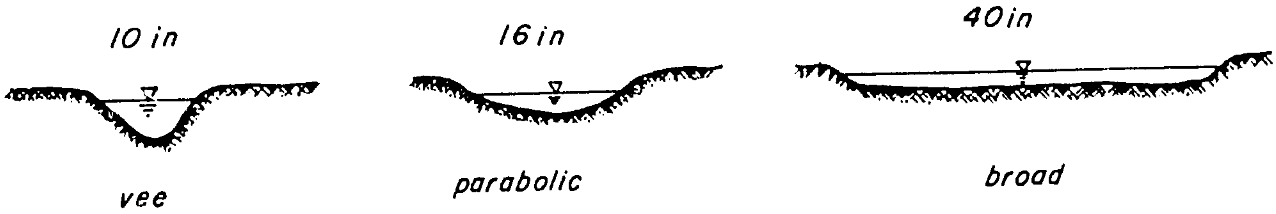


Figure IX-13. Typical furrow channel cross sections.

Sprinklers may well be used in combination with furrows to take advantage of the best features of each system. Light applications are seldom practical with furrows since short furrows requiring much labor are needed to obtain reasonable efficiency. Sprinklers can easily and efficiently apply the light applications needed for seed germination, especially where crop root zones are shallow. However, a light pre-irrigation and heavier first irrigation for seed germination can often be combined to apply moderate depths at both applications to improve furrow irrigation efficiency.

Summary of full evaluation

The field evaluation and analysis described above along with pertinent concluding comments is summarized below. (Low absolute values rather than LQ are used.)

Present system. The evaluated system under the present management had the following conditions:

L = 650 feet $\quad$ SMD = 3.6 inches $\quad$ T_a = 10 hours

q = 17.5 gpm $\quad$ MAD = 3.8 inches $\quad$ T_{adv} = 52 minutes

$D_{(l)}$ = 2.7 inches (underirrigated) $\quad$ AR_a = 1:11 (uneconomically small)

The evaluation produced the following results:

DU_a = 95%

$PELA_{(3.6 \text{ inches})}$ = 29% ("unadjusted")

$AELA_{(2.7 \text{ inches})}$ = 31% (with no cutback)

Since this combination caused no erosion, a larger stream and a longer furrow could be used. There was no cutback, so runoff was excessive. The *AR* was uneconomically small, labor was excessive, and efficiencies were very low.

Practical alternatives. Some practical alternative design and management possibilities are summarized as follows:

1. Longer furrows:

L = 1300 feet $\quad$ q = 17.5 gpm $\quad$ SMD = MAD = 3.8 inches

T_i = 860 minutes $\quad$ T_{adv} = 215 minutes ("desirable advance")

T_a = 1,075 minutes = 18 hours AR_a = 1:4

DU_a = 91% or DU = 94%

$PELA_{(3.8 \text{ inch})}$ = 50% with no cutback ("unadjusted")

PELA = 71% (with single cutback)

PELA = 80% or greater (with double cutback)

PELA = 91% (for return flow system of large capacity and no cutback)

2. Longer furrow with smaller stream (based on unadjusted "raw" data)

L = 1320 feet q = 9.2 gpm SMD = MAD = 3.8 inches

T_i = 1000 minutes T_{adv} = 750 minutes (slow advance rate)

T_a = 1750 minutes = 29.2 hours AR_a = 1:1.3

DU_a = 81% (with no cutback)

PELA = 58% (with no cutback)

PELA = 70% (with single cutback)

PELA = 81% (for small capacity return flow system and no cutback)

3. Longer furrow with smaller stream (based on "adjusted" data):

L = 1320 feet q = 9.2 gpm SMD = MAD = 3.8 inches

T_i = 850 minutes T_{adv} = 750 minutes

T_a = 1600 minutes = 26.7 hours AR_a = 1:1.1 or AR = 1:1.6

DU_a = 70% or DU = 87% (with no cutback)

PELA = 63% or PELQ = 78% (with no cutback)

4. Longer furrow with medium stream to obtain 24-hour duration:

L = 1320 feet q = 12.0 gpm SMD = MAD = 3.8 inches

T_i = 1000 minutes T_{adv} = 440 minutes (moderate advance rates)

T_a = 1000 + 440 *minutes* = 24 *hours* AR_a = 440/1000 = 1:2.3

DU_a = 87% *or* DU = 90%

PELA = 54% *(with no cutback)*

PELA = 67% *(with single cutback)*

PELA = 87% *or* *PELQ* = 95% *(with medium capacity return flow system)*

Additional alternatives which might be considered and studied further would include:

5. Using a gated pipe to permit continuous furrows and to allow length of runs to be varied as *MAD* varies.
6. Using sprinklers for light applications in the early season and for seed germination.
7. Making first irrigation excessive to supplement a moderate pre-irrigation application.

Conclusions. A final decision by management on what irrigation practices should be used for this field would depend on the following:

1. Value of water in terms of its cost or in terms of its productiveness when the water supply is limited
2. Cost and skill of labor
3. Capital investment
4. Secondary problems caused by runoff water and deep percolation.

Based on conservation irrigation alone with a high *PELA* value, the present system of 650-foot furrows, 17.5-gpm streams, and a return flow system putting the runoff back into a reservoir with or without a cutback, would give a *PELQ* of about 95% even for a 2.5-inch application. Using the 9.2-gpm stream, *PELQ* would be 93% or greater. At other times during the season when different *MAD* values are desired, other stream sizes and advance ratios would be desirable.

Actual irrigation practices measured by *AELA* or *AELQ* are invariably lower than *PELA* or *PELQ* since not all furrows react exactly the same because of variations in soils and cultural practices. In addition, the value of the *SMD* determined by any practical method on a field basis is only approximate; the accuracy of measuring furrow streams can seldom be high even though the total depth applied is often adequately measured, and the convenience of labor is frequently a dominant criterion.

The ability to turn off the water when the *SMD* is satisfied is most important for good efficiency since all water subsequently run is 100% wasted. However, with furrows the intake rate at the end of irrigation will have greatly decreased. Therefore, from a 25% over-run of time less than 5% waste of this excess water may go to deep percolation losses and build up of a high water table but the other 20% will be runoff.

When the furrow length is such that T_{adv} is at the "desirable" condition of about $1/4\ T_i$, $(AR = 1{:}4)$, *DU* will be about 95%. Reducing T_{adv} has only a moderate effect on improving *DU*; therefore, a moderate increase in T_{adv} is not very detrimental.

The duration of irrigation, T_i, can be altered within reasonable limits to match hours of water delivery or labor convenience by modifying one or all of the following: stream size and furrow length, which will affect T_{adv}, and *MAD*, furrow spacing, and shape which will affect T_i.

Flexibility in frequency, rate, and duration of supply flow are essential to obtain high efficiency irrigation and to reduce labor requirements. The stream size available in the field should be large enough to keep the irrigator busy and to start initial streams in all furrows simultaneously. The compromises between capital costs and savings of labor and water must be studied. Evaluation of the irrigation system provides the basis for such studies which frequently indicate that a reservoir would be an economical capital investment. Furthermore, a return flow system can be an efficient means for saving water and, more importantly, a labor saver. With good design, semi-automation (automated control of the flexibility in rate and duration of the water supply but manually controlled field application of a larger stream) becomes very practical and economical.

CHAPTER X
BORDER-STRIP IRRIGATION

In border-strip irrigation, a sheet of water flows on a sloping soil surface between low ridges. The ridges may be from 20 feet to over 100 feet apart depending upon the topography, inflow capacity, method of application, farm machinery requirements, and uniformity of application desired. In general, the slope across each border-strip (between the ridges) should be nearly level and the slope down the border-strip may be anywhere from nearly level to preferably less than 1%, but may be much steeper for sod covers. The depth of infiltration at any point along a border-strip is dependent upon soil infiltration characteristics as well as the time surface water is at that point (opportunity time).

Border-strips are of two types and are distinguished by the kinds and amounts of land preparation required for each. This, in turn, is related to economics of land preparation and whether the soil profile can tolerate cuts and fills.

Graded border-strip irrigation requires preparing the ground so that its lengthwise slope is uniform, and the crosswise profile will be level or nearly so to assure uniform water coverage. Figure X-1 shows a field with well-graded border-strips in the process of being irrigated. The photograph was taken shortly after the water had been diverted from the middle to the right hand strip. To obtain uniform infiltration, this type of irrigation must be used with full consideration of varied rates of soil intake. (The basic objective of land grading is to obtain uniform irrigation, not merely to produce a uniform grade.)

Guided border-strips are usually constructed down the steepest grade; this permits them to be nearly level across or become so with a little grading. Variations in grade and soil, along such strips, are tolerated in order to reduce the amount of grading. Often the strips are quite narrow to assure that water spreads over the entire width.

The border-strip method of irrigation can be highly effective, but it requires more skill in irrigation management than any other method because several factors must be coordinated or compromised simultaneously; therefore, a study of the procedures is essential to proper operation. Certain complexities must be understood and they are as follows:

1. Strips should have a specific length for a given irrigation.

2. Short strips may be impractical for use.

Figure X-1. Graded border-strip irrigation in operation.

3. Water usually is turned off before it reaches the lower end of a strip after running long enough to provide adequate irrigation at the upper end.

4. The upper end of a strip may be underirrigated in comparison with the middle section or lower end of the strip, whereas in furrow irrigation the upper end is always overirrigated.

Use of border-strip irrigation may be subjected to either a brief simple evaluation or to a comprehensive study and analysis.

Simple Evaluation

The object of any evaluation is to determine how effectively the land, water, soil, and labor are being used within the framework of other management considerations. Simply determining whether some problem exists in a given field and how serious the problem is requires little work and equipment. Any obvious problems become apparent from studying the simple data gathered in the eight steps listed under Field procedure. But to guide management in understanding the techniques of this system and to provide information needed to improve a given operation, a full study, analysis, and evaluation are needed.

The two basic questions applicable to all systems of irrigation must be asked in analysis of border-strip irrigation, namely, "Is it dry enough to start irrigating?" and "Is it wet enough to stop?" Checking the *SMD* gives the best answer to the first question, but measurement of the evapotranspiration that has occurred since the last preceding irrigation gives a reasonable answer. Probing to check depth of infiltration at the end of irrigation can adequately answer the second question. Additionally, in a border-strip irrigation, water usually should reach about 0.6 to 0.9 of the length of the strip by the time the upper end of the strip has had adequate infiltration and then be turned off. In fact, *satisfying this final point*, which interrelates stream size, *SMD*, intake rate, and length of strip, *is unique to the border-strip method and is the most difficult problem encountered.*

Equipment needed

The equipment needed for the simple evaluation is:

1. A soil auger.
2. A soil probe.
3. An ordinary watch.
4. A 100-foot measuring tape for locating stations along the borders.
5. Lath or stakes to make stations, and a hatchet to drive them.

Field procedure

A simple evaluation does not require measurements of cumulative intake or of streamflow. The following is the sequence of operations for gathering data:

1. Estimate the *SMD* at several locations along the border being investigated.

2. Drive stakes at uniform distances or stations (usually 100 feet apart) along the length of the strip.

3. Observe how well water spreads across the strip. The ground surface should not have excessively high or low spots, and no long-time ponding should occur at the lower end of the strip.

4. Observe and record the time when the water reaches each station. These times will be used later in plotting the advance curve.

5. Record the time and location of the water front when the inflow is turned off.

6. Record the time when the water disappears from the surface at each station. These times will be used later in plotting the recession curve.

7. Observe the rate of runoff. (Duration of runoff is determined from recrods made in steps 4 and 5.)

8. As water recedes along the strip, use the probe to check whether infiltration is uniform and adequate. An additional simple check can be made on adequacy of the irrigation by first calculating the depth of application from the known rate of flow, duration of irrigation, and length and width of strip. Then subtract the depth of runoff which is calculated from the rate and duration of runoff.

Utilization of field data

Following is an analysis of an irrigation of an alfalfa field which had just been mowed where the *MAD* was 50%, a condition widely accepted as good for growth in varied soils and climates. The border-strips were 24-feet wide and 1400 feet long with a supplemental supply line laid halfway down the strip. This analysis is based on data taken in the successive steps previously described.

1. A check of the *SMD* showed that the topsoil was quite moist; this indicated that the *SMD* was still substantially less than the *MAD*. A 50% *MAD* is equivalent to 4.5 inches in the 6 foot-deep root zone of the sandy loam soil which holds 1.5 inches per foot available moisture. The check of *SMD* through the full depth of the root zone indicated that moisture was adequate through the full depth and that the *SMD* was only 2.9 inches. This irrigation could have been delayed a week, but applications were being scheduled to fit timing of harvest operations. To accomplish this, the manager was applying lighter irrigations more frequently than is needed to maintain a 50% *MAD*.

2. Observing flow of the water showed no ponds or dry spots, so the land had been graded well.

3. Curves of water advance and recession at the several stations were plotted. (Figure X-2 shows a plot of these field data.)

4. The time when water was shut off (88 minutes' duration) and location of the water front at that time (Station 6 + 10) were entered in the plot.

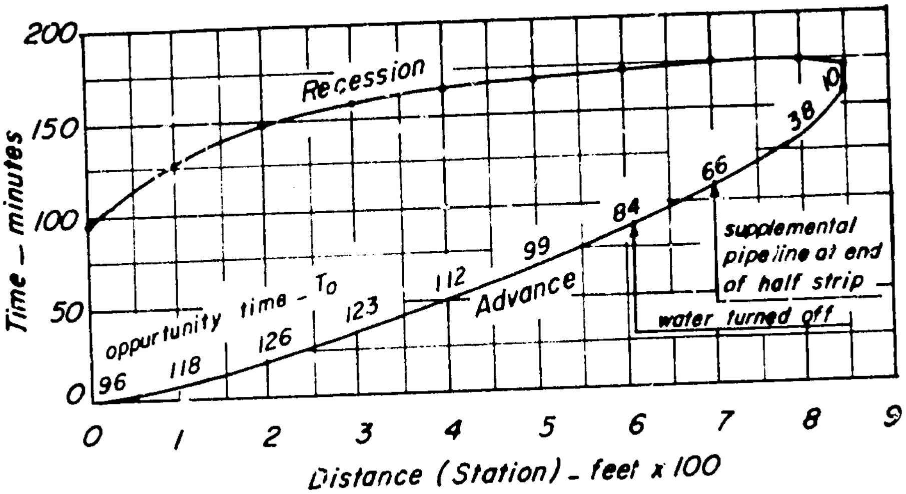


Figure X-2. Plot of advance and recession curves used in simple evaluation of border-strip irrigation, using a 1.20 cfs stream on a mowed alfalfa strip 21 feet wide with a sandy loam soil.

5. Comparison of the advance and recession curves (which converge) in Figure X-2 with those shown in Appendix E shows that the stream was too small. The water front at the time of cutoff was very close to the end of the upper half of the strip (station 7+00), and there was considerable runoff into the lower half; therefore, the cutoff was too late for this length of strip. Figure X-2 does not indicate the adequacy of irrigation, only the T_o.

6. The runoff stream was medium flow and continued for about 66 minutes, as shown by the time interval between the advance and recession curves at Station 7+00. Water should be at the lower end of the strip for as long as was needed to replace the *SMD*, but 66 minutes seems to be too long to replace an *SMD* of only 2.9 inches.

7. Adequacy of penetration at the lower end of the strip was not checked with either the probe or auger as it should have been. Consequently, for this evaluation it can only be surmised that the depth infiltrated was adequate. An auger check in a previously irrigated adjacent strip showed that it had received enough water.

8. The opportunity time, T_o, for water to infiltrate at any point along the border-strip is equal to the time interval between the advance and recession curves. The nearly 2:1 variation in the T_o values shown along the advance curve in Figure X-2 indicate rather poor application uniformity.

It is helpful but not essential to know the rate of flow. This border strip received the full flow of the well, reported to be 1.2 cfs, for 88 minutes. The borders were spaced at 24 feet but only 23 feet were wet; since the strip was 700 feet long, the area irrigated (wetted) was 0.37 acre. The depth of water applied to the strip can be computed by:

$$D = \frac{1.2 \text{ cfs } X \frac{88}{60} \text{ hrs}}{0.37 \text{ ac}} = 4.8 \text{ inches}$$

From this, the application efficiency can be found by:

$$AELA = \frac{\text{minimum depth stored}}{\text{average depth applied}} X\ 100 = \frac{2.9}{4.8} X\ 100 = 60\%$$

Analysis and recommendations

The analysis summarized above suggests the three following recommendations:

1. Delay irrigation a few days until soil becomes drier. If the harvest of green-chop alfalfa requires an early irrigation, a lighter application might suffice. This probably would require a shorter strip for good efficiency (see Appendix E).

2. Use a larger stream, which would flow more rapidly; then the advance and recession curves would plot nearly parallel and infiltration would be more nearly uniform.

3. To reduce runoff, shut off the stream before the water front comes so near the end of the strip but not too soon as this would cause underirrigation of the lower end of the strip.

Summary of simple evaluation

The simple evaluation of the border-strip system provided the following information:

1. The field was irrigated sooner than was justified by a check of the *SMD*.

2. The field had been graded satisfactorily.

3. The T_o and consequently depth infiltrated was not uniform.

4. The stream was cut off too late.

5. The adequacy of this irrigation was not checked by auger or probe, but a check of an adjacent strip irrigated similarly indicated that this irrigation probably was adequate.

6. The *AELA* of about 60% was low.

Using a larger stream to effect more nearly uniform application and shortening duration of flow to reduce runoff would improve efficiency. A smaller *MAD* or a longer strip probably would be necessary to accommodate the desirable changes.

Full Evaluation

Both graded and guided border-strip irrigation systems are evaluated in the same way.

Evaluation

To perform a full evaluation, the first step is to choose a typical location in the field to be irrigated at the time irrigation is due. Information to be gathered includes:

1. Rate of flow and duration of various sized streams turned into several border-strips.

2. Rate of advance of the streams down the strips.

3. Time when the water recedes from the surface at each station.

4. Cumulative intake depth of water into the soil with time.

5. Width of the wetted portion of each strip.

6. The *SMD*.

7. Adequacy of the irrigation as measured a day or two after the application.

Certain additional information desirable for use in more detailed study includes such items as:

8. Ground profile and cross slope of the strips.

9. Soil profile and texture.

10. Rate and duration of runoff at the lower end of each strip.

11. Stage of growth of the crop being irrigated and its effect on retardance of the streamflow.

After the field data have been recorded and plotted, study will show:

1. Distribution Uniformity DU_a (absolute minimum) or *DU*.

2. Potential Application Efficiency, *PELA* (absolute minimum) or *PELQ*.

3. Application Efficiency, *AELA* (absolute minimum) or *AELQ*.

4. Correct duration of irrigation, T_i.

5. Correct stream size.

A more detailed study would show how variations in size of stream, length of field, *MAD*, and time of cutoff or distance of water advance can be varied to affect the potential and actual application efficiencies.

Equipment needed

The equipment needed for the full evaluation of border-strip irrigation is:

1. A 100-foot measuring tape for locating stations.

2. Lath or stakes to mark stations and a hatchet to drive them.

3. An ordinary watch (preferably with a second hand).

4. Devices for measuring flow, such as Parshall flumes, large siphons, weirs, flow meters, horizontal pipe jets, or others that may be improvised; and time or head measuring devices as needed (see Appendix B).

5. A shovel.

6. A soil auger.

7. A soil probe.

8. A cylinder infiltrometer set (usually five cylinders), buckets, and measuring gauge.

9. Forms X-1 and X-2 for recording data.

Additional equipment that is convenient and useful, but not absolutely essential in these more detailed studies, would be:

10. A surveying level and rod.

11. Equipment for measuring *SMD*.

Field procedure

Following is the sequence of activities for gathering the field data needed for a full evaluation of border-strip irrigation:

1. Choose a location at which the soil, slope, and crop are representative for the whole field. This location should have a steady source of water.

2. Select three strips that may be adjacent to each other but alternate strips are preferred because they permit work without walking on wet soil.

3. Set six or more stakes adjacent to a strip (usually at 100-foot intervals). Measure the width of each wetted strip and spacings between ridges and record in part 3 of Form X-2.

4. Set a flow measuring device at the inlet of each strip. Another one may also be set at the lower end of the strip to measure runoff if desired.

5. Estimate the *SMD* and fill in parts 2 and 3 of Form X-1 (see Table I-1). Compare the *SMD* with the desired *MAD*. If the *SMD* differs appreciably from the *MAD*, the evaluation will be noticeably affected because rates of intake and advance are affected by the amount of moisture in the soil.

6. Set four or more cylinder infiltrometers in a carefully chosen "typical" location, conduct an infiltration test (see Appendix D), and enter the data in Form X-1.

7. Set a constant rate stream of usual size in one border strip; also set a larger and a smaller stream in the other two strips. Record the flow rates of these three streams and check rates for consistency during the test. Record the time when flow was started and shut off and any variations in Form X-2. (Usually water is shut off when the stream has advanced about 0.7 of the length of the strip for fine textured and 0.9 of the length for coarse textured soils.)

Form X-1. BORDER-STRIP IRRIGATION INFILTRATION EVALUATION

1. Location *G. Ranch, Santa Maria*, Observer *JLM*, Date *16 Aug 1976*
2. Crop *alfalfa*, Root zone depth *6* ft, MAD *50* %, MAD *4.5* in
3. Soil: texture *sandy loam*, available moisture *1.5* in/ft, SMD *2.9* in
4. Crop history: *alfalfa green chop, equipment traffic in middle*
5. Remarks: *soil not dry enough to warrant irrigation. Cylinder*
6. *#4 refilled.*

Cylinder					*1*
Time minutes			Infiltration inches		
watch	diff	cumu	depth	diff	cumu
10:55		*0*	*2.50*		*0*
56	*1*	*1*	*.60*	*.10*	*.10*
59	*3*	*4*	*.80*	*.20*	*.30*
11:01	*2*	*6*	*.85*	*.05*	*.35*
05	*4*	*10*	*3.00*	*.15*	*.50*
17	*12*	*22*	*.30*	*.30*	*.80*
26	*9*	*31*	*.45*	*.15*	*.95*
38	*12*	*43*	*.60*	*.15*	*1.10*
12:03	*25*	*68*	*4.00*	*.40*	*1.50*
21	*18*	*86*	*.10*	*.10*	*1.60*
39	*18*	*104*	*.35*	*.25*	*1.85*
1:20	*41*	*145*	*.80*	*.45*	*2.30*
58	*38*	*183*	*5.30*	*.50*	*2.80*

Cylinder					*2*
Time minutes			Infiltration inches		
watch	diff	cumu	depth	diff	cumu
10:57		*0*	*1.70*		*0*
58	*1*	*1*	*.90*	*.20*	*.20*
11:06	*8*	*9*	*2.40*	*.50*	*.70*
18	*12*	*21*	*.70*	*.30*	*1.00*
27	*9*	*30*	*.90*	*.20*	*1.20*
49	*22*	*52*	*3.40*	*.50*	*1.70*
12:13	*24*	*76*	*.85*	*.45*	*2.15*
31	*18*	*94*	*4.15*	*.30*	*2.45*
49	*18*	*112*	*.50*	*.35*	*2.80*
1:30	*41*	*153*	*5.15*	*.65*	*3.45*
2:08	*38*	*191*	*.95*	*.80*	*4.25*

Cylinder					*3*
Time minutes			Infiltration inches		
watch	diff	cumu	depth	diff	cumu
10:59		*0*	*2.20*		*0*
11:00	*1*	*1*	*.50*	*.30*	*.30*
02	*2*	*3*	*.60*	*.10*	*.40*
07	*5*	*8*	*.70*	*.10*	*.50*
18	*11*	*19*	*.90*	*.20*	*.70*
27	*9*	*28*	*3.00*	*.10*	*.80*
49	*22*	*50*	*.25*	*.25*	*1.05*
12:14	*25*	*75*	*.50*	*.25*	*1.30*
50	*36*	*111*	*.95*	*.45*	*1.75*
1:30	*40*	*151*	*4.35*	*.40*	*2.15*
2:08	*38*	*189*	*.80*	*.45*	*2.60*

Cylinder					*4*
Time minutes			Infiltration inches		
watch	diff	cumu	depth	diff	cumu
11:03		*0*	*1.40*		*0*
04	*1*	*1*	*2.00*	*.60*	*.60*
08	*4*	*5*	*.25*	*.25*	*.85*
18	*10*	*15*	*.70*	*.45*	*1.30*
27	*9*	*24*	*.90*	*.20*	*1.50*
49	*22*	*46*	*3.35*	*.45*	*1.95*
12:14	*25*	*71*	*.95*	*.60*	*2.55*
50	*36*	*107*	*4.60*	*.65*	*3.20*
1:30	*40*	*147*	*5.50*	*.90*	*4.10*
2:08	*38*	*185*	*6.30*	*.80*	*4.90*
08	*0*	*185*	*2.15*	*0*	*0*
36	*28*	*213*	*2.65*	*.50*	*5.40*

Form X-2. BORDER STRIP IRRIGATION WATER ADVANCE AND RECESSION EVALUATION

1. Location *G. Ranch, Santa Maria*, Observer *JLM*, Date *16 August 1976*
2. Crop and Condition *alfalfa - just mowed*, Border condition *well graded*
3. Border: spacing *24* ft, strip width *21* ft, wetted width *23* ft, slope *0.5%*
4. Irrigation: duration *88 min*, frequency *variable*, water spread *evenly across border*
5. A: *Advance* B: *Recession* C: *Profile Data* D:

Stream *1.20 cfs* --

Rod Readings

A: *Advance*

Time – min. Watch	Time – min. Diff.	Time – min. Cumu.	Station feet
10:51		0	0 + 00
10:59	8	8	1
11:12	13	21	2
26	14	35	3
41	15	50	4
59	18	68	5
12:18	19	87	6
40	22	109	7
13:06	26	135	8
32	26	161	8 + 50

B: *Recession*

off

Time – min. Watch	Time – min. Diff.	Time – min. Cumu.	Station feet
10:51		0	0 + 00
12:19	88	88	0
12:27	8	96	0 + 00
59	32	128	1
13:18	19	147	2
29	11	158	3
33	4	162	4
38	5	167	5
41	3	170	6
45	4	174	7
43	-2	172	8
42	-1	171	8 + 50

C: *Profile Data* — *Rod Readings*

Time – min. Watch	Time – min. Diff.	Time – min. Cumu.	Station feet
		rod	
		3.70	0 + 00
		4.55	1
		4.75	2
		5.00	3
		5.50	4
		6.00	5
		6.48	6
		7.00	7
		7.50	8 + 00

D:

Time – min. Watch	Time – min. Diff.	Time – min. Cumu.	Station feet

8. Record the time when each stream reaches each station in Form X-2. (If the moving stream front is irregular, use an average front.)

9. Record the time when the water disappears at each station in Form X-2. This may be difficult because of puddles and small channels or sod in pastures. The purpose of this record is to determine when there is no longer an opportunity for water to infiltrate at that station. Consistency in choosing the disappearance condition of all stations is important.

The recession curve drawn from these data is the key control in the evaluation procedure. The lag time, T_l, between turning off the stream and disappearance of surface water at the upper end (station 0 + 00) of the strip will be appreciable.

10. Measure or observe and describe the rate of runoff at different times. The beginning and end of runoff can be readily observed from the advance and recession curves.

11. Check the adequacy of the application a day or two after irrigation by using a soil auger or tube. During irrigation, the penetration of the water can be determined to a depth of approximately three feet by using a probe. Water will continue to move deeper for several days.

Additional information useful for either a more detailed study or for designing other systems may consist of:

12. Detailed analysis of the soil profile.

13. Elevations at stations to determine the gradient of the strips.

Utilization of field data

Graphic presentation of data taken in the field facilitates analysis. It is desirable to plot the data in the field as soon as they are recorded so that possible inconsistencies may be noted and immediately corrected.

Cumulative intake curves. The cumulative intake curve for each infiltrometer is plotted on 3-cycle log-log paper. The curves in Figure X-3 are plotted from the data on Form X-1. These curves usually appear as straight lines but may curve slightly and often "dogleg" as in Figure X-3.

Some curves steepen after only a few minutes either because of sudden release of air (usually in very sandy soil) trapped by water

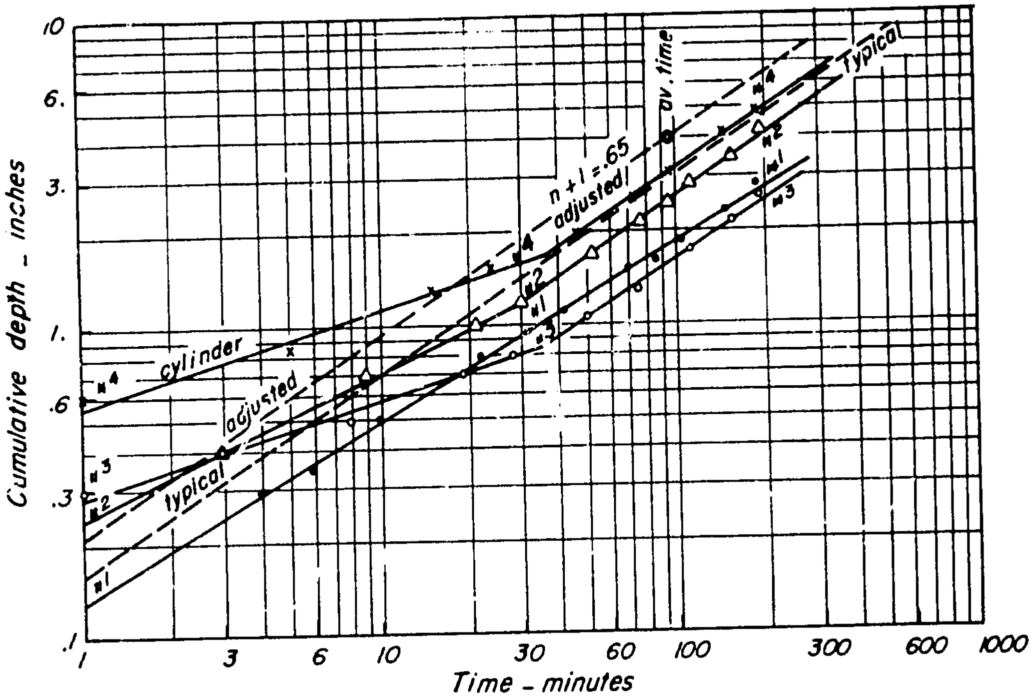


Figure X-3. Cumulative cylinder infiltration curves for the data in Table X-1 from a slightly moist silt loam soil with a crop of alfalfa.

covering the soil surface or because the infiltrometer was not driven deeply enough. Soils that have openings into which water quickly disappears often yield curves that for a few minutes are steep and then flatten. Plow pans have a similar effect but this effect usually is delayed. (Data from the cylinders should not be averaged before plotting because doing so would modify the correct slope of the line and thus mask various soil conditions and the range of rates of intake.)

The initial reading and the half-minute readings usually are not plotted on the log-log paper, but they are valuable in checking unusual conditions. After all curves in a test operation have been plotted and the deviations have been considered and allowed for, a "typical," line can be drawn for use in evaluation. Its position should be checked later and adjusted as may be necessary to show the correct duration for irrigation (see Figure X-3).

<u>Advance and recession curves.</u> Advance and recession curves for each test strip are plotted on coordinate paper, a separate sheet for each

strip. Each plot should be identified with the corresponding Forms X-1 and X-2 for the strip identification, width, stream, size (in cfs), *SMD*, soil texture, crop, description of retardance, degree of slope, and other pertinent information. The advance and recession curves in Figure X-4 shows the plot of the data recorded on Form X-2. These data, like those for the cumulative intake curves, should be plotted as soon as they have been recorded. Watch time may be plotted, but it is easier to plot cumulative time.

Analysis

The following analysis of data recorded on Form X-1 was used to determine the DU_a, *PELA*, and *AELA* of a border strip test operation and to determine how to improve use of the system. Only one strip was irrigated in this test operation because all the water came from a well where volume of the streamflow was small and rate of flow was invariable.

The border-strip irrigated in this test was the upper half of a 1400-foot-long field that had a supplementary pipeline at 700 feet below its upper end. Water that flowed beyond this midpoint would normally be considered runoff unless the supplementary line and the upper line were used simultaneously to irrigate the entire 1400-foot strip.

In typical fields, the border-strip terminates at the end of the field, and the advance and recession curves may be extrapolated to their intersection to portray the runoff graphically. This extrapolation could be simulated for a strip by cutting off the flow prematurely. Fortunately for this test, actual curves could be plotted beyond station 7+00.

Cumulative intake curves plotted (Figure X-3) from data recorded on Form X-1 show infiltration from four cylinders. One curve is a straight line, two others "dogleg" appreciably, and the fourth doglegs only slightly. Anticipating the effect of rapid initial intake but using the slope of the consistent portion of the lines, a straight dashed line, presumed to be typical for all, was added and labeled. Later the "adjusted" line, using the procedure described below, was drawn and was used for the evaluation process because it shows an average intake rate for the whole field and therefore is more representative than the data from any one of the four cylinders. Averaging the data from all four cylinders to plot only one line would produce a misleading curve because it would not indicate the range of conditions that actually exist.

Adjusted cumulative intake is developed as shown in Figure X-4. At each station on the total strip (actual and extrapolated portions), the opportunity time (time that water was on the ground), T_o, was noted by measuring the time interval between the advance and recession curves. The corresponding depth infiltrated, *D*, was taken from the "typical" cumulative intake curve in Figure X-3 and tabulated in Table X-1 for

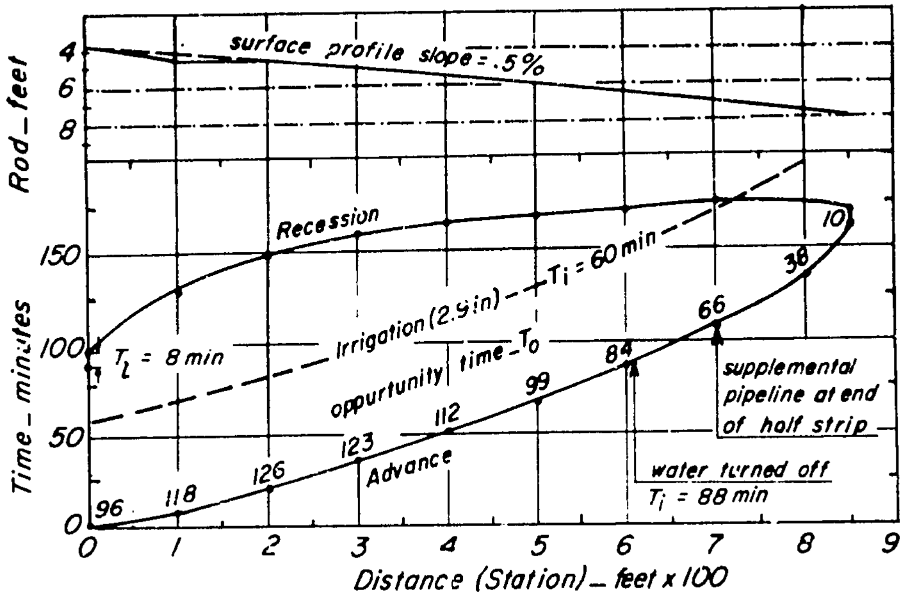


Figure X-4. Soil surface profile plus advance recession, and irrigation curves for border-strip irrigation evaluation data presented on Forms X-1 and -2, using a stream of 1.2 cfs.

Table X-1. Depth infiltrated based on opportunity times, T_o from Figure X-4 and depths infiltrated, D, taken from the "typical" and "average" lines in Figure X-3.

Item	Station - feet X 100									
	0	1	2	3	4	5	6	7	8	9
T_o - min.	96	118	126	123	112	99	84	66	38	10
	Typical Intake Curve Data									
Depth - in.	3.0	3.4	3.5	3.5	3.3	3.0	2.8	2.4	1.7	.7
Av. Depth		3.2	3.5	3.5	3.4	3.2	2.9	2.6	2.1	12/2
Av. Depth	on 850 feet = 25.0 in/8.5 = 3.0 inches									
	Adjusted Intake Curve Data									
Depth - in.	3.9	4.5	4.7	4.7	4.4	4.1	3.7	3.1	2.4	.9
Av. Depth		4.2	4.6	4.7	4.5	4.2	3.9	3.4	2.8	1.8/2
Adj. Depth	on 850 feet = 33.2 in/8.5 = 3.9 inches									

the same stations. The average depth for each 100 feet, $\overline{D}/100$ *feet*, was determined and entered as shown in Table X-1. Since the end section of the border-strip was only 50 feet long instead of the usual 100-foot unit length, its average was determined proportionally to its length (50:100). Thus, the average depth infiltrated for the entire strip (extrapolated) was found to be approximately 3.0 inches as indicated.

To check correctness of the location at which the "typical" curve was drawn, the actual average depth of water applied was computed by using the relationship 1.0 cfs X 1.0 hr = 1.0 acre-inch. The border spacing is 24 feet and the strip width is 21 feet, but the effective wetted width is presumed to be about 23 feet, which for the wetted strip length of 850 feet is 0.45 acre; so the depth applied for the application time of 88 minutes is:

$$D = \frac{1.20\ cfs}{0.45\ ac} \ X\ \frac{88}{60}\ hrs = 3.9\ inches$$

The "adjusted" line (Figure X-3) was drawn parallel to the "typical" line through this depth of 3.9 inches at 96 minutes, the time at which the "typical" line has average depth of 3.0 inches.

As a check, and since the values would be used later, the adjusted depths at each station, the average depths between stations, and the average depth for the whole length (extrapolated) were computed again using the "adjusted" curve (Table X-1), and found to be 3.9 inches. This adequately checks the 3.9 inches computed depth of inflow and indicates that the "adjusted" curve on Figure X-3 is reasonably correct.

The "adjusted" depths of infiltration along the strip are plotted on Figure X-5. This curve is easy to understand and graphically shows how much water was stored in the root zone, how much penetrated too deeply, and how much was runoff. The relative area under the curve can be used to compute DU_a, *PELA*, and *AELA*, as shown in Table X-2.

Distribution Uniformity

The *DU* is the percent of the minimum depth (absolute or low quarter respectively) infiltrated to the average depth infiltrated on the actual strip length. It describes how uniformly the water was distributed along the strip for the condition tested. A high percentage would indicate that the advance and recession curves are "parallel" but would not tell whether the irrigation was adequate. For this percentage, which concerns only the infiltrated water, runoff is not pertinent; therefore, only the actual length of the field is used. The average infiltration for the 700 feet was found as before from the computations as tabulated in Table X-1 or graphically from Figure X-5. From Table X-1, the average depth infiltrated along the first 700 feet of the border-strip is:

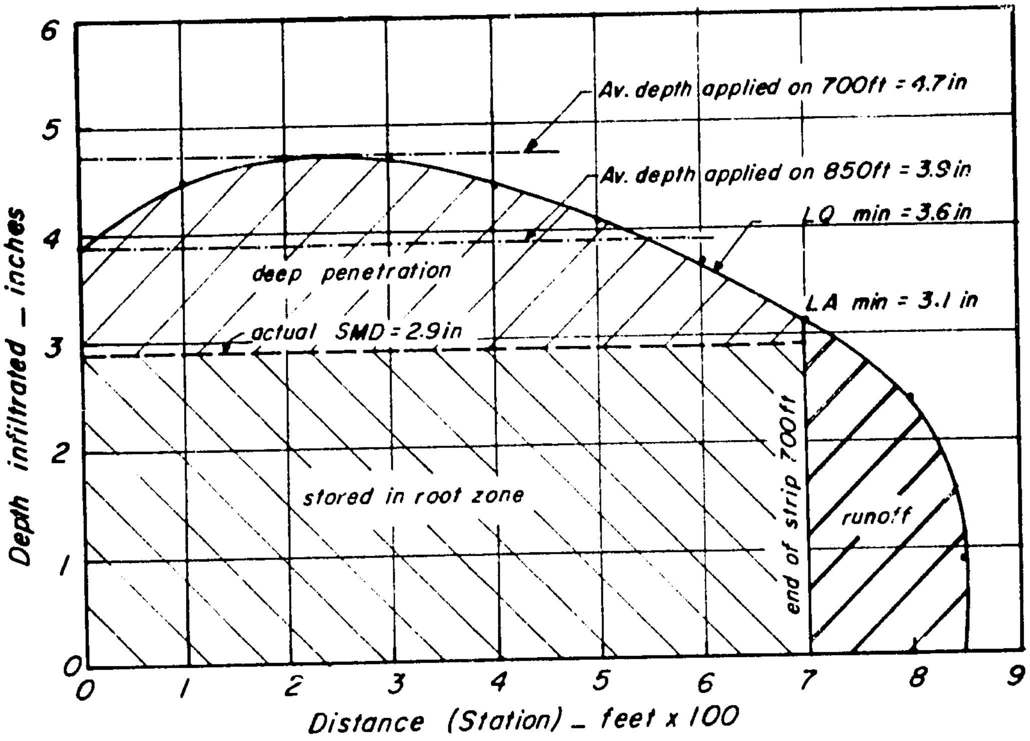


Figure X-5. Adjusted depth infiltrated along the tested border-strip.

Table X-2. Graphical determination of DU_a, $PELA$, $AELA$, % runoff, and % deep percolation.

Area from Figure X-5	Squares
Under whole curve	33.2
Runoff	3.7
Deep percolation	9.2
Stored in root zone	20.3
Between LA = 3.1 inches and Station 7	21.7

Evaluation of Parameters	
DU_a = [21.7/(33.2 - 3.7)] X 100	= 74%
$PELA$ = (21.7/33.2) X 100	= 66%
$AELA$ = (20.3/33.2) X 100	= 61%
% runoff = (3.7/33.2) X 100	= 11%
% deep percolation = (9.2/33.2) X 100	= 28%

$$Av.\ D = \frac{29.5}{7.00} = 4.2\ inches$$

Minimum depth can be defined as the absolute, *LA* minimum (3.1 inches), occurring at station 7+00, or as the low quarter, *LQ* minimum, which is the average depth of the lowest one-quarter (3.6 inches) for the last 175 feet in this test; these are shown graphically on Figure X-5. From these minimum values:

$$DU_a = \frac{3.1}{4.2} X\ 100 = 74\%$$

and

$$DU = \frac{3.6}{4.2} X\ 100 = 86\%$$

Potential Application Efficiency

The *PELA* or *PELQ* is the percent ratio of the minimum depth, absolute or low quarter respectively, infiltrated when it just equals the *MAD* or the *SMD*, to the average depth applied. It describes how well the *system* can operate under the tested condition. Figure X-5 shows that the *LA* minimum was 3.1 inches and the *LQ* minimum was 3.6 inches. From Table X-1, the average depth of the total water applied on the 700-foot long field, including the portion that was runoff, was:

$$D = \frac{33.2}{7.00} = 4.7\ inches$$

So if *MAD* equaled the minimums:

$$PELA = \frac{3.1}{4.7} X\ 100 = 66\%$$

and

$$PELQ = \frac{3.6}{4.7} X\ 100 = 77\%$$

It is convenient for study of an evaluation to use the *LA* minimum; however, any comparison with another irrigation system to be valid, must use the *LQ* minimum. Frequency of irrigation should be computed by using the *LQ* minimum since it is not good practice to try to completely satisfy the *SMD* of the *LA* minimum spot.

Application Efficiency

The *AELA* or *AELQ* is the percent ratio of the minimum depth, absolute or low quarter, respectively, stored in the root zone to the average depth applied. This tells how well the system is actually being used.

At the time of this irrigation, the soil was quite moist because the owner irrigated immediately after cutting alfalfa for green-chop feed. Irrigation was done without any knowledge of the *SMD* of his field. The *SMD* was estimated by using the soil moisture and appearance relationship chart (Table I-1). Soil samples were taken with an auger; they represented each foot increment of the sandy loam soil to a depth of 5.0 feet. The *SMD*'s for successive 1-foot depths were estimated to be 1.0, 0.8, 0.6, 0.4, and 0.1 inch, respectively, for a total of 2.9 inches. This *SMD* is all of the available storage so 2.9 inches can be used as the depth stored and plotted on Figure X-5. The time needed to infiltrate 2.9 inches is 60 minutes.

To visually present the adequacy of an irrigation, the irrigation curve is plotted on the same grid as the advance-recession curves as shown on the lower part of Figure X-4 (also the depth of the *SMD*, assuming it equals the stored depth, may be plotted on Figure X-5). The irrigation curve showing the ideal condition, is plotted above the advance curve (Figure X-4) by a distance equal to the time, T_i, needed to infiltrate 2.9 inches, which for this evaluation is 60 minutes. Whenever the irrigation curve is below the recession curve, irrigation is too long and that portion of the strip is overirrigated. Whenever the irrigation curve is above the recession curve, that portion of the strip is underirrigated. On the corresponding depth infiltrated curves (Figure X-5) the excess or deficiency is shown in depth rather than in time. This is illustrated below.

Since the *LA* and *LQ* minimum depths infiltrated (3.1 and 3.6 inches) were both more than the *SMD* of 2.9 inches, the *AELA* and *AELQ* are equal and may be computed as:

$$AELA = AELQ = \frac{2.9}{4.7} = 62\%$$

The actual application efficiency is lower than it would have been if the operator had waited a couple of days until the *SMD* had become about 3.6 inches. Then the *AELA* and *PELQ* would have equaled the *PELA* of 66% and *PELQ* of 77%, respectively. This analysis illustrates the management controllable effect of changing *MAD* to save both water and labor.

The *correct time* (duration) of irrigation, T_i, to meet the 2.9-inch *SMD* is observed from the "adjusted" curve (Figure X-3) to be 60 minutes. This must be considered only as an approximate time because many variables exist. For the 66 minutes that water actually infiltrated at the lower end of the strip, the corresponding *LA* minimum, *MAD* would be 3.1 inches, or, allowing the last 75 feet to be slightly underirrigated (*LQ* minimum), *MAD* would be 3.6 inches and *PELQ* would be 77%.

This test did not show the *best stream size* because the entire flow of the well was used and no larger stream could be applied. Since the recession and advance curves converge, it is obvious that the stream was too small and that a larger stream would have advanced more rapidly (see Appendix E). This would tend to make the advance and recession curves nearly parallel. Likewise, it would have achieved a more nearly uniform irrigation, would have permitted earlier cutoff, and would have reduced the overirrigation on the upper portion of the border-strip.

For the field irrigated in this study, a larger stream could be obtained by using a reservoir; or the strip could be narrowed when the field is replanted to increase the rate of flow per foot of width.

Adequacy of irrigation was checked on an adjacent strip that had been similarly irrigated on the previous day. The soil there was at or above field capacity to a depth of 5.0 feet. This confirmed the overirrigation indicated by the evaluation.

Summary of full evaluation

The information recorded and plotted above provides the following determinations:

Irrigation was applied too soon to match the capability of the system as it was being operated; *DU* of 86% can be improved by using a larger stream, which would advance more rapidly; *PELQ* of 77% could be improved by using a larger stream and larger *MAD; AELQ* could be made equal to *PELQ* at 77% simply by delaying irrigation two days so that the *SMD* would equal the *MAD*; and increasing the size of the stream would improve all conditions.

It must be remembered that none of these values are exact, but all are very significant for they indicate what should be done to improve the operation. Additional analysis may develop other useful practices and may show their effects so economic comparisons can be made.

Additional analysis

Additional study and information provide the basis for more detailed recommendations. From this additional information, alternatives may be developed and economic comparisons may be made.

The shape but not the starting time of the recession curve is relatively unchangeable; therefore, it becomes the key item in management. The four fundamental conditions of border-strip irrigation that management can control and adjust to improve irrigation are:

1. Stream size, which affects rate of advance and duration.

2. The *SMD* at which the crop is irrigated (which should equal the *MAD*), as it affects duration and frequency.

3. The position of the water front down the strip at the time of cutoff.

4. The length of the strip, which sometimes can be varied by using portable pipe or combining fields.

Other factors (e.g., having uniform soil and land grading) also may be important. They are more difficult to change but may be considered in planning irrigation of new fields.

Observation of the advance, recession, and irrigation curves plotted on Figure X-4 identified several problems: too small a stream, over-irrigation of the entire length of the border-strip, and an unnecessarily low *MAD*. An additional noticeable condition is the abnormal hump, rather than the typical *S-curve*, at the beginning of the recession curve and the change in slope of the advance curve at about station 1+00. Since the minor variations in shape of these curves are informative diagnostic tools, plotting must be done accurately.

Advance and recession curves indicate abnormal changes from uniform normal conditions in retardance, slope, or rates of intake (see Appendix E). The steep initial 200-foot portion of the recession curve (Figure X-4) indicates slow runoff; this steepness was not caused by increased retardance because the crop was uniform, but it could have been caused by a flatter grade or a reduced rate of intake. The flatter initial 100-foot portion of the advance curve indicates rapid advance; it was not caused by reduced retardance but could have been caused by a steeper grade or reduced rate of intake. The only factor common to both advance and recession was reduced intake and this would normally be assigned as the cause.

More careful observation shows that the reduced recession was effective on about 200 feet and increased advance affected only about 100 feet. This requires further explanation. Though this is not usually done, a ground profile had been made for this evaluation and was plotted near the top of Figure X-4, using rod readings because they are easier than elevations. This ground profile showed that the cause was due to two changes in grade: steep for about 100 feet then flatter. These contrasting grades adequately explain the shape of both curves. Rate of intake probably was uniform. The recession curve probably would have started flatter and would have indicated the true problem if an advance and a recession reading had been made at station 0+50.

If the upper part of the strip were brought back to grade, probably the relative steepness of the hump in the upper 100-foot portion of the recession curve would be reduced by increasing the lag time, T_l, to give the normal *S-shaped* curve. Also, the advance curve would become uniformly smooth. Such curves could be estimated (assuming the grades were corrected), efficiencies could be computed, and an economic study of regrading could be made. The major effect of these changes would be on T_l and probably would have little economic value. However, this analysis illustrates the diagnostic capabilities of studying the curves.

Stream size. The efficiency of the irrigation can be improved significantly by increasing the stream size per unit of border width. The convergence of the advance and recession curves in Figure X-4 indicates that the stream was too small. The fundamental control condition in adjusting size of a stream is that the general shape and slope of the recession curve does not change appreciably except with rather extreme alterations in irrigation practice. Each time the last water will disappear at about the same rate of intake and velocity of flow unless changes in *SMD* and/or duration are large; both of these affect rate of intake. Slope of the ground remains constant, but retardance may vary. As stream size changes, T_l may vary, especially on flat gradients and on soils having slow rate of intake.

The general shape of the recession curve is fixed, as shown in Figure X-6, which describes performance of three streams of different sizes used in another test. A larger stream should have been run in that test because the advance curve of even the 2.6 cfs stream was converging with the recession curve. The recession curve for the largest stream plotted here shows the typical *S-shaped* pattern. A dike at the lower end of the strip ponds the water. The dotted lines show the extrapolated curves that might have been plotted if there had been no dike and runoff had occurred. The recession curve for the medium sized stream and distance shows the *S-shape* but it is flatter (faster recession) at the lower end resulting from less flow from the shorter and shallower body of water ponded upstream. The smallest stream with the pronounced drop at the lower end illustrates the extreme results of using a grossly inadequate stream resulting in water disappearing from the lower end before disappearing in the midportion.

For the evaluation presented in Figure X-4 during which only one stream size could be run, the question is, "How much larger should it have been ideally?" The evaluation procedure can provide an approximate answer.

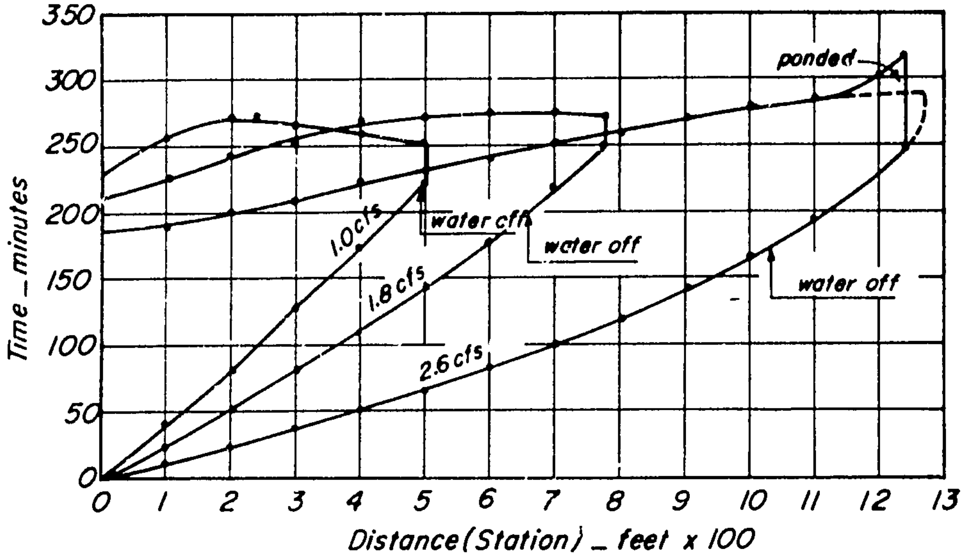


Figure X-6. Advance-recession curves for streams of 1.0, 1.8, and 2.6 cfs in 60-foot wide border-strips with a dry and bare silty clay soil having a slope of 0.12%.

Proper stream size is correlated with several conditions required for an efficient irrigation. First, the beginning of recession equals duration of irrigation; i.e., at the upper end of the strip this is:

$$T_{o(u)} = T_i = T_a + T_l$$

Second, at almost all points the irrigation curve will be below the recession curve using the low quarter definition of minimum and at all points for the absolute minimum. Third, at the time when flow is cut off, the stream has adequately advanced down the strip so that the ponded water on the upper part is sufficient to flow to the end and irrigate the lower part of the strip. In practice, it is rare that all three of these conditions can be satisfied simultaneously.

Ideal conditions for *MAD* of 2.9 inches are shown in Figure X-7, which uses the absolute minimum for convenience of study. The recession

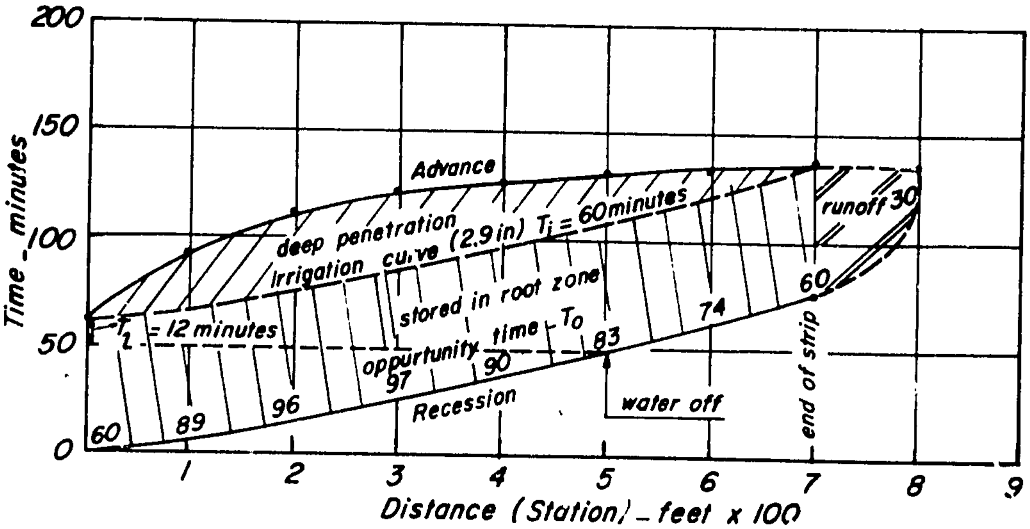


Figure X-7. Anticipated evaluation curves for the tested border-strip with an assumed stream of 1.8 cfs and *SMD* = *MAD* = 2.9 inches.

curve starts at T_i which is 60 minutes and is plotted in the shape determined by the field evaluation, a control condition that is relatively constant for each field and each crop condition as discussed earlier. At station 7+00, a point is located for the advance curve 60 minutes below the recession curve to insure adequate irrigation there. An advance curve is then plotted in a shape similar to the tested shape, but flatter--to represent a larger stream. Lag time, T_l, is estimated to be about 10 to 12 minutes since the stream will be larger than the 1.2 cfs which had a T_l of 8 minutes. Cut off time, T_a, is then 60 - 12, or 48 minutes. The estimated distance water has flowed down the field by this time is about 500 feet. This may be nearly correct because it is 300 feet from the extrapolated end, and the actual 1.2 cfs stream flowed 260 feet after cut off.

The T_o from Figure X-7 and estimated depth at each station were used to compute the average depth on the entire extrapolated curve (including the runoff) following the procedure illustrated in Table X-1. This was 27.9/8.00 = 3.5 inches. From the width of the wetted strip (23 feet) and the extrapolated length (800 feet), the field's area was computed as 0.42 acre giving a stream flow rate of:

$$Q = \frac{3.5 \text{ inches} \times 0.42 \text{ acre}}{48/60 \text{ hour}} = \pm\ 1.8 \text{ cfs}$$

If trial of the 1.8 cfs stream showed that duration of 48 minutes was too brief, the stream could run a few minutes longer, which would slightly overirrigate the upper end of the strip. Alternatively, a larger stream could be tried or *MAD* could be increased. Also, a medium sized stream could be run for a longer time, although this would have lower efficiency. Admittedly, the numbers developed here may not be considered precise, but they clearly indicate what can be done.

On the 23-foot wide wetted strip, desired rate of flow of 1.8 cfs would be about 0.08 cfs per foot of width. For the stream available (1.2 cfs), the wetted strips should be about 15 feet wide. This might be impractical to farm, but it could have a *PELA* of about 72% (2.9/4.0 X 100) and a *PELQ* of about 85% for a *MAD* of about 3.5 inches. An engineering cost comparison involving a reservoir to provide larger delivery capacity (capable of irrigating several strips simultaneously or wider strips with the desired 0.08 cfs per foot of strip width), and a saving of water and labor, would likely show such changes to be economical.

To obtain high efficiencies, it is essential that flexibility in frequency, rate, and duration of water delivery be made to match constantly varying field conditions, such as crops, *MAD*, rate of intake, retardance, and weather.

Management Allowed Deficiency. The *MAD* at which irrigation should be applied varies with depth of root zone of annual crops but is fairly constant for perennials. The *MAD* can be varied within limits to suit the labor, convenience, crop growth, and irrigation efficiency. For the field evaluated, the *SMD* was about 2.9 inches to accommodate cutting the alfalfa crop. For a 6-foot root zone on this sandy loam soil having about 1.5 inches of available moisture per foot, the percent *MAD* was:

$$MAD = \frac{2.9 \text{ inches}}{6.0 \text{ feet} \times 1.5 \text{ inches/foot}} \times 100 = 32\%$$

This is a very low value and for this soil, crop, and cool climate, *MAD* of 60 percent would be reasonable; therefore, *SMD* of about 60% could be used if practical for labor and harvest conditions. This would occur when the *SMD* is 5.4 inches.

This condition is shown in Figure X-8 where *SMD* = *5.4 inches*, T_i = *150 minutes, and Q* = *1.2 cfs* (existing stream size). The original advance curve and recession curve shape plotted from field data (Figure X-4) are unmodified. With the large increases in *SMD* from 2.9 to 5.4 inches, the soil's initial rate of intake would actually be faster; thus, the anticipated advance rate would be slower (steeper), and the lag time would be greater. Compensating for this, the curve for the anticipated recession would also be a little slower (steeper) because the final rate of intake would decrease due to the much longer time of application, and runoff would be prolonged. The original curves gave reasonable,

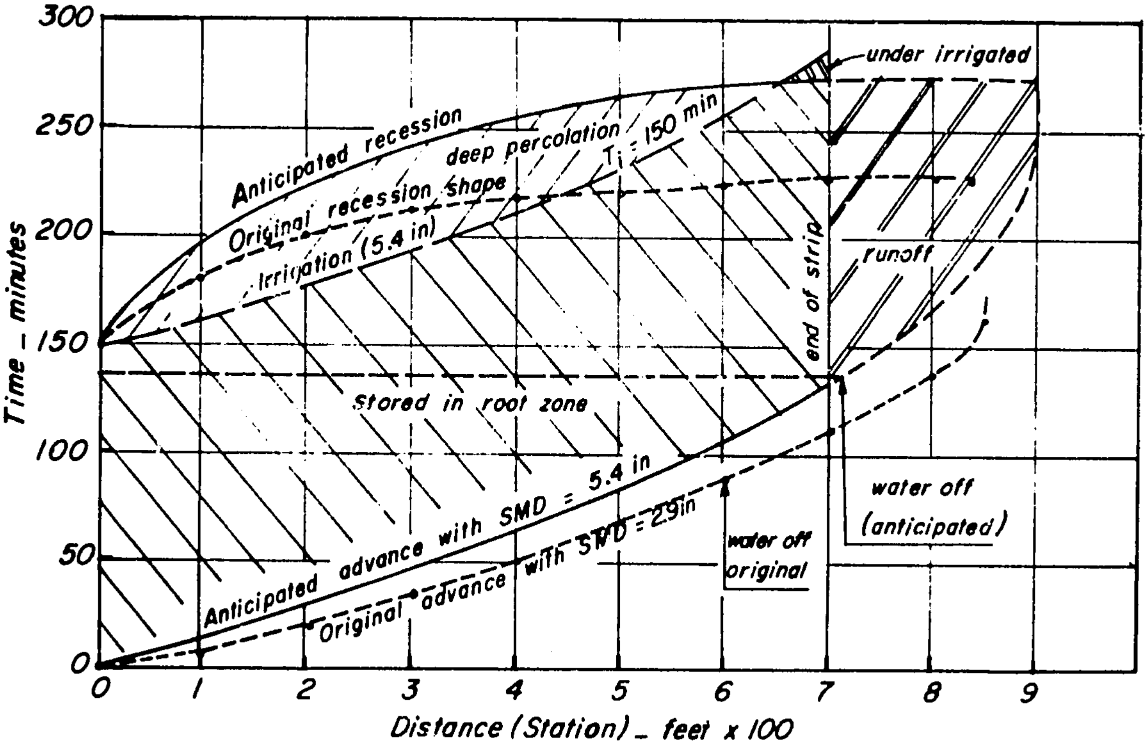


Figure X-8. Anticipated evaluation curves for the tested border-strip with stream of 1.2 cfs and an assumed *SMD* = *MAD* = 5.4 inches.

though not accurate, values for studying possible modifications of this extreme magnitude, i.e., nearly doubling *SMD*.

The anticipated and irrigation curves presented in Figure X-8 show adequate depth infiltrated at the beginning, too much along most of the strip, and a little underirrigation near the lower end. Runoff was excessive since the water was cut off about 20 minutes after it had reached the end. However, since this strip is only the upper half of a 1400-foot field, very high efficiency could be achieved by using continuous border-strips accomplished by opening the valve at station 7+00 when flow reached this point, and closing the valve at station 0+00 about 20 minutes later. Runoff then would be entirely utilized, and water backed up at the middle would be compensating for the underirrigation that had existed previously. Runoff would then occur only at the lower end of the second strip. A dike there, ponding water, and making an earlier cut off, would bring these two strips to a high *AELQ* at the increased *MAD*. Furthermore, the less frequent irrigations would reduce labor requirements.

For the single upper strip, high efficiency is impossible under these conditions because the strip is too short for the large *MAD*. Other possibilities for improvement would be:

1. To run two strips with half-size streams, which would reduce runoff but which would overirrigate the upper end of the strips. This is probably the most practical procedure.

2. To use a runoff return flow system to put the runoff water into storage for later reuse.

3. Cutting back the size of the stream when it has advanced about half way down the border strip.

Strip length. The length of the border strip can be varied when a supplemental line is installed or portable pipe is used. Changing the *MAD* requires different lengths of strips, which is a very important consideration. Annual crops with an expanding root zone require deeper irrigation and correspondingly longer strips. At the beginning of the season a strip might be started in three sections; later it could be reduced to two or even one section, or sprinklers could be used for the early applications.

For the evaluated strip, if *MAD* were 5.4 inches and the desired stream flow of about 2.0 cfs were available, the anticipated curves shown on Figure X-9 would be indicative of results. The recession curve would be stretched in the middle and raised because of the lower rate of intake caused by the larger *MAD*; the larger stream would advance more rapidly resulting in a *PELA* of about 78% for a 1400-foot border-strip.

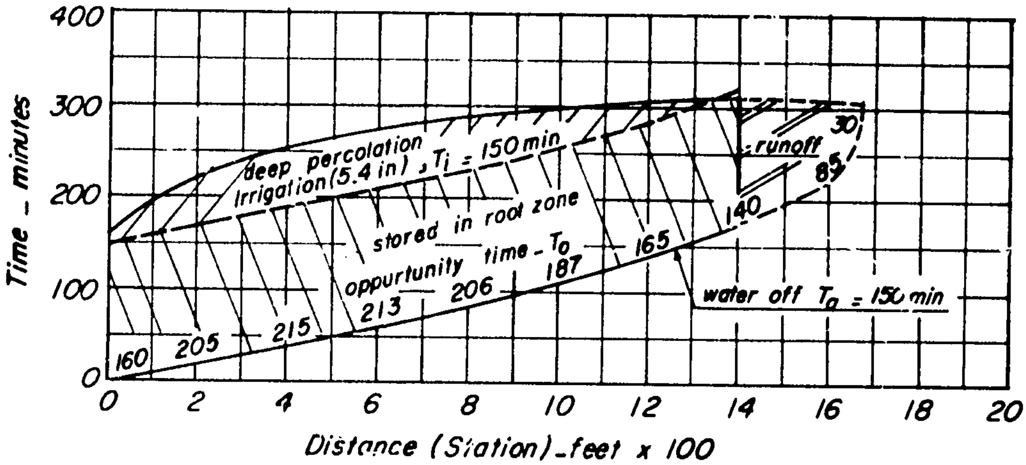


Figure X-9. Anticipated evaluation curves for the border-strip assuming a length of 1400 feet, stream of 2.0 cfs and *SMD = MAD* = 5.4 inches.

This theoretical study or projection based on the extension of the evaluation data indicates what may be tried later in the field. A dike to pond water at the lower end of a strip would be a further improvement.

It would have been very desirable to have run several stream sizes at the time the operation was being evaluated which would have provided a better estimate of different trial advances.

Summary of additional analysis

The additional analysis just presented shows several important facts. Much can be learned about the grade of the strip and variations in intake rate by observing the simultaneous changes in shape of the advance and recession curves (see Appendix E). The shape of the recession curve remains similar for any particular strip, and minor changes in management can have a predictable effect on the curves. Only one stream size and resulting advance curve ideally match the fixed recession curve and *MAD*. A change in *MAD* for a given stream size requires a change in strip length. Interrelated adjustment in stream size, *MAD*, time and distance at cutoff, and sometimes length of strip are practical means to improve efficiency and save labor. To make these desired adjustments, water deliveries must be flexible in frequency, rate, and duration.

CHAPTER XI
BASIN IRRIGATION

Basin irrigation is a system in which low dikes are built up around the area to be watered. Basins may be as small as a few square feet around a single tree or as large as 10 or more acres; but a large basin must have perfectly level uniformly textured soil, and it must be fed by a stream of water large enough to cover it fairly quickly. The shape and size of each basin should be selected to match the soil types, the field boundaries, and the available stream size. Dikes to enclose basins can be farmed over and can be built up and broken down easily to enable cultural practices so non-rectuangular basins matching soil boundaries are feasible.

Basin irrigation is an easy way to irrigate crops that can be partially submerged for a while, and it is adaptable for pre-irrigation or leaching (Figure IX-1); but it is not generally recommended for use during germination or for a soil that is prone to crusting. Beds or furrows can be constructed within the basins to raise crops above the ponded water.

Figure XI-1. Typical basin irrigation leaching operation.

Evaluation

Evaluation of basin irrigation is mostly by observation, but a few measurements are needed. To estimate Application Efficiency. *AELQ*, the irrigator must know the uniformity, rate of inflow, duration of flow, and the area of the basin. It is impractical to try to determine very exact values of *AELQ* because small variations in soil infiltration rate in various parts of the basin and low spots cause appreciable differences in the depth infiltrated. Aerial photos, soil surveys, reaction to tillage, variations in crop appearance, and salinity all provide information that will help in dividing a field into basins where infiltration is likely to be relatively uniform.

For evaluating a basin irrigation, the following items need to be prepared, measured, or observed:

1. A sketch of the field layout drawn to scale.
2. The *SMD* and *MAD*.
3. The rate and duration of inflow.
4. The way the water spreads, noting the rate of filling the basin and the smoothness of the basin.
5. The infiltration rate or time required to replace the *SMD*.
6. Variations in infiltration rate within the basin.
7. The adequacy (depth) of penetration by using a probe or auger in various areas.

Equipment needed

The following equipment is needed for the evaluation of basin irrigation:

1. A soil auger.
2. A soil probe.
3. A watch with a second hand.
4. A flow measuring device.
5. A 100-foot surveying tape and a compass for measuring basin area.
6. A hand level.

7. A staff gauge.

8. Paper and clip board for recording data.

9. Lath or stakes for setting out grids in large basins.

Field procedure

Select one (or two) basins that appear to be typical for the field and irrigation being evaluated.

1. Draw a map of the basin (or basins) being studied.

2. Check the *SMD* in several locations and observe differences in the crop growth, soil texture, and soil profile. Compare the maximum *SMD* to *MAD* to determine if it is dry enough to irrigate.

3. Determine the rate of inflow and record the times of starting and shutting off the streamflow.

4. Observe the advance of the water front across the basin. On the map of the basin, sketch the position of the water front at six or eight time intervals. An uneven advancing front line indicates location of high and low areas. Having a grid of stakes in the field would increase accuracy of this sketching, but problems can be identified accurately without stakes unless the basin is very large.

5. Sketch the position of the receding water front at several different times as the water level drops after streamflow has been shut off. Note any major high spots or ponds and low spots. The receding water front at successive times can be drawn with a different color or different style of lines on the sketch map used to show the water advance. (The maps of advance and recession can be drawn as overlays on sheets of tracing paper laid over the basin map drawn in Step 1.) Only approximate accuracy is needed to indicate noticeably high or low areas in the basin. The difference between the arrival time and the recession time at any point is the opportunity time, T_o.

6. Determine the rate of infiltration in the basins. This can be done with reasonable accuracy from either: (a) field infiltration depth measurements or (b) cylinder infiltrometer test data which can be analyzed and "adjusted" to give predictive results.

a. A staff gauge is set near the inlet of the basin. (It is very desirable to use a basin small enough to be filled, not just covered, in a short period of time--about one-tenth of T_o.) The falling water level stages and times should be recorded similar to a cylinder infiltrometer test with zero being the maximum gauge height (see Appendix E and Form X-1). The depth must be adjusted to equal the actual measured inflow depth by the process described for border-strips in Chapter X. The magnitude of the adjustment will be related to the speed of filling the basin (since an appreciable depth may infiltrate during filling), the uniformity of the soil infiltration within the basin, the uniformity and levelness of the bottom of the basin, and whether the wind may have pushed water up at one side thereby affecting the gauge readings.

b. Cylinder infiltrometer tests may be run independently to provide approximate predictive information. For more accurate analysis, cylinder infiltrometer test data may be used in conjunction with the advance and recession curves and the onflow depth. With this additional information, an "adjusted" intake curve can be developed by the process described for border-strips in Chapter X.

7. Observe variations in infiltration rates within the basins. Nonuniformity of infiltration may indicate the need for relocating the dike around a basin to obtain a more uniform intake. This may be done by any of the following:

a. Water will flow toward areas with high infiltration rates; however, this flow may be so slow that it is difficult to see. Walk around within the basin after it is filled to stir up a little suspended soil to help make the flow visible.

b. After the basin has filled, quickly construct (plow in) small dikes that barely reach to the water surface to divide the basin into as many small subbasins as is practical. Observation of the drop in water surface, usually measured from datum stakes, indicates the relative infiltration rates in adjacent subbasins. Allowance must be made for the probable differences in relative rates of intake because water did not arrive in all the subbasins at the same instant. Comparing the absolute infiltration rates in the subbasins would not necessarily be meaningful because they might be only the average for areas having high and low rates.

c. Construct subbasins as described above but leave gaps in the dikes. Water will flow through these gaps from subbasins that have slow infiltration rates to those that have faster rates. This is the most sensitive method for observing dissimilar infiltration rates. Again, allow for water arriving at different areas at different times.

d. Construct several subbasins prior to the start of the test and quickly (in about one-tenth of T_o) fill each of them with an equal depth of water calculated by (cfs x time)/acres. Note the length of time it takes for the water to disappear from the ground surface of each subbasin. Staff gauges may also be set and the rate at which water infiltrates may be measured and plotted as described in 6 above.

8. Using a soil probe just after the water has disappeared from the ground surface shows the depth and uniformity of penetration. Water will continue to percolate as the upper part of the soil profile drains down to field capacity. A check then or soon afterwards will indicate whether water has already percolated too deeply or is still percolating. Soil probes do not work well in fine textured soil nor to depths greater than about 3.5 feet. Checking with a soil auger a few days after the irrigation would give more precise information about its adequacy, but it would not indicate overirrigation.

Utilization of field data

The objective of any evaluation is to determine how effective present management practices are and to learn where management could be improved.

Comparing SMD with MAD will tell whether an irrigation was too early, too late, or correctly timed. The *SMD* will show what depth of water needs to be replaced by irrigation, and it is a key number in computing any efficiency term because it corresponds to the maximum depth of water that can be stored in the root zone at that location.

Depth of water applied, D, is computed by multiplying the inflow rate to the basin by the duration of the application and then dividing by the basin area, thus:

$$\text{Depth applied (inches)} = \frac{\text{inflow (cfs)} \times \text{duration (hrs)}}{\text{area (acres)}}$$

or

$$\text{Depth applied (inches)} = \frac{96.3 \times \text{inflow (gpm)} \times \text{duration (hrs)}}{\text{area (square feet)}}$$

For example, assume a 1.4 cfs stream is turned into a 0.75 acre basin for 96 minutes. Thus the depth applied is:

$$D = \frac{1.4 \times 96/60}{0.75} = 3.0 \text{ inches}$$

Distribution Uniformity, DU, is important and can be estimated fairly well. The two determining factors are T_o and infiltration rate.

If the entire basin can be covered in about one-fourth of the time needed to irrigate it fully (Advance Ratio, $AR \approx 1/4$), the adverse effect of the unequal T_o values on *DU* will be minimum. If the basin were level and the entire surface became free of water at about the same moment, *DU* would be very high for medium and fine textured soils since an average of only about 5% of the water would penetrate too deeply because less than 10% more water would infiltrate where it entered the basin than at the far side. (For coarse textured soils this entry loss could be considerably higher.) This would be true only if the infiltration rate were uniform throughout the basin. The uniformity of infiltration within the basin should be checked by one of the methods listed under Step 7 of the Field procedure.

Nearly all of the water ponded in low areas may be considered as going too deep. This statement is based on the assumptions that: (1) the minimum depth infiltrated, which should just satisfy the *SMD*, occurs at the first areas in the basin that become exposed as the water receded, and (2) the infiltration rate is uniform over the whole basin. This volume of water that percolates too deeply can be estimated from the average depth of any ponds within the basin and their areas. This volume will be in addition to the approximate 5 percent entry loss that went too deep because of the advance time.

To illustrate this, assume that the water disappeared in half of the basin at about the same moment and that the remaining water was ponded to an average depth of 0.4 inch. This would correspond to a average depth of 0.2 inch over the entire area. If 4.0 inches had been applied, the loss to deep percolation from the remaining ponded area would be 5 percent.

The *DU* can be approximated from the recorded information by the formula:

$$DU = \frac{\text{average low quarter depth infiltrated}}{\text{average depth infiltrated}} \times 100$$

For basins, since they have no runoff, this may be rewritten:

$$DU = \frac{\text{avg. depth applied} - \text{avg. depth ponded when } 1/8 \text{ area exposed}}{\text{avg. depth applied}} \times 100$$

The *DU* or DU_a can be determined more precisely using the information obtained in Field procedure step 6 and the subsequent development of the depth infiltrated curve as needed to develop the "adjusted" infiltration curve. However, to determine *DU*, the "adjusted" curve is not essential since the unadjusted intake will give similar values.

Potential Application Efficiency, PELQ, will be equal to *DU* if the proper depth has been applied, and reasonably close even though over- or underirrigation occurred.

Actual Application Efficiency, AELA, may be determined by dividing the *SMD* by the depth of water applied, *D*. The *AELQ* can be closely approximated by noting the difference between *DU* and DU_a and reducing *D* accordingly.

Summary comments

Basin irrigation can be highly efficient only when:

1. The basin is carefully graded and level.

2. The intake rates of the soils in each basin are uniform.

3. The correct depth of water is applied in less than one-half of the required irrigation time.

The practical problems associated with the first two items usually have appreciable effect on *PELQ*. If the *SMD*, flow rate, or duration of application are not correctly or precisely determined, the resulting *AELQ* value will have the same magnitude of error. For example, if water is applied for 22 minutes when 20 minutes would have been adequate, the *AELQ* would be decreased by 10 percent. Therefore, basins seldom have very high *AELQ* values even though *PELQ* may be quite high.

CHAPTER XII
POND IRRIGATION

Ponding is a method of irrigation in which an area is flooded, the water is ponded for an adequate length of time to infiltrate the desired minimum depth, and then the excess is drained off. It has similarities with basin, border-strip, and rice paddy irrigation. The land does not need to be leveled but it should be graded so that surface water will drain. The infiltration rate of the soil needs to be uniform within each pond area, and each area needs to be surrounded with a dike that will contain the ponded water which will vary in depth over the area. Also similar to basins, each pond should be covered in about one-fourth of the time of irrigation, but this may be compensated for by the recession curve like with border-strip irrigation.

This pond method can have a high *PELQ* and *AELQ* if the excess water is turned into another pond or utilized and there are no low, undrained areas. Since flow rates do not need to be steady, like most methods, excess flows of water can be conveniently added to the supply stream. The method is controlled by the duration of ponding, or opportunity time, T_o, and excess time represents less excess depth since the extra time is at the end of irrigation when infiltration rates are slowest. The speed of draining each pond is easily controlled. Drainage is done from the lowest side and if this is opposite the filling side, the advance and recession can often be controlled to improve uniformity.

In operation, a large stream is turned into the pond area, preferably along the higher side to cover it quickly. The stream should either be run long enough at a fast rate to pond more than enough water for the irrigation, or be run at a slow rate to maintain surface coverage at a shallow depth for the required duration.

The ponded depth of water may vary appreciably over the area, from one or two-tenths of a foot to over a foot if dikes are made high enough, without appreciably affecting uniformity. The pond areas can also be put on the "contour-like" basins without removing the cross slope, or have down slopes like the border-strips.

Pond irrigation is well adapted for leaching salts from the soil and pre-irrigation on fine textured soils where large applications take several days to infiltrate. Like basin or border-strip irrigation, it is suitable for orchard or field crops that are not harmed by flooding during irrigation. It can be adapted for use with "dead-level" furrows to facilitate light, frequent applications giving very high efficiencies, and easily automated since it is time responsive and can accommodate variable stream sizes.

Evaluation, equipment needed and field procedure

The evaluation process, equipment needed, and field procedure are similar for pond and basin irrigation including finding the *SMD* and *MAD* (see Chapter XI).

Advance and recession. Briefly, a plan of the tested pond area should be sketched to scale and lines drawn showing the location of the advancing water front at several times; and similarly, the location of the receding water front should also be indicated. From these the opportunity time, T_o, can be obtained at each of 8 to 12 or more points representing equal areas. These can be arranged in sequence and plotted as an opportunity time versus portion of the pond area (instead of distance) curve similar to the border-strip advance-recession curves presented in Chapter X but with instantaneous advance.

Intake rate and depth. A cylinder infiltrometer test can be run and the cumulative intake curve plotted and "adjusted." The actual average infiltrated depth is determined by measuring the onflow rate and duration to obtain the average depth applied to the ponded area. The outflow rate at a number of times must also be determined so the runoff volume and corresponding average depth can be calculated. The difference between onflow and outflow depths is the infiltrated depth. This depth can then be used to "adjust" the cylinder infiltrometer curve as described in Chapter X for border-strip irrigation.

Utilization of field data and summary

Utilizing the "adjusted" cumulative intake and the opportunity time curves, a cumulative depth infiltrated versus portion of the ponded area curve can be developed as was done for the border-strip method (see Figure X-5). From this curve and the *SMD* and *MAD* values, the uniformity and efficiency terms can be estimated and an analysis of the pond irrigation system made.

REFERENCES

Christiansen, J. E., "Irrigation by Sprinkling," Bulletin 670, Agricultural Experiment Station, University of California, Berkeley, California, October 1942.

Criddle, Wayne D., Sterling Davis, Claude H. Pair, and Dell G. Shockley, "Methods for Evaluating Irrigation Systems," Agricultural Handbook No. 82, SCS, USDA, Washington, D. C., 1956.

Keller, J., "Design Use and Management of Solid Set Systems," National Irrigation Symposium, Page AA-1-10, November 10-13, 1970.

Keller, J., and D. Karmeli, "Trickle Irrigation Design Parameters," Transactions of ASAE, Vol. 17, No. 4, pp. 678-684, 1974.

Merriam, J. L., Irrigation System Evaluation and Improvement, Blake Printery, San Luis Obispo, California, 1968.

Merriam, J. L., "A Management Control Concept for Determining the Economical Depth and Frequency of Irrigation," Transactions of the ASAE, Vol. 9, No. 4, 1966, pp. 492-498.

Robinson, A. R., "Parshall Measuring Flumes of Small Sizes," Technical Bulletin 61, Experiment Station, Colorado State University, Fort Collins, Colorado, August 1960.

Scott, Verne H., and Clyde E. Houston, "Measuring Irrigation Water," University of California Agricultural Experiment Station Circular, No. 473, January 1959.

SCS National Engineering Handbook, "Planning Farm Irrigation Systems," Chapter 3, Section 15, USDA, Washington, D. C., July 1967.

Smerdon, E. T., and Glass, L. I., "Surface Irrigation Water Distribution Efficiency Related to Soil Infiltration," Transactions of the ASAE, Vol. 8, No. 1, 1965.

Pair, Claude (Ed.) Sprinkler Irrigation Association, Sprinkler Irrigation, 4th Edition, Silver Spring, Maryland, 1975

Willardson, L. S., and A. A. Bishop, "Analysis of Surface Irrigation Application Efficiency," Journal of the Irrigation and Drainage Division, ASCE, Vol. 93, No. IR2, June 1967.

GLOSSARY

AELA	*Application Efficiency Absolute Low* indicates the actual efficiency being achieved with a given system and is expressed as a percent relating the minimum depth of water stored in the root zone to the average depth of water applied.
AELQ	*Application Efficiency of Low Quarter* indicates the actual efficiency being achieved with a given system and is expressed as a percent relating the average low quarter depth of water stored in the root zone to the average depth of water applied.
AR_a *or* *AR*	*Advance Ratio* is the ratio of the time required for a stream to flow to the lower end of its furrow (T_{adv}) to the length of time the water is visible there $(T_{o(l)})$. (For design, or where the furrow system is well operated, water should be visible at the lower end of the furrow just long enough to provide the desired irrigation (T_i).
	Adequate irrigation is irrigation where the *MAD* rather than the *SMD* is placed in the entire area to the depth planned for irrigation. It is usually associated with irrigation practice in which only part of the potential root zone is watered.
	Advance curve is a plot that shows the distance traveled by the forward front of an onflow stream flowing down a furrow or border against the elapsed time since the beginning of the irrigation onflow.
	Alternate sets (or settings) is the practice of placing the sprinkler line at each irrigation midway between the sets used in the previous irrigation. It is used mainly for portable sprinkler irrigation as a means of improving *DU*.
	Alternate side irrigation is the practice of wetting one side of a crop and then, after about half the normal interval between irrigations, applying water to the other side; this provides full coverage for the crop at approximately the normal frequency of waterings. (This practice is sometimes called "alternate furrows" for row crops or "alternate middles" for orchards or vineyards.)

	Available moisture is the moisture that can be held in the root zone between field capacity and wilting point. (Field capacity is the moisture remaining in a soil following wetting and natural drainage until free drainage has practically ceased. Wilting point is the moisture content of the root zone soil after plants can no longer extract moisture at a sufficient rate for survival.)
	Cutback stream is the stream size to which the initial stream that starts flowing down a furrow or border strip is reduced to hold runoff to the minimum.
D	*Average depth of water* applied to the whole field area in sprinkle systems or infiltered in surface irrigation systems.
D_a	*Overall average depth of water* applied based on the whole field area in trickle or orchard sprinkler systems.
D_{aw}	*Average depth of water* applied to the wetted area in trickle or orchard sprinkle systems.
D_n	*Minimum depth of water* applied in sprinkle and trickle systems or infiltered in surface irrigation systems and is equal to D multiplied by *PELQ*.
D_S	*Average depth of water infiltrated* based on a furrow spacing, S.
DU	*Distribution Uniformity* indicates the uniformity of infiltration (or application in the case of sprinkle or trickle irrigation) throughout the field and is expressed as a percent relating the average depth infiltrated in the lowest one quarter of the area to the average depth of water infiltrated.
DU_a	*Distribution Uniformity Absolute* indicates the uniformity of infiltration throughout the field and is expressed as a percent relating the minimum depth infiltrated to the average depth of water infiltrated.
	Deep percolation is the infiltrated water that is in excess of the *SMD* at any point in a field.
ER	*Efficiency Reduction* is the reduction in *PELQ* and/or *AELQ* due to pressure variations throughout a sprinkle system and is approximately 20% of the pressure difference in the system divided by the average sprinkler pressure.

ERF	*Efficiency Reduction Factor* is the reduction in *AELQ* or *PELQ* throughout a trickle irrigation system caused by pressure variations throughout the system.
EU	*Emission Uniformity* indicates the uniformity of emission from the trickle irrigation emitters throughout a field (or subunit of a field) and is expressed as a percent relating the minimum rate of discharge to the average rate of discharge per plant.
	Full irrigation is an irrigation that fully replaces the *SMD* in the entire area irrigated.
I	*Infiltration rate* expressed as gpm/100 ft in furrow irrigation or in/hr in all methods of surface irrigation.
	Initial stream is the stream that starts flowing down a furrow or border strip. (Usually it is fairly large, but it should not be large enough to cause erosion. Often it may be smaller than the largest nonerosive stream.)
	Irrigation curve is plotted by uniform time intervals above the advance curve. (The interval for plotting is the time, T_i, needed for water to infiltrate the depth corresponding to the *SMD*.
LR	*Leaching requirement* is the depth of infiltrated water required to dissolve and transport enough salts through the soil profile to maintain a salt balance favorable to economic plant growth.
	Limited irrigation is any of a group of procedures which result in under irrigation to conserve water but do not reduce yields.
MAD	*Management Allowed Deficit* is the desired soil moisture deficit at the time of irrigation and may be expressed as the percent of the total available soil moisture in the root zone or the corresponding depth of water that can be extracted from the root zone between irrigations to produce the best economic balance between crop returns and cost of irrigation.
	Moisture stored in root zone refers to the water applied which is not in excess of *SMD* and is stored in the root zone.

PELA	*Potential Application Efficiency Absolute Low* is the measure of how well a system can perform under reasonably good management when the desired irrigation is being applied. It is expressed as a percent relating the minimum depth infiltrated when equal to *MAD* to the average depth of water applied.
PELQ	*Potential Application Efficiency Low Quarter* is the measure of how well a system can perform under reasonably good management when the desired irrigation is being applied and is expressed as a percent relating the average low quarter depth infiltrated when equal to *MAD* to the average depth of water applied.
Q	*Flow rate* from a sprinkler, or the stream flow into, along, or out of a furrow basin or border.
R	*Sprinkler application rate* expressed as the in/hr or iph is a function of sprinkler flow rate divided by the area served by the sprinkler.
R_n	*Minimum sprinkler application rate* is the sprinkler application rate multiplied by the *PELQ*.
	Recession curve is a plot that shows the position where water has just disappeared from the surface of a furrow or border against the length of time from the beginning of the irrigation onflow.
	Return flow system is a system that recycles runoff water by either pumping it back to the supply or using it sequentially on a lower field. (Often a reservoir is required to enable flexible operation and to save labor.)
	Runoff is the water that leaves an area or field as surface flow.
S	*Spacing* between furrows.
SE	*Storage Efficiency* indicates the actual efficiency being achieved with a given system which only wets part of the area (such as orchard sprinklers and trickle). It is expressed as a percent relating the average depth stored in the root zone in the wetted area to the average depth applied to the wetted area.

SMD	*Soil Moisture Deficit* is expressed numerically as a depth (in inches) indicating the dryness of the root zone at the time of measurement.
	Stress irrigation is a management practice in which the depth or frequency of irrigation, or both, is insufficient to result in maximum production but does increase economic returns or yields per unit of water applied.
T_a	*Time (duration) of application* is the duration of time water flows onto or is otherwise applied to an area.
T_{adv}	*Time of advance* is the duration of time required for water to flow from the upper to the lower end of a field.
T_i	*Time (duration) of irrigation* is the duration of time water should be sprinkled or trickled onto or cover the surface in order to replace the *SMD* at a given point.
T_l	*Lag time* is the duration of time required for water to disappear from the upper end of a field after it has been turned off and is equal to $T_{o(u)}$ minus T_a.
T_o	*Opportunity time* is the duration of time water on the soil surface has opportunity to infiltrate at a given point. (At the upper end of a furrow or border, T_o would be expressed as $T_{o(u)}$ and at the lower end, $T_{o(l)}$.)
UC	*Uniformity Coefficient* (Christiansen's coefficient of uniformity) is a statistical representation of the uniformity of sprinkle or trickle irrigation. It is expressed as a percent which relates the average catch minus the average deviation from the average catch to the average catch.
	Under irrigation is when a single or series of irrigations leave an appreciable area of a field with a substantial *SMD*.

APPENDICES

APPENDIX A

STABILIZING RATES OF ONFLOW TO FURROW OR BORDERS

For quick approximate checks for efficiency of irrigation by streams from a fluctuating primary source, some fluctuation in rates of onflow poses no problem. For precise evaluations, stable rates of onflow are essential and special field procedures are necessary for stabilizing the flow.

One means for stabilizing flow is to use a bypass controlled by a rectangular or trapezoidal weir on the primary ditch in conjunction with such furrow or border turnouts as gates, siphon, short tubes, or orifices. As discussed in Appendix B, the flow over the weir varies as the 1.5 power of the upstream flow depth over the weir crest, $H^{1.5}$, and the flow through the turnout varies as the square root of the difference in water depth on either side of the turnout, $\sqrt{H}$ or $H^{0.5}$. Therefore, a 10% change in H due to flow variation in the primary ditch will change the flow over the weir by 15%, but only change the flow through the siphons (to the test furrows) by 5%. The longer the weir and the greater the proportion of flow over it, and/or the greater the H on the siphons as compared to the H on the weirs, the smaller will be the fluctuations on the turnout.

In order to obtain even greater accuracy or where the primary ditch is apt to have extreme fluctuations a secondary ditch and weir can be set up as shown in Figure A-1.

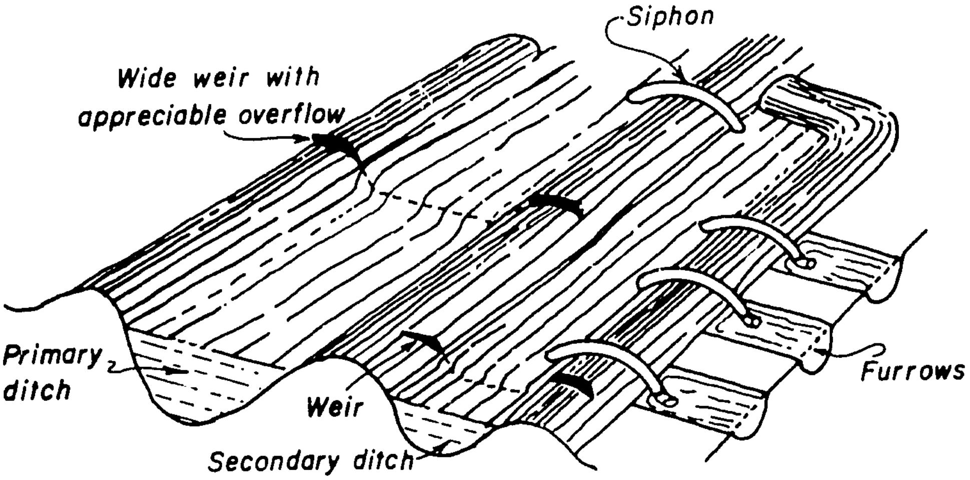


Figure A-1. Flow stabilizing setup using double weirs and siphons for very accurate flow controls.

APPENDIX B

FLOW MEASURING DEVICES

Measurements of flow are essential for good irrigation and for all evaluations. The degree of accuracy of such measurements varies according to conditions. Many measuring instruments are available commercially, and many improvements can be made based upon principles of hydraulics. Devices commonly used for evaluation and their operation are described here and others are mentioned. Accuracy of all procedures but the volumetric is seldom closer than 25%. Many texts and pamphlets publish detailed tables and discussions. Figure B-1 graph powers and roots of numbers, and flow rates of Parshall flumes, and siphons.

Volumetric Measurement

Flow from sprinklers is diverted by a short length of hose into a container having known volume--usually 1 gallon--and the time required to fill it is measured, preferably by stop watch. The container must be large enough so that duration of flow into it can be measured accurately.

For measuring flow in furrows, a container can be set into a hole and stream flow directed into it by a short tube or length of hose. A similar process can be used at the upper end of furrows using gated pipe or siphons. When the container is large enough, this is the most accurate procedure.

Orifice

The principle of measuring head on an orifice or short tubes and relating this to the corresponding velocity of flow, Q, through the area of an opening has many applications. It is expressed by the formula:

$$Q = AV = C\ A\ 8\ H^{0.5}$$

when C is a shape and entrance condition constant, A is area in square feet, H is head in feet, and Q is cubic feet per second, cfs. Values of C are published for many conditions. The minimum value for a sharp-edged orifice is 0.61; 0.64 is more nearly an average. Head is measured from the water surface to the center of the orifice, and for accurate flow readings this distance should be at least as great as the orifice diameter. For submerged orifices, H is the difference in level between water surfaces.

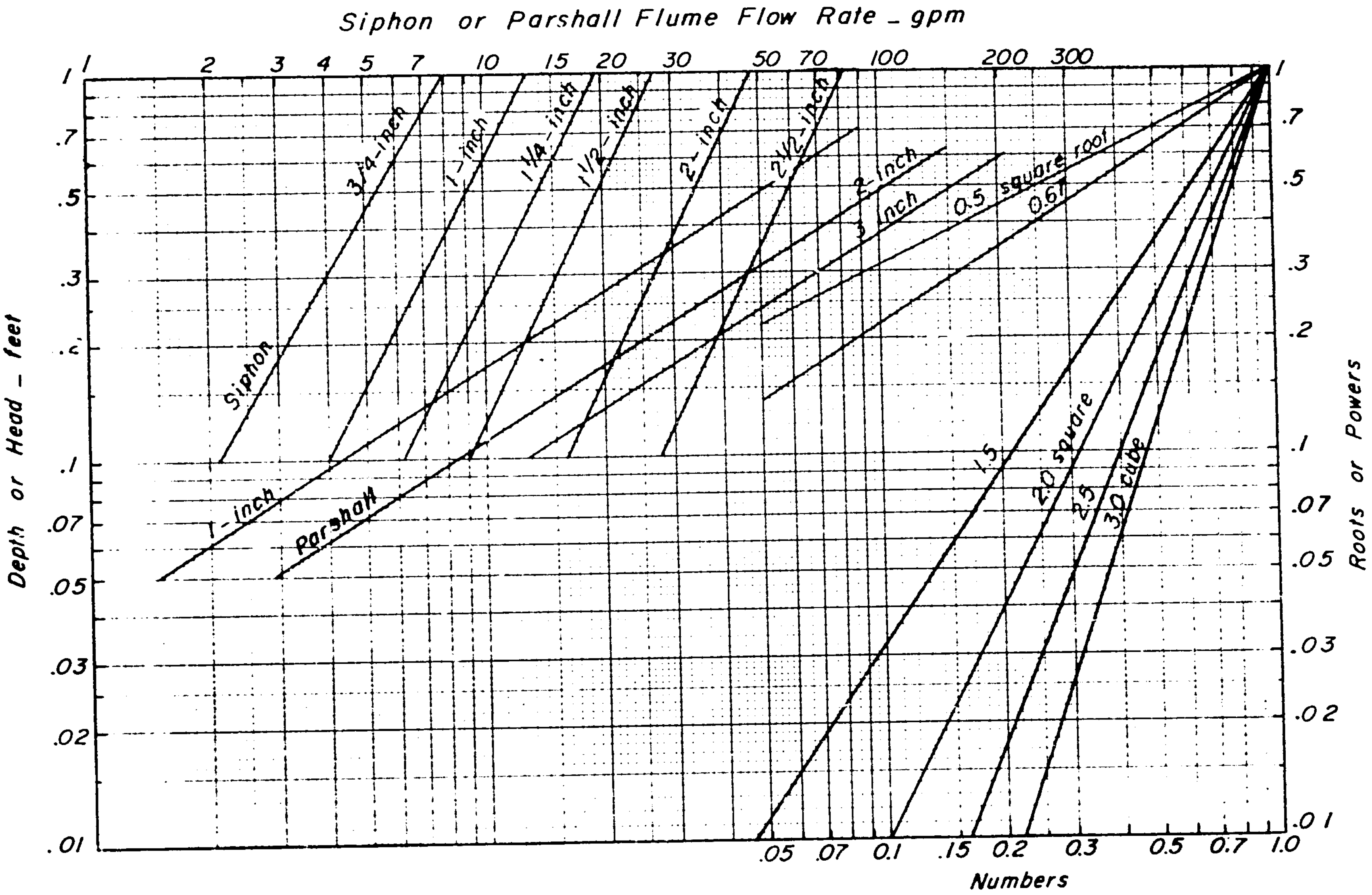


Figure B-1. Flow rates of Parshall flumes and siphons and powers of numbers

Figure B-2 shows a typical orifice board installed for a furrow test. Standard conditions at the entrance to orifices or short tubes require that they be clear of debris that would distort flow for at least one diameter on all sides and that the flow approaching it be slow and uniform. The edge of the orifice must be "sharp" (i.e., unrounded) and the face smooth. Orifice plates may be submerged in holes so that space around the orifice is adequate on all sides.

Figure B-2. Orifice board installed for a furrow test with only one orifice open.

Parshall flumes

The Parshall flume is a special horizontal converging channel carefully built to specific dimensions. Small lightweight portable Parshall flumes are well adapted to techniques of flow measurement for evaluation (Figure IX-4, page 159). Parshall flumes require very little drop through them and they usually do not collect sediment. When a Parshall flume is to be placed in a furrow to measure inflow minus outflow, it should be set as deep as is practical to reduce ponding upstream but should not be set so deep as to be "drowned out" by downstream flow covering the shooting flow through its throat. Small canvas aprons at the upper end of the flume can be buried in the soil to prevent bypass flow. Parshall flumes must be set exactly horizontal by using a spirit level. Larger flumes can be used to measure onflow to border strips.

Depth of flow is measured at one-third the throat length from the upstream edge. Depths must be measured accurately and then converted to flow rates by using tables or appropriate graph in Figure B-1. Using a point gauge to measure down to the water surface gives greatest accuracy.

Weirs

A weir is a notched barrier, usually made of sheet metal, which is placed across an open channel so that water falls freely over it. Notches for weirs have many shapes. The three most common ones are the 90° V-notch ∨ , the rectangular ⊔ , and the trapezoidal ∪ , which has 1:4 side slopes. The V-notch provides accurate measurements of low flows and can be used in furrows on moderate to steep gradients. The other two are useful in larger channels. Use of any weir requires appreciable loss in head.

For use under standard conditions, distances from the sides and bottom of the weir notch to the channel should be two to three times the depth of flow over the weir. Edges of the weir must be sharp, like those for orifices, and the upstream face must be smooth and vertical; flow approaching it must be slow and uniform, and water must not back up above the lip on the downstream side.

Head, H, on weirs is the height of the water above the weir crest in feet. This height should be measured at a location at least three times the depth of overflow away from the crest. Depth of flow should be greater than 1/2 inch. Flow, Q, in cfs for the three most common weirs may be computed from the following formulas:

V-notch $Q = 2.5 \times H^{2.5}$

Rectangular $Q = 3.33 \times (L - 0.2H)H^{1.5}$

Trapezoidal $Q = 3.37 \times L \times H^{1.5}$

where L is the length of the crest in feet. (See Fig. B-1 for powers of numbers.) For more precise calibration of weirs, published values for C to replace the 2.5, 3.33, or 3.37, respectively, must be consulted.

Pipe jets

A jet or stream of water flowing from the end of a horizontal pipe can be used as a simple flow measuring device. For horizontal pipes flowing full, the horizontal distance L in inches from the end of the pipe to where the jet has dropped 12 inches can be used to estimate the flow, Q, in gallons per minute (gpm) by the formula:

$$Q = AL$$

where A is the area of the pipe in square inches. To compute flow in sloping or only partially full pipe, one must consult published tables.

For low vertical jets (where height, H, of the jet is less than 40% of the pipe diameter, 0.4d), practical estimates of flow can be obtained from the weir type formula:

$$Q = 8.8 \ X \ d^{2.5} \ X \ H^{3.5}$$

in which the value of Q is cubic feet per second (cfs) and measurements of d and H are in feet.

For vertical jets where H is greater than 1.4d, practical estimates of flow can be obtained from the orifice type formula:

$$Q = 5.6 \ X \ d^{2} \ X \ H^{0.5}$$

For values of H greater than 0.4d but less than 1.4d, the discharge estimated by either equation will be a little higher than actual flows.

Velocity measurements

In using velocity methods for estimating flow, a channel must first be subdivided into representative cross sections. The area (square feet) of each section must be multiplied by the velocity (feet per second) of the stream in that portion of the channel. Then these incremental flow values must be totaled for the entire cross section of the channel to obtain an estimate of the total flow.

Methods for *direct velocity measurement* are numerous. Current meters which have cups or propellers that rotate when the device is placed in a moving stream can be used to accurately measure the water velocity in a channel. Eight-tenths (0.8) of the velocity of a surface float approximates the average velocity along the path of the float. A vertically held stick whose lower end nearly touches the bottom of the channel and is moved by the current will indicate the average velocity along its line of travel. Dyes such as fluorescein, which is visible at concentrations of only a few parts per mission, ppm, can also be used to estimate velocity.

Methods for *indirect velocity measurement* consist of converting velocity energy to pressure head in feet, which can be used to compute velocity, V, in feet per second (fps) by the formula:

$V = 8\ H^{0.5}$

where H is the length of rise in feet.

An L-shaped tube can be used as a crude pitot gauge for estimating H. When the L-shape tube pointing directly into the stream is inserted into it, water rises in the vertical section to a height, H, above the stream surface. A clear plastic vertical tube facilitates reading this H value. Refinements of the Pitot tube apparatus are available commercially for measuring pipe flows and the pressure head of sprinkler jets.

A flat board having a width about equal to the expected height of rise, H, in the Pitot gauge can also be used to estimate flow. When the board is placed across the stream, water is forced up the front face by the velocity of the current. The distance the water rises above the stream surface is H. This method can be used only for streams having velocities from about 1.6 to 5.0 fps which have corresponding H values from 0.04 to about 0.4 feet.

Miscellaneous

Constricted channels, either artificial or natural, can be used in conjunction with principles of hydraulics to estimate flows either by forcing critical depth or nonuniform flow.

Meters for measuring flow are available commercially in various types and in many sizes.

Summary

The portable devices commonly used for measuring flow are:

For sprinklers: Calibrated container and stop watch, Pitot pressure gauge and orifice area.

For furrows: Small Parshall flume, orifice plate, calibrated container, short tube, and V-notch weir.

For border strips: Parshall flume, weir (rectangular or trapezoidal notched), horizontal or vertical jet and commercial meter.

APPENDIX C

DRAWING INTAKE CURVES FOR FURROWS FROM FIELD DATA

Use the following procedure to draw intake rate and cumulative intake curves for furrows at any spacing as shown in Figure C-1.

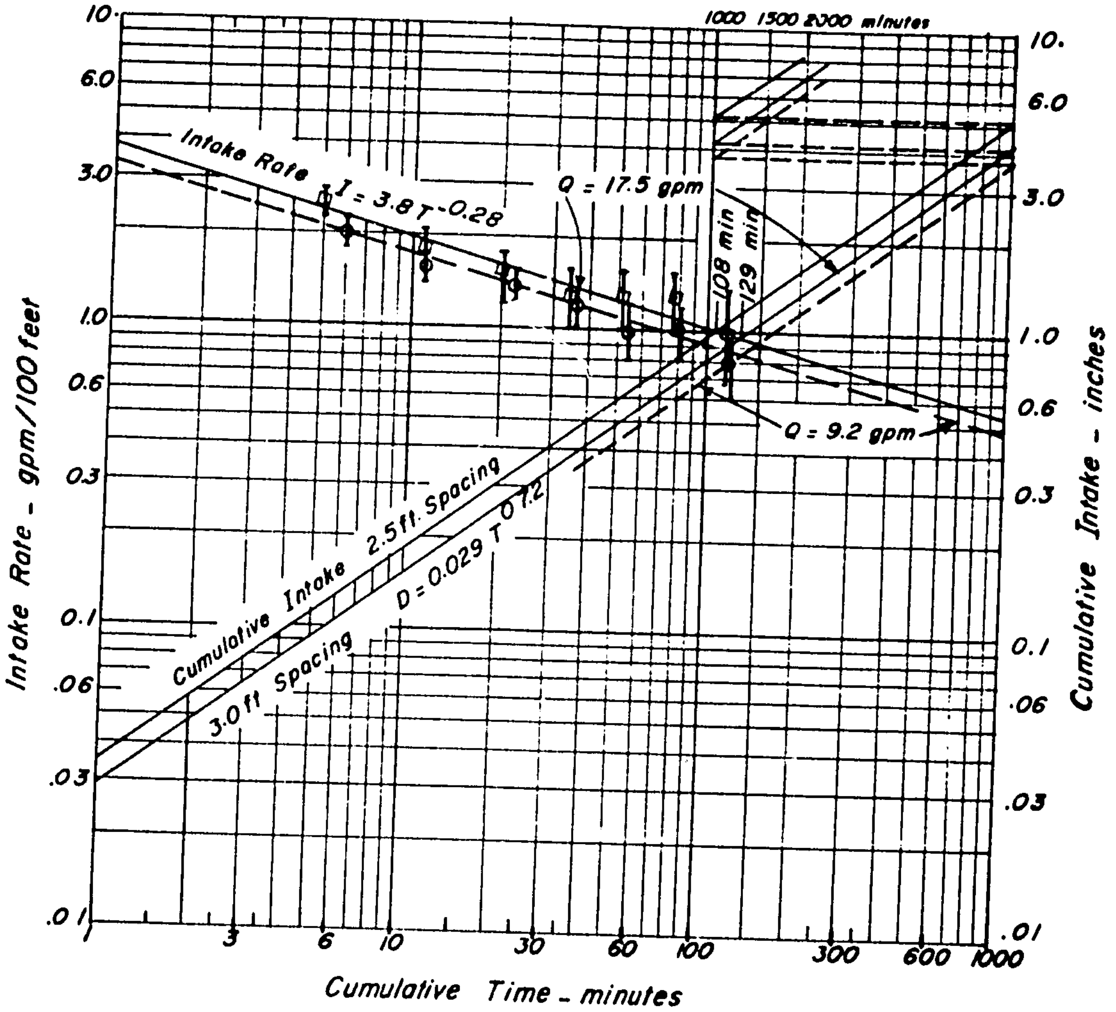


Figure C-1. Plot of typical furrow intake rate and cumulative intake curves.

1. On a sheet of 3 X 3 cycle logarithmic paper write a title and show the location, date, type of soil, steepness of slope, moisture condition, and furrow shape and condition for the irrigation

being plotted. Label the bottom (horizontal) scale *time* from 1 to 1000 minutes. Calibrate the vertical scale for two sets of *intake units*, gpm/100 feet and depth from 0.1 to 100 or from 0.01 to 10 inches as needed.

2. From data from furrow tests, plot intake rate in gpm/100 feet against time, and draw a straight line through the points plotted for each test. Then draw a line typical of all tests across the full width of the graph paper. If the plots for individual furrow tests vary greatly, draw two typical curves to represent the range.

3. Determine the slope, v/h, of the typical gpm/100 feet intake rate curve. To do this measure the horizontal, h, and vertical, v, lengths of the line using any convenient linear scale.

4. For the desired furrow spacing, S (feet), compute a time, T' (minutes) using the equation:

$$T' = 60\ (1 - \frac{v}{h})\ S$$

and mark it on the typical gpm/100 feet intake rate curve drawn in Step 2. This T' point is where the gpm/100 feet intake rate curve and the cumulative intake curve intersect.

5. Measure the horizontal distance from this point to the line $T = 1.0$ minute (left border) by any linear scale or by marks on a piece of paper.

6. Next, from where the gpm/100 feet intake rate curve crosses the line $T = 1.0$ minute, measure down the distance found in Step 5 and mark it.

7. Through the T' point plotted in Step 4 and the point on the left border plotted in Step 6, draw a line that represents the cumulative intake after any time, T, for the desired furrow spacing, S.

8. For other furrow spacings, repeat Step 4 and draw lines through the corresponding T' points parallel to the line drawn in Step 7.

The resulting cumulative curves are representative of the test, but they should not be construed as being more than a reasonable guide for other conditions because intake rate varies with antecedent soil moisture content, size of stream, condition of the furrow (new, or previously used), and soil structure.

APPENDIX D

FIELD PROCEDURE FOR USING CYLINDER INFILTROMETERS

The cylinders should be 10 or more inches in diameter, 12 to 15 inches long, and should be made of 14 or 12 gauge steel. A reference datum should be marked on the rim or side of each cylinder. Cylinders should be driven about 6 inches straight into the ground without wobbling so that there will be no open cracks around the edge. A heavy steel plate to cover the upper end (for protection of the edges) and a heavy (10 to 15 lbs.) hammer are used. The person doing the driving should stand on the plate to provide added weight; this facilitates the cylinder's going into the ground. Some protective material such as vegetation or a piece of paper or cloth should be placed in the bottom of the cylinder to prevent soil from eroding when water is poured in. If this protective material has appreciable volume, it must be removed immediately after the cylinder is filled and before the first reading of infiltration is taken.

To begin a test, quickly pour 4 to 5 inches of water into the cylinder and immediately start timing the infiltration. As soon as possible, the first measurement of infiltration should be made from the datum line down to the water surface. On most soils, the second reading should be taken after 1 minute, but when cylinders are in soils that have cracks or very high rates of intake, the second reading should be taken after only 30 seconds; the third reading should be taken 1 minute later. Subsequent readings, to a total of eight or more measurements for the test, should be taken at increasingly longer intervals. If a cylinder needs refilling, "before" and "after" readings should be taken quickly but recorded as though made at the same time. Other cylinders can be filled in sequence as convenient.

Water surface readings should be made only to the nearest 0.05 inch since the plotting procedure averages out the values and the variation between cylinders is appreciable. These readings must be made from the datum to the water surface using a rule, a point gauge, or a hook gauge, although the latter does not measure the last inch or more of depth.

When tabulating the depth, an estimated value should be entered opposite the starting time to account for the often appreciable depth (0.1 to 0.4 inch) that water infiltrates during the first increment of time before the water level stabilizes and can be measured.

APPENDIX E

BORDER STRIP ADVANCE AND RECESSION CURVES

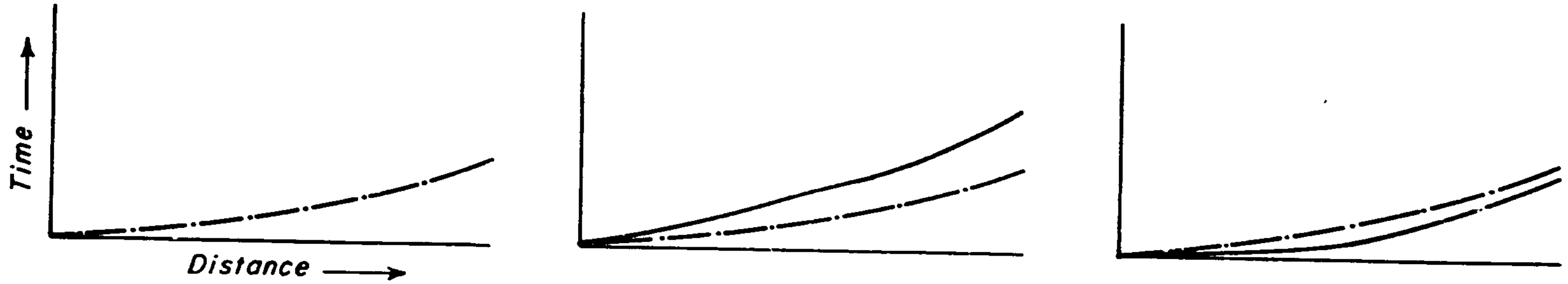
Figure E-1 shows a normal (ideal) border strip advance curve along with a group of advance curves with various deviations from normal. (An advance curve is a plot of the distance of water advance down the border versus the length of time the water has been running.) The normal curve is depicted in each sketch (dashed line) for comparative purposes and the associated problem with the deviation is briefly noted below each curve.

Figure E-2 shows a normal border strip recession curve along with a group of recession curves with various deviations from normal. (A recession curve is a plot of the position where water has just disappeared from the surface, i.e., location of the water front as it recedes down the border, versus the length of time from the beginning of irrigation.) As before, the normal curve and associated problem is presented with each sketch.

Figure E-3 shows a normal combined advance curve and recession curve with the associated irrigation curve (dashed line), cutoff time and runoff portion (dotted tip). Figure E-3 also shows a set of combined curves representing various deviations from the normal curve. The physical conditions and associated problem is also presented for each of the curves.

For the normal combined curves, the advance and recession are nearly parallel. The irrigation curve is always plotted parallel to the advance curve (a uniform time interval above the advance curve). The proper interval is the time of irrigation, T_i, needed for water to infiltrate the depth corresponding to the *SMD*. The time of cutoff equals T_i minus a small lag time, T_l. The proper time of cutoff is when the advance has reached about three-fourths the border strip length; but it must be such that the lower end is adequately irrigated and there is very little runoff.

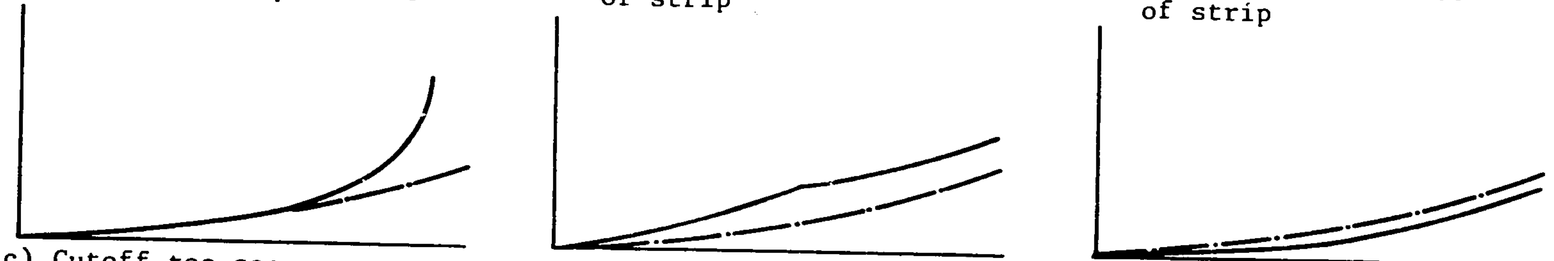
For the other combined curves, the irrigation curve is also parallel to the advance curve; but the time of irrigation is such that there is too little or too much irrigation along all or part of the border strip.



NORMAL - A gradually steepening sickle-shaped curve

a) Faster intake in upper half of strip

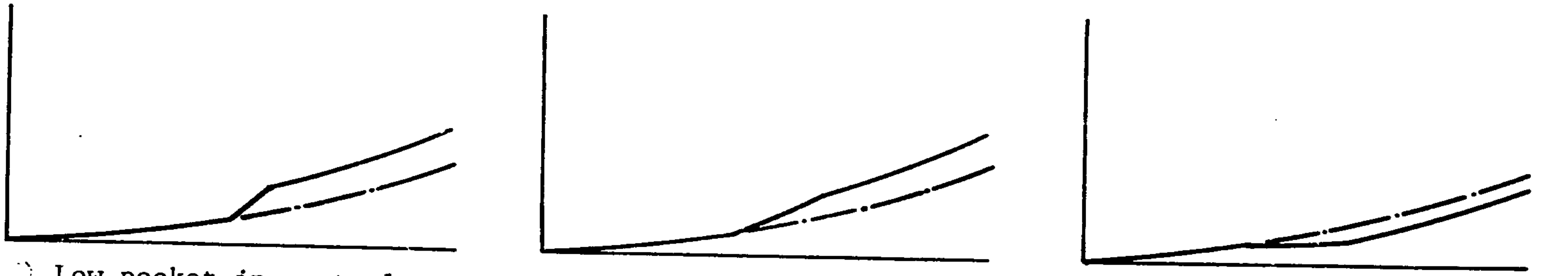
b) Slower intake in upper half of strip



c) Cutoff too soon

d) Flatter slope in upper half of strip

e) Steeper slope in upper half of strip

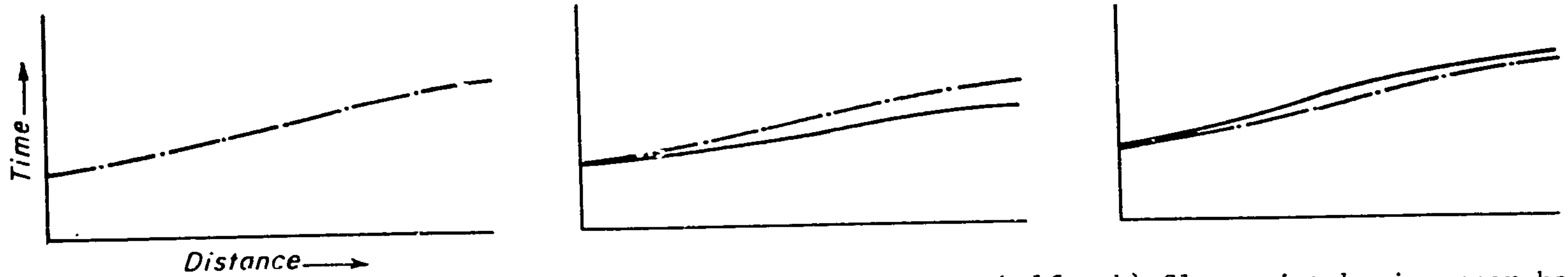


) Low pocket in central portion

g) Faster intake or flatter slope in central portion

h) Slower intake or steeper slope in central portion

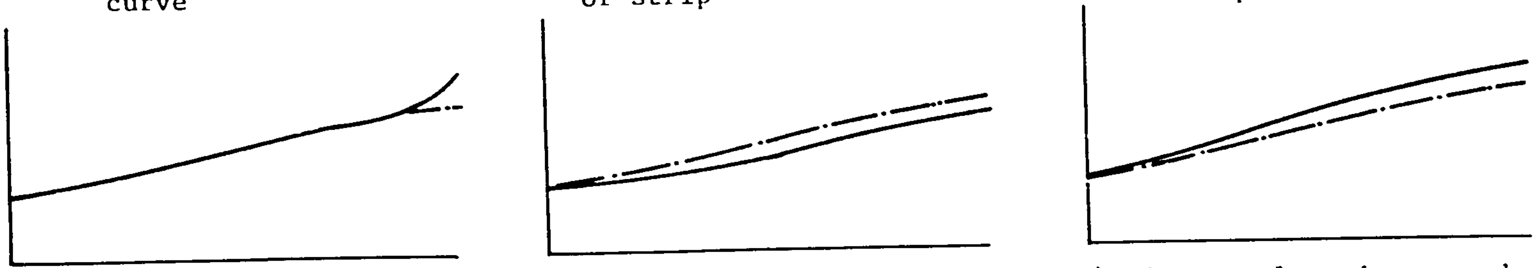
Figure E-1. Various border strip advance curves showing deviations from normal.



NORMAL - A slightly S-shaped curve

a) Faster intake in upper half of strip

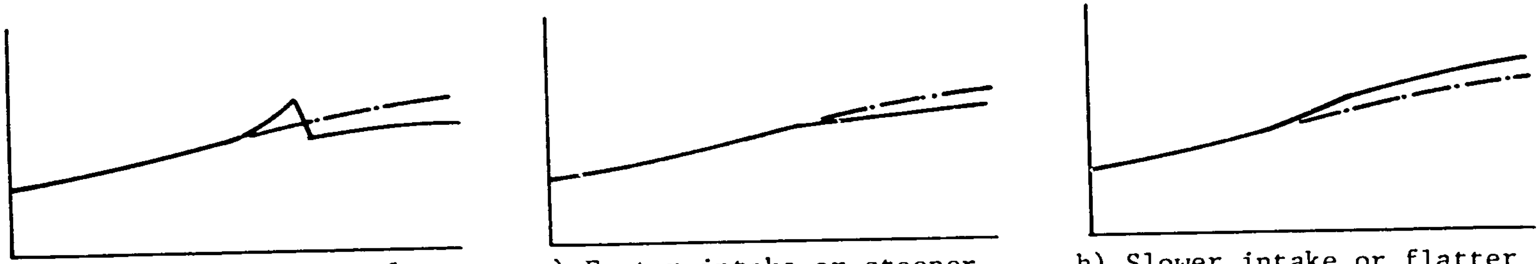
b) Slower intake in upper half of strip



c) Dike at lower end ponding water

d) Steeper slope in upper half of strip

e) Flatter slope in upper half of strip

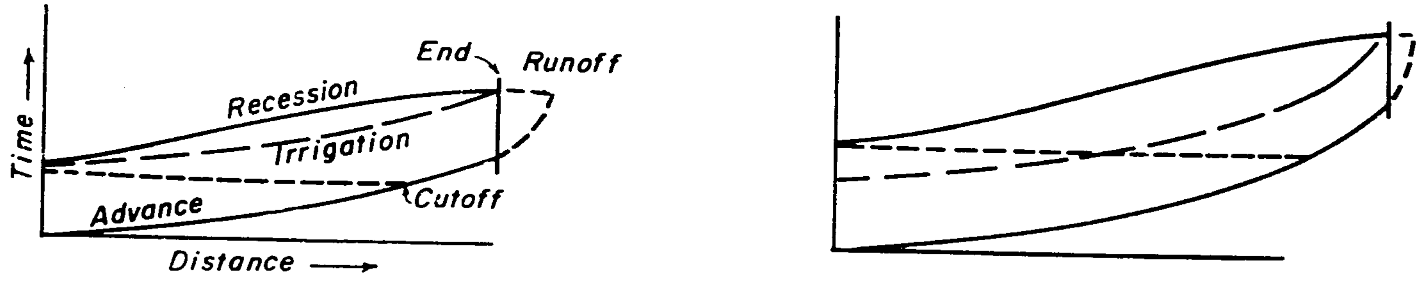


f) Low pocket in central portion

g) Faster intake or steeper slope in central portion

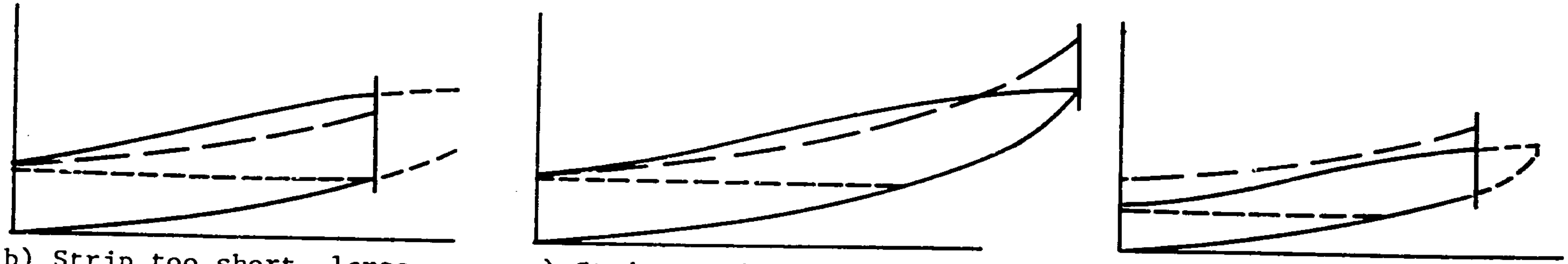
h) Slower intake or flatter slope in central portion

Figure E-2. Various border strip recession curves showing deviations from normal.



NORMAL - Advance and recession nearly parallel, adequate irrigation, minimal runoff

a) Strip too long, over irrigates whole strip

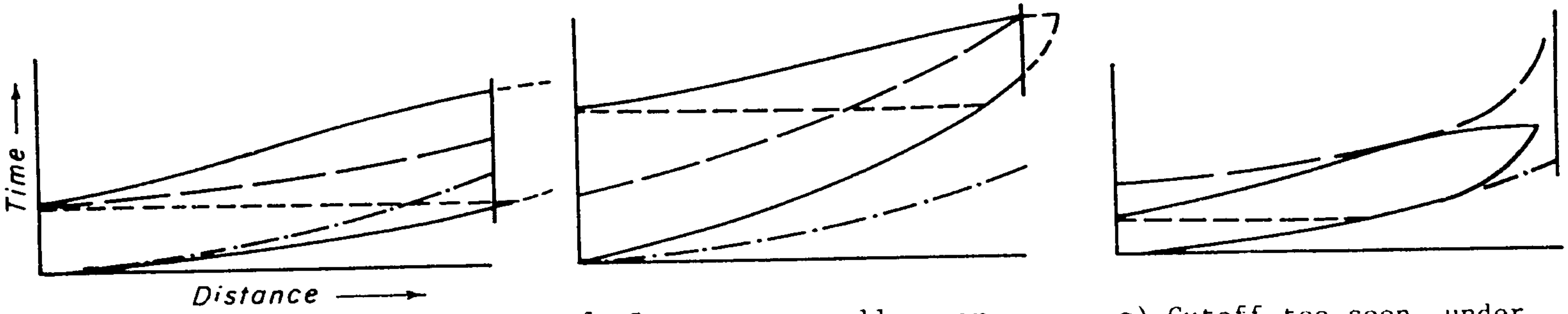


b) Strip too short, large amount of runoff, over irrigates lower portion

c) Strip too long, under irrigates the lower portion, no runoff

d) Strip too short, under irrigates whole strip

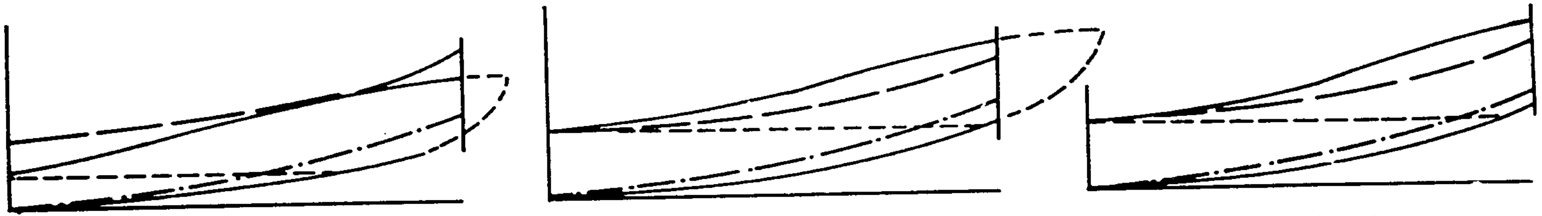
Figure E-3. Various border strip combined advance and recession curves with associated irrigation curves, cutoff times and runoff portions.



e) Stream too large, over irrigates lower portion

f) Stream too small, over irrigates upper portion

g) Cutoff too soon, under irrigates whole strip



h) Stream too large, under irrigates upper and lower portions

i) Steeper slope in upper portion, adequate irrigation, excessive runoff

j) Slower intake in upper portion, adequate irrigation, excessive runoff

Figure E-3 (Continued). Various border strip combined advance and recession curves with associated irrigation curves, cutoff times and runoff portions.

APPENDIX F

SOIL PROBE

The soil probe used in the field to determine the depth of penetration of irrigation water is a very useful tool in studying irrigation practices. Essentially the probe consists of a bulbous-tipped steel rod 3/8- to 5/16-inch in diameter by 4 feet long, with a handle on the end opposite the bulb; this handle gives the probe a "T" shape. The bulbous tip is necessary to make the diameter of the hole in the soil larger than that of the rod so that side friction is negligible; this leaves only the tip to cause resistance to entry. To facilitate measuring, the rod can be marked in 1 foot increments or any other convenient unit.

The irrigator can determine the depth of water penetration during or shortly after irrigation by simply pushing the probe into the wetted soil. The probe easily penetrates the wetted profile but encounters resistance to penetration when it reaches dry soil. The irrigator measures the penetrated depth by reading the marks on the probe. By repeating this procedure systematically, the irrigator will have a very good idea of water penetration in the whole irrigated field and can then exercise good control of irrigations. He can also measure lateral movement of the water by using the probe. This is useful in studying furrow irrigation, where it may be advantageous to measure the lateral spread of water from furrows.

The probe is not sensitive if the soil is already quite wet (as often occurs at appreciable depth) because there is very little difference in resistance. The probe does not work well in fine textured or dense subsoils. It works very well during irrigation when the water has penetrated 2 to 3 feet and is still in fairly dry soil.

When using the probe to determine when to stop irrigating, it is important to note that the wetting front will continue to move downward for several days after irrigation. Therefore, irrigation should be stopped before the wetting front has penetrated the full depth of dry soil in the plant root zone.

APPENDIX G

FURROW ADVANCE RATIO AND EFFICIENCY

In furrow irrigation the Advance Ratio, AR_a, is the ratio of the time it takes a furrow stream to reach the lower end of the field, T_{adv}, to the duration of time water is at the lower end, $T_{o(l)}$. (For basin irrigation it is the ratio of the time it takes water to cover a basin to the duration water is on the last area covered.) Thus, the advance ratio can be expressed as:

$$AR_a = T_{adv}/T_{o(l)}$$

Ideally the water should be at the lower end just long enough to provide the desired irrigation, T_i. For system design and/or good management:

$$AR_a = T_{adv}/T_i$$

The Distribution Uniformity, DU, and the Potential Application Efficiency, $PAELQ$, are greatly dependent on the AR_a. Figure G-1 shows the interrelationships between AR_a and the relative dispersion of equal amounts of applied water for the range in which good irrigation can be expected. An AR_a slower than 1:1 can seldom be justified. From Table G-1 it can be seen that without a return flow system or cutback streams, maximum $PELQ$ is obtained between AR_a values of 1:2 and 1:1 with a return flow or cutback system, the fastest practical AR_a is the most efficient; however, an AR_a faster than 1:2 would be satisfactory.

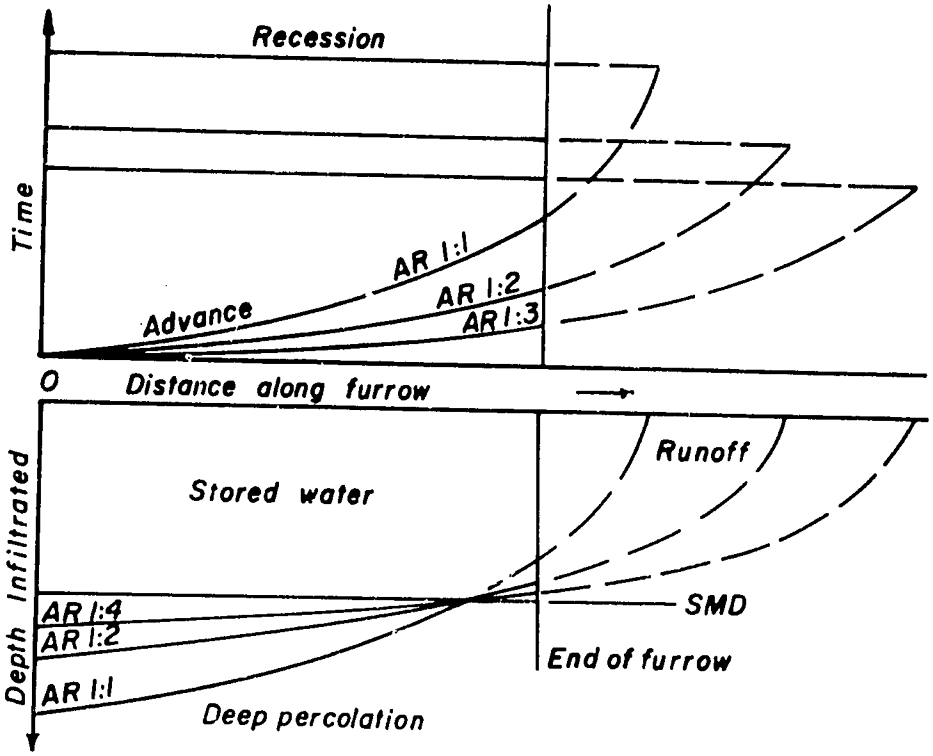


Figure G-1. Theoretical advance and recession curves plotted above the resulting water dispersion curves for different furrow advance ratios.

Table G-1. Theoretical water dispersion, distribution, and uniformity percentage for various furrow advance ratios with and without return flow.

Item	Advance Ratio Without return flow 1:4	 1:2	 1:1	Advance Ratio With return flow 1:4	 1:2	 1:1
Applied water	100%	100%	100%	--	--	--
Portion infiltrated	68	80	93	100%	100%	100%
Portion stored	61	68	70	91	85	75
Deep percolation loss	7	12	23	9	15	25
Runoff loss	32	20	7	0	0	0
Distribution Uniformity, *DU*	91	85	75	91	85	75
Potential Efficiency, *PELQ*	61	68	70	91	85	75

BLANK DATA FORMS

Form II-1. SPRINKLER-LATERAL IRRIGATION EVALUATION

1. Location ____________________, Observer ________, Date ________
2. Crop ______________, Root zone depth ____ft, MAD ______%, MAD ____in
3. Soil: texture ________, available moisture ____in/ft, SMD ______in
4. Sprinkler: make ____________, model _____, nozzles ______ by _____in
5. Sprinkler spacing _____ by _____ft, Irrigation duration ______hrs
6. Rated sprinkler discharge ______gpm at ______psi giving ______in/hr
7. Lateral: diameter ____in, slope ______%, Riser height ______in
8. Actual sprinkler pressure and discharge rates:

	Sprinkler location number on test lateral					
						end
Initial pressure (psi)						
Final pressure (psi)						
Catch volume (gal)						
Catch time (min or sec)						
Discharge (gpm)						

9. Wind: direction relative to
   Part 10: initial _____, during _____, final _____
   Speed (mph): initial _____, during _____, final _____
10. Container grid test data in units of _____, Volume/depth ______ml/in
    Container grid spacing _____ by _____ft
    Test: start _______, stop _______, duration ____hr ____min = ______hr

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

11. Evaporation container: initial _______ final ______ loss ________in
12. Sprinkler pressures: max ____psi; min ____psi, ave ____psi
13. Comments ____

____

Form III-1. PERFORATED PIPE SPRINKLE IRRIGATION EVALUATION

1. Location ____________________ Observer __________ Date __________
2. Crop __________ ,Root zone depth _____ft, MAD _____%, MAD ________in
3. Soil: Texture __________, available moisture ______in/ft, SMD _____in
4. Perforated pipe: make ______, type _____, hole diameter ______in
5. Perforated lateral pipe spacing _____ft, Irrigation duration _____hrs
6. Rated pipeline discharge _____gpm/_____ft at _____psi giving _____in/hr
7. Pipe: diameter _____in, material ________, length _____ft, slope ____%
8. Holes per pattern sequence _____, Pattern sequence interval _____ft
9. Wind: direction arrow relative
   to pipe flow direction ⟶ Initial _____ Final _____
   speed (mph) Initial _____ Final _____
10. Actual pipeline performance:
    Discharge estimates from _____ holes per pattern sequence and
    measured in _______ (3785 ml = 1.0 gal, 128 oz = 1.0 gal)

	Position along perforated pipeline			
	Inlet	Middle	End	
11. Pressure (psi)	_____	_____	_____	diff _____
12. Wetted width: total (ft)	_____	_____	_____	ave _____
upwind (ft)	_____	_____	_____	
downwind (ft)	_____	_____	_____	
13. Jet trajectory: length (ft)	_____	_____	_____	
uniformity	_____	_____	_____	
alignment	_____	_____	_____	
Holes clogged or eroded	_____	_____	_____	
14. Catch: volume (oz)	_____	_____	_____	
volume (gal)	_____	_____	_____	
time (seconds)	_____	_____	_____	
Ave. discharge: gpm/hole	_____	_____	_____	
gpm/ft	_____	_____	_____	ave _____

15. Discharge pressures: max _______psi, min _______psi, ave _______psi
16. Comments: ____

____

____

Form IV-1. ORCHARD SPRINKLER IRRIGATION EVALUATION

1. Location ____________, Observer ______, Date ____________
2. Crop ________, Root zone depth ____ ft, MAD ____ %, MAD ______ in
3. Soil: texture ________, available moisture ____ in/ft, SMD ___ in
4. Tree: pattern __________, spacing ____ by ______ ft
5. Sprinkler: make ________, model ________, nozzles _____ by ___ in
   spacing ____ by _____ ft, location to trees __________
6. Irrigation: duration ____ hrs, frequency ____ days
7. Rated sprinkler discharge _____ gpm at _____ psi and diameter _____ ft
8. Sprinkler jet: height _____ ft, interference ______________
9. Actual sprinkler pressure and discharge (see back for location):

Sprinkler locations:	_____	_____	_____	_____
Pressure (psi)	_____	_____	_____	_____
Catch volume (gal)	_____	_____	_____	_____
Catch time (sec)	_____	_____	_____	_____
Discharge (gpm)	_____	_____	_____	_____
Wetted diameter (ft)	_____	_____	_____	_____

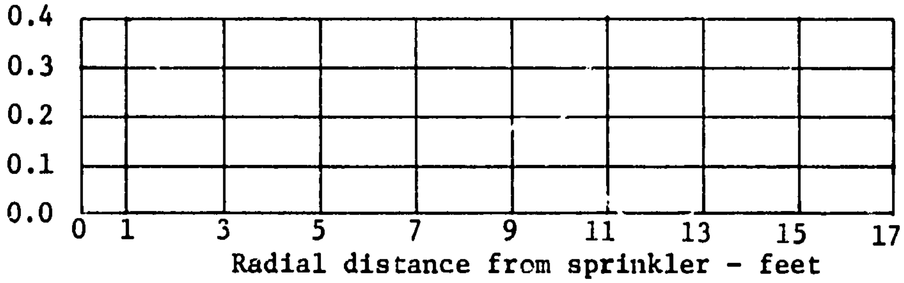
Comments: ______________________________

10. Container row test data in units of ______, Volume/depth _____ ml/in

Test: start ________, stop ________, duration ____ hr ____ min= ______ hr

Catch (   ): ____ ____ ____ ____ ____ ____ ____ ____ ____

Rate (iph): . . . .



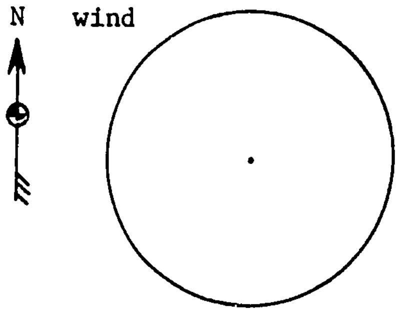
11. Discharge pressures: max _____ psi, min _____ psi, ave ________ psi
12. Comments: ______________________________

____

____

Form V-1. CENTER PIVOT SPRINKLE IRRIGATION EVALUATION

1. Location ____________, Observer _____, Date & Time ______________
2. Equipment: make _______, length ______ft, pipe diameter _______in
3. Drive: type _______ speed setting ____%, water distributed? _____
4. Irrigated area = $\frac{3.14\ (\text{wetted radius}\ \underline{\qquad\qquad}\ \text{ft})^2}{43{,}560}$ = ________acres
5.



*Mark position of lateral, direction of travel, elevation differences, wet or dry spots and wind direction.

Wind ____mph, Temperature _______°F

Pressure: at pivot __________psi

at nozzle end ______psi

Diameter of largest nozzle ____in

Comments: ______________________

____

6. Crop: condition ______________________________, root depth _______ft
7. Soil: texture ____________, tilth ______, avail. moisture _____in/ft
8. SMD: near pivot ______in, at 3/4 point ______in, at end _________in
9. Surface runoff conditions at 3/4 point ______, and at end ________
10. Speed of outer drive unit ______ft per ______min = __________ft/min
11. Time per revolution = $\frac{(\text{outer drive unit radius}\ \underline{\qquad\qquad}\ \text{ft})}{9.55\ (\text{speed}\ \underline{\qquad\qquad}\ \text{ft/min})}$ = ________hr
12. Outer end: water pattern width _______ft, watering time ______min
13. Discharge from end drive motor ______gal per ______min = ______gpm
14. System flow meter ____________gallons per _______min = ________gpm
15. Average weighted catches:

System = $\frac{(\text{sum all weighted catches}\ \underline{\qquad\qquad})}{(\text{sum all used position numbers}\ \underline{\qquad\quad})}$ = _______ml = ______in

Low 1/4 = $\frac{(\text{sum low 1/4 weighted catches}\ \underline{\qquad\qquad})}{(\text{sum low 1/4 position numbers}\ \underline{\qquad\quad})}$ = _______ml = ______in

16. Minimum daily (average daily weighted low 1/4) catch:

$$\frac{(\underline{\qquad}\ \text{hrs operation/day}) \times (\text{low 1/4 catch}\ \underline{\qquad}\ \text{in})}{(\underline{\qquad}\ \text{hrs/revolution})} = \underline{\qquad\qquad}\ \text{in/day}$$

Form V-1. CENTER PIVOT SPRINKLE IRRIGATION EVALUATION (Cont.)

17. Container catch data in units of ______, Volume/depth ______ ml/in

Span length ______________ ft, Container spacing __________ ft

Evaporation: initial ______ ml ______ ml

final ______ ml ______ ml

loss ______ ml ______ ml, ave ____ ml = ____ in

Span no.	Container			Span No.	Container		
	Position Number	X Catch =	Weighted Catch		Position Number	X Catch =	Weighted Catch
	1				37		
	2				38		
	3				39		
	4				40		
	5				41		
	6				42		
	7				43		
	8				44		
	9				45		
	10				46		
	11				47		
	12				48		
	13				49		
	14				50		
	15				51		
	16				52		
	17				53		
	18				54		
	19				55		
	20				56		
	21				57		
	22				58		
	23				59		
	24				60		
	25				61		
	26				62		
	27				63		
	28				64		
	29				65		
	30				66		
	31				67		
	32				68		
	33				69		
	34				70		
	35				71		
	36				72		

Sum all: used position numbers ________, weighted catches ____________

Sum low 1/4: position numbers ________, weighted catches ____________

Form VI-1. TRAVELING SPRINKLER IRRIGATION EVALUATION

1. Location ______________, Observer __________, Date ______________
2. Crop __________, Root zone depth ______ft, MAD ____%, MAD ______in
3. Soil: texture _________________, available moisture ________in/ft
4. SMD: near tow path ____in, at 1/4-point ____in, at mid-point ___in
5. Sprinkler/Traveler makes and models _______________/_______________
6. Nozzle: size _____in, type ____, pressure _____psi, discharge ____gpm
7. Hose: length _____ft, diameter _____in, type ________________________

   inlet pressure _____psi, outlet pressure ______psi
8. Drive: type ________, discharge (if piston) ___gal/ _____min = ___min
9. Towpath: spacing ______ft, length _______ft, slope ± ___________%
10. Evaporation loss: (_____ml catch = 1.0 in)

    cup #1 initial - final volume = _______ - _______ = ________ml

    cup #2 initial - final volume = _______ - _______ = ________ml

    average evaporation loss = ______________ml = ___________in
11. Traveler speed check at:

    beginning _____ft/ _______min = __________ft/min

    at test site _____ft/ _______min = __________ft/min

    terminal end _____ft/ _______min = __________ft/min
12. Total: discharge __________________gpm, pressure loss ________psi
13. Average application rate:

$$\frac{96.3 \times (\text{sprinkler discharge } \underline{\qquad\quad} \text{ gpm}) \times 360}{(\text{towpath spacing } \underline{\qquad} \text{ ft})^2 \times (\text{wet sector } \underline{\quad}\,°)} = \underline{\qquad} \text{ in/hr}$$

14. Average depth applied:

$$\frac{96.3}{60} \times \frac{(\text{sprinkler plus piston discharge } \underline{\qquad} \text{ gpm})}{(\text{path spacing } \underline{\qquad} \text{ ft}) \times (\text{travel } \underline{\qquad} \text{ ft/min})} = \underline{\qquad} \text{ in}$$

15. Average overlapped catches:

$$\text{System} = \frac{(\text{sum all catch totals } \underline{\qquad} \text{ in})}{(\text{number of totals } \underline{\qquad})} = \underline{\qquad} \text{ in}$$

$$\text{Low } 1/4 = \frac{(\text{sum of low } 1/4 \text{ catch totals } \underline{\qquad} \text{ in})}{(\text{number of low } 1/4 \text{ totals } \underline{\qquad})} = \underline{\qquad} \text{ in}$$

16. Comments (wind drift, runoff etc.): _________________________________

    ____

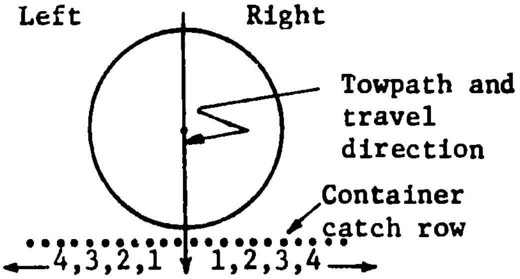
Form VI-1 TRAVELING SPRINKLER IRRIGATION EVALUATION (Cont.)

17. Container test data in units of ________, Volume/depth ______ ml/in

Wind: speed ________ mph

direction

Note part circle operation and the dry wedge size in degrees



Patch Spacing feet	Container Catch Volume				Right plus Left Side Catch Totals	
	Left side of path		Right side of path			
	Catch No.	Catch	Catch No.	Catch	ml	inches
330 320 310	Start with number 1 opposite the towpath spacing and number down		Start with number 1 at bottom of column and number up			
300 290 280						
270 260 250						
240 230 220						
210 200 190						
180 170 160						
150 140 130						
120 110 100						
90 80 70						
60 50 40						
30 20 10			*3* *2* *1*			

Sum of all catch totals ________

Sum of low 1/4 catch totals ________

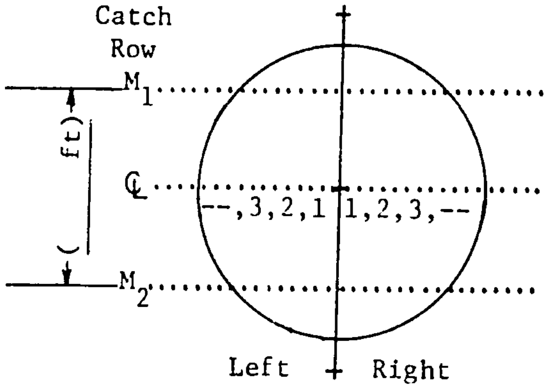
Form VII-1. GUN SPRINKLER OR BOOM IRRIGATION EVALUATION

1. Location ______________, Observer ___________, Date _________
2. Crop __________, Root zone depth _____ft, MAD ____%, MAD ______in
3. Soil: texture__________, tilth ______, avail. moisture ____in/ft
4. SMD ℄ : near lateral ___in, at 1/4 point ____in at mid-point ___in

   SMD M : near lateral ___in, at 1/4 point ____in at mid-point ___in
5. Sprinkler: make _____________, model ________________________,

   nozzle (taper or ring) ____________________-inch
6. Sprinkler spacing _______-ft by _____-ft, Irrig. duration _____hrs
7. Design sprinkler discharge ______gpm at _____psi giving _____in/hr
8. Actual sprinkler pressure and estimated average discharge:

   initial ____psi, final ____psi, ave ____psi estimated _____gpm
9. Test layout:



Wind: speed _______mph

direction

Note wet or dry areas and sketch the wetting pattern over the circle.

10. Evaporation: initial ____ml, final _____ml, loss ____ml = _____in
11. Average catch rates for ___.___hr test (______ml/hr = 1.0 in/hr):

    System = (sum all catch totals ______ml) / (number of totals __) X (____hrs) = ____ml/hr = _____in/hr

    Low 1/4 = (sum of low 1/4 catch totals ______ml) / (number of low 1/4 totals ____) X (____hrs) = _____ml/hr

    = _____in/hr
12. Estimated average rate applied over area:

    96.3 X (estimated sprinkler discharge ______gpm) / sprinkler spacing (_______ft) X (______ft) = ________in/hr
13. Comments (wind drift, runoff, etc.) ____________________

    ____

    ____

Form VII-1 GUN OR BOOM SPRINKLER IRRIGATION EVALUATION (Cont.)

14. Container row test data in units of ______, Volume/depth ______ ml/in

Container spacing: in rows ______ ft, between rows ______ ft

Start ______, Stop ______, Duration ___ hr ___ min = ______ . ___ hr

Lat-eral spac. (ft)	Container Numbers and Catch Volumes								Right+Left Side Totals		M_1+ M_2 plus ℄ Totals
	Left side of lateral				Right side of lateral						
	Catch No.	M_1 Catch	M_2 Catch	℄ Catch	Catch No.	M_1 Catch	M_2 Catch	℄ Catch	M_1+M_2 Catch	℄ Catch	
360 350 340	Start with number 1 opposite the lateral spacing and number down										
330 320 310											
300 290 280											
270 260 250					Start with number 1 at bottom of column and number up						
240 230 220											
210 200 190											
180 170 160											
150 140 130											
120 110 100											
90 80 70											
60 50 40											
30 20 10					3 2 1						

Sum of all catch totals		
Sum of low 1/4 catch totals		

Form VIII-1. TRICKLE IRRIGATION EVALUATION

1. Location ________________, Observer _______, Date _______________
2. Crop: type ___________, age _____years, spacing ___-by____-feet
   root depth _____ft, percent area covered or shaded _____%
3. Soil: texture _______________, available moisture ________in/ft
4. Irrig: duration ___hrs, frequency ___days, MAD ___%, ________in
5. Filter pressure: inlet ___psi, outlet ____psi, loss _________psi
6. Emitter: make _____________, type _______, point spacing _____ft
7. Rated discharge per emission point _______gph at _________psi
   Emission points per plant ____, giving ___gallon per plant per day
8. Hose: diameter ____in, material ____, length ____ft, spacing____ft
9. System layout, general topography, and test locations:

10. System discharge _____gpm, No. of manifolds _____ and blocks _____
11. Average test manifold emission point discharges at _________psi

$$\text{Manifold} = \frac{(\text{sum of all averages} \_\_\_\_\_\_\_\_ \text{gph})}{(\text{number of averages} \_\_\_\_\_\_\_\_)} = \_\_\_\_\_\_\_\_\_ \text{gph}$$

$$\text{Low } 1/4 = \frac{(\text{sum of low } 1/4 \text{ averages} \_\_\_\_\_\_ \text{gph})}{(\text{number of low } 1/4 \text{ averages} \_\_\_\_\_)} = \_\_\_\_\_\_\_\_\_ \text{gph}$$

12. Adjusted average emission point discharges at ___________psi
    System = (DCF _____) X (manifold average _____gph) = ________gph
    Low 1/4 = (DCF ____) X (manifold low 1/4 _____gph) = ________gph
13. Comments: ____

____

____

Form VIII-1. TRICKLE IRRIGATION EVALUATION (Cont.)

14. Discharge test volume collected in ____min (1.0 gph = 63 ml/min)

Outlet Location on Lateral		Lateral Location on the Manifold							
		inlet end		1/3 down		2/3 down		far end	
		ml	gph	ml	gph	ml	gph	ml	gph
inlet end	A B								
	Ave								
1/3 down	A B								
	Ave								
2/3 down	A B								
	Ave								
far end	A B								
	Ave								

15. Lateral inlet ____psi ____psi ____psi ____psi
closed end ____psi ____psi ____psi ____psi

16. Wetted area ____ft^2 ____ft^2 ____ft^2 ____ft^2
per plant ____% ____% ____% ____%

17. Estimated average SMD in wetted soil volume ________in

18. Minimum lateral inlet pressures, MLIP, on all operating manifolds:

Manifold:	Test	A	B	C	D	E	F	G	Ave.
Pressure-psi:	____	____	____	____	____	____	____	____	____

19. Discharge correction factor, DCF, for the system is:

$$DCF = \frac{2.5 \times (\text{average MLIP} \quad \_\_\_\_\_\_ \text{psi})}{(\text{average MLIP} \quad \_\_\_\_\_\_ \text{psi}) + 1.5 \times (\text{test MLIP} \quad \_\_\_\_ \text{psi})} = \_\_\_\_\_\_$$

or if the emitter discharge exponent x = ________ is known

$$DCF = \left[\frac{(\text{average MLIP} \quad \_\_\_\_\_\_ \text{psi})}{(\text{test MLIP} \quad \_\_\_\_\_\_ \text{psi})} \right]^{x=} \_\_\_\_ = \_\_\_\_\_\_\_\_\_\_$$

Form IX-1. FURROW IRRIGATION WATER ADVANCE EVALUATION

1. Location ______________, Observer ____________, Date ______________________

2. Crop ___________, Age _________, Root depth _____ ft, Row: spacing _____ in, length _____ ft

3. Soil: texture ________________, available moisture _____ in/ft, SMD _______________ in

4. Irrigation: duration _____ hrs, frequency __________ days, MAD _______ %, MAD _______ in

5. A: ______________ B: ______________ C: ______________ D: ______________

Stream: _______ gpm ___________ gpm ___________ gpm ___________ gpm

Time – min.			*Station*	*Time – min.*			*Station*	*Time – min.*			*Station*	*Time – min.*			*Station*
Watch	*Diff.*	*Cumu.*	*feet*	*Watch*	*Diff.*	*Cumu.*	*feet*	*Watch*	*Diff.*	*Cumu.*	*feet*	*Watch*	*Diff.*	*Cumu.*	*feet*

6. Comments: ____

Form IX-2. FURROW INFILTRATION EVALUATION

1. Location ______________________________, Observer ______, Date ________

2. Furrow: Identity ________, shape ____________, condition ____________
age ________, soil ____________, moisture ______, slope ___%

a	*b*	*c*	*d*	*e*		*f*	*g*		*h*
Time			***Station A — Flow Rate***			***Station B — Flow Rate***			***Intake***
Watch	*Diff. min.*	*Cum. min.*		___	***gpm***		___	***gpm***	***gpm/100ft***
						X	X	X	
Accuracy range									

2. Furrow: Identity ________, shape ____________, condition ____________
age ________, soil ____________, moisture ______, slope ___%

Time			***Station A — Flow Rate***			***Station B — Flow Rate***			***Intake***
Watch	*Diff. min.*	*Cum. min.*		___	***gpm***		___	***gpm***	***gpm/100ft***
						X	X	X	X
Accuracy range									

3. Comments: ____

Form X-1. BORDER-STRIP IRRIGATION INFILTRATION EVALUATION

1. Location ______________________, Observer _____, Date ____________
2. Crop __________, Root zone depth _____ft, MAD ________%, MAD _____in
3. Soil: texture __________, available moisture ______in/ft, SMD ___in
4. Crop history: ____
5. Remarks: ____

____

6.

Cylinder ___					
Time minutes			Infiltration inches		
watch	diff	cumu	depth	diff	cumu

Cylinder ___					
Time minutes			Infiltration inches		
watch	diff	cumu	depth	diff	cumu

Cylinder ___					
Time minutes			Infiltration inches		
watch	diff	cumu	depth	diff	cumu

Cylinder ___					
Time minutes			Infiltration inches		
watch	diff	cumu	depth	diff	cumu

Form X-2. BORDER STRIP IRRIGATION WATER ADVANCE AND RECESSION EVALUATION

1. Location ____________________, Observer ______________, Date ________________
2. Crop and Condition ________________________, Border condition ________________
3. Border: spacing ________ft, strip width ________ft, wetted width ______ft, slope ________ ________
4. Irrigation: duration ______, frequency ________, water spread ________________
5. A: __________ B: __________ C: __________ D: __________
Stream __________ __________ __________ __________

Time – min.			Station	Time – min.			Station	Time – min.			Station	Time – min.			Station
Watch	Diff.	Cumu.	feet	Watch	Diff.	Cumu.	feet	Watch	Diff.	Cumu.	feet	Watch	Diff.	Cumu.	feet