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## **Increased Water use Efficiency Through Trickle Irrigation**

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**Texas Water Resources Institute**

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**Texas A&M University**

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INCREASED WATER USE EFFICIENCY  
THROUGH TRICKLE IRRIGATION

Principal Investigator

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The authors also wish to thank Dale Brown of Submatic, Inc., David Whelan of UNIROYAL, Inc., Dick Krupp and Jeffrey Brown of Controlled Water Emission Systems, and Roy Ussery of Ussery Engineering for supplying some of the trickle irrigation equipment used in this study.

## ABSTRACT

The gap between supply and demand of water for agricultural and municipal uses is rapidly closing at a time when world food requirements are increasing at an alarming rate. To meet the demand for agricultural products, new lands must be brought into production or higher yields must be realized from existing lands. In either case, more efficient use of water is prerequisite. Trickle irrigation is an approach to obtain increased water use efficiencies (ratio of weight of grain harvested to weight of total crop water use) and therefore a way to increase food production with our limited water resources.

The ultimate goal of this investigation was the development of required crop inputs for selected crops to optimize the design of trickle irrigation systems and obtain an optimum water balance for living plants. Specific objectives were as follows:

1. To quantitatively determine optimum irrigation timing and necessary water application amounts for selected crops when using trickle irrigation; and
2. To develop a general method for the hydraulic design of trickle irrigation systems using inputs from the first objective for optimizing the system.

To achieve these objectives, experiments were conducted in field lysimeters and in a well-instrumented field plot installation for evaluating the crop inputs. Complete control of the soil water balance can be achieved by the use of these facilities. By knowing the required crop inputs and utilizing known principles of fluid mechanics

proper design procedures were developed to provide optimum design for trickle irrigation systems.

To achieve the first objective, three research experiments were conducted at the research lysimeters of the Department of Agricultural Engineering at Texas A&M University for which grain sorghum was selected as the experimental crop. The first two experiments were designed to study the response of grain sorghum to trickle and subsurface irrigation. A comparison of water use efficiencies under well-watered conditions using both intensified and conventional water application methods and the evaluation of water use efficiencies with trickle irrigation applications designed to limit the availability of water were the specific objectives. The results indicated higher water use efficiencies and better crop response when the trickle method of application was used. Also, the results showed that higher water use efficiencies can be obtained by applying sparing amounts.

An additional investigation carried out under a different research project of the Texas Water Resources Institute (TWRI Project No. A-024-TEX) was designed to develop a computer model to simulate grain sorghum yield and water use under high frequency irrigation. The simulation methods used in this study can be used to simulate a complete irrigation experiment greatly reducing research costs and allowing the determination of water requirements for many crops under many different soil and climatic conditions.

The objective of the third research experiment conducted in 1974 was to determine if different irrigation frequencies would influence

the growth and water use efficiency of grain sorghum when irrigated at optimum levels. Results indicated that frequency of application had no significant effect on the water use efficiency of grain sorghum for irrigation intervals up to 7 days.

To attain the second goal of this investigation two trickle irrigation lateral design methods were developed. With the first method the pressure loss and emitter flow ratio for trickle irrigation laterals can be determined. The design method is based upon known principles of fluid mechanics. A computer program was written to determine the lateral pressure loss and emitter flow ratio at a given design length as function of pipe size, tree spacing, number of emitters per tree, emitter spacing, downstream lateral pressure and lateral slope. For a given set of design inputs, the program can be used to determine if the given pipe size will be adequate to limit the pressure loss and flow variation along the lateral to limits acceptable for the design lateral length. In the second method design equations are utilized to calculate the maximum lateral length for a given value of the uniformity of application coefficient. The solution depends upon the emitter flow function, elevation change, pipe size, reduction coefficient for dividing flow, pipe roughness coefficient, the average emitter flow rate, and either the average emitter spacing or the number of emitters per lateral. For a given uniformity the solution is a linear log-log line with a slope that depends only on the flow rate exponent in the pipe friction loss equation. Dimensionless graphs were developed that can be used to design the trickle irrigation laterals.

It is believed that the results obtained in this research would provide far-reaching state, national and international benefits.



## CHAPTER 1

### INTRODUCTION

In approaching the solution of a design problem, it is necessary to consider at least two steps. First the functional requirements of the proposed system must be determined. Then an engineering design must be formulated and implemented which will meet these functional requirements.

In the proper design of an irrigation system, the first step must be determination of the irrigation requirements of the crop to be grown. Then a satisfactory approach must be available for designing the irrigation system based on the crop requirements. Trickle irrigation as used in this report may be defined as irrigating by means of droplets on the surface of the soil near the plant.

An appraisal of the present state-of-the-art regarding trickle irrigation design indicated that knowledge concerning both the crop inputs and the design approach was seriously lacking. At the same time, research has shown that drastic increases in water use efficiency can be achieved with trickle irrigation when compared with conventional irrigation methods. Water use efficiency as used here is defined as the crop yield per unit of applied water.

#### Objectives

The purpose of this research was to develop information necessary for maximizing water use efficiency with trickle irrigation. The specific objectives were as follows:

1. to quantitatively determine optimum irrigation timing and

necessary water application amounts for selected crops when using trickle irrigation; and

2. to develop a general method for the hydraulic design of trickle irrigation systems using inputs from 1. for optimizing the system.

To achieve these objectives, experiments were conducted in a well-instrumented field lysimeter installation for evaluating the crop inputs. Complete control of the soil water balance can be achieved with these facilities. By knowing the required crop inputs and utilizing known principles of fluid mechanics, proper design procedures were developed to provide optimum design for trickle irrigation systems.

#### Significance of Research

The recent World Food Conference in Rome, Italy, recognizing the need for better water management and irrigation methods as means of bringing new land into production and producing greater harvests from existing farms, made the following recommendation in its Technical Resolution No. 7\*:

"To take urgent action in the identification of groundwater resources, exploration of the economic feasibility of using non-conventional sources of water and *research and development efforts in the most economical use of water with such techniques as drip and sprinkler irrigation in arid areas where shortage of water, rather than land, is the limiting factor in crop production.*"

The world needs and will continue to need to produce more food with the limited amount of water it has in order to minimize human suffering.

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\* Reproduced here in Figure 1.

This is and will be the greatest challenge to humanity for many years to come.

This trickle irrigation research was directed specifically toward maximizing the water use efficiency of crops, i.e. producing more food with less water consumption. Increasing crop water-use efficiency is extremely important, particularly in the Western United States, because there irrigation is by far the major user of our dwindling water supply. Thus, if we are to continue to produce enough human food for our populous to survive, it is imperative that means for increasing crop water-use efficiency be found. In Texas where water supply is such a problem that plans for importing water and for developing large desalting plants have been seriously considered, increased crop water-use efficiency is particularly important because of the large cost to the user of such water.

Research has indicated that water use efficiency can be increased by 50 percent using trickle irrigation when compared with surface irrigation (Hiler and Howell, 1972, and several others). This means, in effect, for a given water supply that 1.5 times as many acres could be irrigated with trickle irrigation as with surface irrigation; or, in other terms, two-thirds as much water would be needed to irrigate a given acreage with trickle irrigation compared to surface irrigation. In areas where irrigation water supplies are rapidly dwindling, such as is the case in the Southwestern United States, this reduction in irrigation water requirement is very important. Specific crop requirements and design methods are badly needed to make trickle irrigation a feasible reality in the near future.

## RESOLUTION VII

**Scientific Water Management: Irrigation, Drainage and Flood Control***The World Food Conference*

*Recognizing* the vital role of water in agricultural development and consequently of completing projects under construction, improving existing irrigation systems and developing new irrigation facilities in developing countries.

*Recognizing* that extending the area under assured irrigation has become particularly urgent, since variability in weather and climate is becoming an increasingly important factor in influencing the world food situation.

*Noting* that considerable ground and surface water resources are yet to be exploited and that available evidence on benefit/cost is favorable to their development and utilization.

*Noting* that a large number of irrigation schemes are operating at low levels of efficiency.

*Noting* also that extensive irrigated areas have gone out of cultivation or their production capabilities have been reduced due to waterlogging, salinity and alkalinity.

*Noting* that colossal damage to crops due to floods has become an increasingly recurring phenomenon in some regions, calling for urgent action with respect to control measures.

*Noting* that efficient water conservation and use will be essential for increasing agricultural production in semi-arid and arid areas, as well as for desert creep control.

*Considering* that the principal obstacles to fully exploiting the potential water resources and adopting effective drainage and flood control measures are shortage of financial resources, equipment and trained manpower, to ensure regional cooperation and to evolve ecologically sound policies.

1. *Recommends* urgent action to be taken by governments and international agencies such as FAO and WMO to implement the following:

a. Undertake, wherever needed, exhaustive climatic, hydrological and irrigation potential, hydro-power potentials and desert creep surveys.

b. Rapid expansion of irrigation capacities in areas where surface water and/or groundwater reserves are available for rational exploitation, so as to facilitate both the improvement of productivity and intensity of cropping.

c. Development of techniques for the safe utilization of brackish water for food production in areas where sweet surface/groundwater is not available.

d. Reclamation of areas affected by waterlogging, salinity and alkalinity and prevention of salinization or irrigated areas.

e. Identification of groundwater resources, exploration of the economic feasibility of using non-conventional sources of water and research and development efforts in the most economical use of water with such techniques as drip and sprinkler irrigation in arid areas where shortage of water, rather than land, is the limiting factor in crop production.

f. Sound exploitation of groundwater resources, water harvesting and conservation in the soil profile and in runoff farm ponds together with techniques for the efficient use of the water thus made available in semi-arid and in drought-prone areas.

g. Flood protection and flood control measures, including watershed management and soil conservation to mitigate the damage to crops in high rainfall and flood-prone areas; to render where feasible, the flood-free period into a major cropping season through development of lift irrigation and groundwater exploitation.

h. Establishment of suitable drainage systems and appropriate steps to control salinity in swampy areas as well as in areas exposed to tidal inundation.

i. Taking all necessary measures and developing techniques to combat desert creep.

2. *Calls on* international institutions and bilateral and multilateral aid agencies to provide substantially increased external assistance to enable the developing countries to undertake rapidly action set out under paragraph 1.

3. *Urges* governments and international agencies to assess and make appropriate arrangements for meeting the energy requirements for irrigation and to encourage intensive research on using solar, hydroelectric power, geothermal and wind energy in agricultural operation.

4. *Urges* governments and international agencies to strengthen and where necessary to initiate national, regional research and training in all aspects of water technology related to specific farming systems and to improve the administration and management of water delivery systems. ••

Figure 1. Technical Resolution VII, World Food Conference, Rome, Italy. 1975.

In addition to reduced water requirements, trickle irrigation has other desirable characteristics. Irrigation labor requirements are reduced since trickle irrigation lends itself to complete automation. Pest, weed and disease problems are also often reduced by more desirable water placement. Precise control of moisture and aeration conditions in the root zone, necessary for high quality crop yields, can be maintained. Trickle irrigation systems can be used as a vehicle for the application of soluble fertilizers and possibly pesticides and carbon dioxide. The ability to apply small amounts of water continually with trickle systems increases the practicality of using low-yielding wells as an irrigation water supply. Also in areas where salinity of the irrigation water is a hazard, trickle irrigation has distinct advantages because of the lesser amount of salt applied and the maintenance of high water content levels in the soil root zone.

The gap between supply and demand of water for agricultural and municipal uses is rapidly closing at a time when world food requirements are increasing at an alarming rate. To meet the demand for agricultural products, new lands must be brought into production or higher yields must be realized from existing lands. In either case, more efficient use of water is prerequisite. It is believed that very significantly increased water use efficiencies can be realized using the aforementioned approach. Thus, the results of this research could provide far-reaching state, national and international benefits.

## CHAPTER 2

### REVIEW OF RELATED RESEARCH

Research on trickle and subsurface methods of application of irrigation water dates back to 1866 when research on subsurface irrigation was conducted in Germany (Rutenberg, 1971). This research was named the "Loebner Experiment 1866." The aim of the research was to combine drainage with subsurface irrigation while maintaining good aeration of the soil. The results of the experiments showed that even in soil of inferior structure, crop yields were double the normal.

Research on trickle and subsurface irrigation through pipes was very sparse, however, between 1866 and 1960. Rutenberg (1971) in a comprehensive literature survey lists only ten experiments which were conducted during that period of nearly a century.

This pattern has changed significantly in the last 15 years. Research on trickle and subsurface irrigation through pipes with emitters has been performed in primarily three locations, Australia and New Zealand, Israel and the United States. A bibliography prepared by the Trickle and Subsurface Irrigation Committee of the American Society of Agricultural Engineers (1971) contains over 50 references to work on trickle and subsurface irrigation in the United States. Goldberg and Gornat (1971) list 29 references on research papers from Israel. Similar emphasis has been placed on trickle and subsurface irrigation in Australia and New Zealand (Halsall, 1970).

Many companies are also manufacturing trickle and subsurface irrigation systems and emitters. A list developed by the Trickle and Subsurface

Irrigation Committee of the American Society of Agricultural Engineers (1971) indicates that there are over 20 manufacturers of trickle and subsurface emitters in the United States alone. At the present, there are over 65 manufacturers in the world manufacturing drip and subsurface equipment (Millingen, 1973).

In November 1970 a National Irrigation Symposium was held at Lincoln, Nebraska, in which seven papers were presented on trickle and subsurface irrigation. An Experts Panel Meeting on Irrigation held in September 1971 in Herzilya, Israel, had 28 papers on trickle and subsurface irrigation with participating representatives from Israel, United States and Australia. Cole (1971) surveyed trickle and subsurface irrigation research literature for the problems and potentials of these methods. He cited 58 research papers dealing with trickle and subsurface irrigation.

In July 1974 the Second International Drip Irrigation Congress was held in San Diego, California, in which 96 papers were presented on all aspects of trickle irrigation. Results obtained in this project concerning trickle irrigation systems design were presented at this Congress by Howell and Hiler (1974).

A world-wide drip irrigation survey showed that in the United States there were approximately 72,000 acres in trickle irrigation in 1974 with an estimated 217,000 acres within the next five years. It also showed that Australia, Canada, a group of Central American countries, Cyprus, Israel, Mexico, New Zealand and South Africa had approximately 71,000 acres in trickle irrigation in 1974 with an estimated 83,000 acres in the next five years (Gustafson, et al, 1974).

A comprehensive review of the present state-of-the-art concerning trickle and subsurface irrigation based on progress during the past 15 years can be summarized as follows:

1. It has been well established that significant increases in water use efficiency can be achieved with trickle and subsurface irrigation.
2. Trickle and subsurface irrigation have several other significant advantages over other conventional methods. These include labor-savings, increased yields, decreased water usage through reduced water losses to evaporation and deep seepage, decreased tillage, increased fertilizer efficiency, reduced disease, reduced salinity hazard, higher quality products and the possibility of irrigation from low yielding wells.
3. Significant advances have been made in the development of machinery for manufacturing and installing trickle and subsurface irrigation systems.
4. Vast improvements have been made in the development of emitters and porous tubing for use in trickle and subsurface irrigation.
5. The trend in use is toward trickle (surface droplet application) over subsurface irrigation. There are several reasons for this trend as follows (Rutenberg, 1971): (a) blockages of emitters resulting from poor filtration of the water, root penetration, and



deposits are difficult to locate and their replacement often damages the crop when using subirrigation; (b) placement of the subirrigation system in the soil increases initial investment and maintenance; (c) the subirrigation system cannot be used as a mobile system; and (d) salinity is a greater hazard with subirrigation because the salinization horizon is formed in the root zone itself.

## CHAPTER 3

## SUMMARY OF RESEARCH RESULTS\*

Without adequate knowledge of crop response and crop water requirements expressed in quantitative terms the design of trickle irrigation systems will remain vague. Therefore, a sound trickle irrigation system design procedure must be based on the peak consumptive use rate of the crop for which the system is to be designed. The peak consumptive use rate of crops depends on the type of crop and the environment in which it is grown. Environmental factors include climatic and soil factors. Thus, crop water requirements and response data for different crops and different environmental conditions are greatly needed to enable the engineer to design trickle irrigation systems at minimum cost and for optimum water use. This need has made the first objective of this research project the determination of optimum timing and necessary application amounts for selected crops when using trickle irrigation. Once it is determined "when" and "how much" water to apply to a particular crop using trickle irrigation, then the designer can proceed to use these crop inputs to design trickle irrigation systems at a minimum cost that will optimize the use of water for the crop and the environmental conditions under consideration. Hence, the second objective of this investigation was to develop a general method for the hydraulic design of trickle irrigation systems using inputs obtained from the first objective for optimizing the system.

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\*Since nearly all of the results of research on this project have been published, only a summary is given here; reprints of the principal resulting publications are given in the Appendix.

To achieve the first objective, three research experiments were conducted at the research lysimeters of the Department of Agricultural Engineering at Texas A&M University for which grain sorghum was selected as the experimental crop. The first two experiments were designed to study the response of grain sorghum to trickle and subsurface irrigation. A comparison of water use efficiencies under well-watered conditions using both intensified and conventional water application methods and the evaluation of water use efficiencies with trickle irrigation applications designed to limit the availability of water were the specific objectives. The results indicated higher water use efficiencies and better crop response when the trickle method of application was used. Also, the results showed that higher water use efficiencies can be obtained by applying sparing amounts. The results obtained in these two experiments were reported in a paper published in the *Transactions of the American Society of Agricultural Engineers* (Hiler and Howell, 1973). A copy of the paper is included as Appendix A of this report in which a detailed discussion of the research methodology and the results obtained can be found.

An additional investigation carried out under a different research project of the Texas Water Resources Institute was designed to develop a computer model to simulate grain sorghum yield and water use under high frequency irrigation. The simulation methods used in this study can be used to simulate a complete irrigation experiment greatly reducing research costs and allowing the determination of water requirements for many crops under many different soil and climatic conditions. The results obtained

in this investigation (TWRI Project No. A-024-TEX) were published as Technical Report No. 62 of the Texas Water Resources Institute in December 1974 (Hiler and Howell, 1974). They also presented two papers on this work at 1974 National Meetings of the American Society of Agricultural Engineers (Howell and Hiler, 1974b, 1974c). An abstract of this study is included as Appendix B of this report.

The objective of the third research experiment conducted in 1974 was to determine if different irrigation frequencies would influence the growth and water use efficiency of grain sorghum when irrigated at optimum levels. Results indicated that frequency of application had no significant effect on the water use efficiency of grain sorghum. A paper reporting the results obtained in the experiment will be presented at the 1975 Winter Meeting of the American Society of Agricultural Engineers (Ravelo, Hiler and Howell, 1975). The research proposal and the preliminary results obtained are included as Appendix C of this report.

To attain the second goal of this investigation, two trickle irrigation lateral design methods were developed. With the first method the pressure loss and emitter flow ratio for trickle irrigation laterals can be determined. The design method is based upon known principles of fluid mechanics. A computer program was written to determine the lateral pressure loss and emitter flow ratio at a given design length as function of pipe size, tree spacing, number of emitters per tree, emitter spacing, downstream lateral pressure and lateral slope. For a given set of design inputs, the program can be used to determine if the given pipe size will be adequate to limit the pressure loss and flow

variation along the lateral to limits acceptable for the design lateral length. In the second method design equations are utilized to calculate the maximum lateral length for a given value of the uniformity of application coefficient. The solution depends upon the emitter flow function, elevation change, pipe size, reduction coefficient for dividing flow, pipe roughness coefficient, the average emitter flow rate, and either the average emitter spacing or the number of emitters per lateral. For a given uniformity the solution is a linear log-log line with a slope that depends only on the flow rate exponent in the pipe friction loss equation. Dimensionless graphs were developed that can be used to design the trickle irrigation laterals.

Two papers were published that cover both design methods in detail. The first method was reported in the *Transactions of the American Society of Agricultural Engineers* (Howell and Hiler, 1974d). The second method was published in the *Journal of the Irrigation and Drainage Division of the American Society of Civil Engineers* (Howell and Hiler, 1974e). Copies of the papers are included as Appendix D and Appendix E, respectively. Computer listings and program documentation are also included for reference and use as Appendix F.

## CHAPTER 4

### SUMMARY AND CONCLUSIONS

The goal of this investigation was the development of required crop inputs for selected crops to optimize the design of trickle irrigation systems and to obtain an optimum water balance for living plants. Experimental investigations were conducted to study the response and water use of grain sorghum under trickle irrigation. Design methods were developed to provide optimum design for trickle irrigation systems.

The gap between supply and demand of water for agricultural and municipal uses is rapidly closing at a time when world food requirements are increasing at an alarming rate. To meet the demand for agricultural products, new lands must be brought into production or higher yields must be realized from existing lands. In either case, more efficient use of water is prerequisite. Trickle irrigation is an approach to obtain increased water use efficiencies and, therefore, a way to increase crop production with our limited water resources. Therefore, the results of this research could provide far-reaching state, national and international benefits.

Detailed conclusions and inferences drawn from the results obtained in the individual experimental investigations and those drawn from the investigation concerning the development of design methods for optimum trickle irrigation systems can be found in the published papers included in the Appendix of this report.

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20. ----- . 1970. Proceedings of the National Irrigation Symposium. Sponsored by the American Society of Agricultural Engineers in cooperation with six other national professional societies. Lincoln, Nebraska, November 10-13.

One additional project-related publication deserves mention at this point. The work leading to this publication was not directly related to the objectives of this project, but was done in conjunction with work of this project. This publication is:

Seifert, W. J., Jr., E. A. Hiler, and T. A. Howell. 1975.  
Trickle irrigation with water of different salinity levels.  
Transactions of the ASAE 18(1):89-94.

A reprint of this publication is given as Appendix G.



## APPENDIX

- A: Grain Sorghum Response to Trickle and Subsurface Irrigation
- B: ABSTRACT - Optimization of Grain Sorghum Water Use Efficiency Under High Frequency Irrigation by System Simulation and Stochastic Dynamic Programming
- C: Effects of Trickle Irrigation Frequency on Grain Sorghum Growth and Yield - Description of Research and Preliminary Results
- D: Trickle Irrigation Lateral Design
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APPENDIX A

# Grain Sorghum Response to Trickle and Subsurface Irrigation

E. A. Hiler, T. A. Howell

MEMBER ASAE    ASSOC. MEMBER ASAE

THE vast majority of consumptive water use in the Western United States can be attributed to irrigated agriculture. As our water supplies become shorter and more costly, it becomes increasingly important that more efficient water application methods for irrigation be found. Two such methods which offer considerable promise for increased efficiency of water use are trickle (or drip) and subsurface irrigation.

Davis and Nelson (1970) defined subsurface irrigation as "the application of water under the soil surface so that it moves by capillarity into the root zone of the crop." They also stated that "applying water at the surface in a similar manner is called trickle irrigation." Subsurface irrigation should be distinguished from subirrigation, which requires raising the water table to wet the root zone. Subsurface and trickle irrigation are accomplished normally by using either small-diameter tubes with emitters at selected spacings or porous tubes.

Cole (1971) has presented an excellent comprehensive review of present knowledge pertaining to subsurface and trickle irrigation. He lists 58 references in his literature survey of the potentials and problems related to subsurface and trickle irrigation. Potential benefits of these methods include the following, as listed by Cole (1971): (a) water savings, in comparison to other methods; (b) beneficial crop response; (c) labor savings; (d) fertilizer savings and pollution abatement; (e) weed control cost savings; (f) insect control cost savings; and (g) possible use of saline water. Cole (1971) indicated his literature review revealed that quantitative information of general applicability is needed badly on all of these items.

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Knowledge of crop water use with trickle and subsurface irrigation is necessary not only for comparison with conventional methods but also to ascertain functional water requirements for the precise engineering design of these systems. Because intensified interest in subsurface and trickle irrigation has come only within the last decade, very little information from controlled experiments is available on crop water use and efficiencies of water use with these application methods.

Trickle and subsurface irrigation trials have generally shown a 25 to 50 percent reduction in application amount for row crops and even greater savings for citrus groves (Braud et al 1965; Zetzsche and Newman 1966; Davis 1967; Hanson et al 1970; Davis and Nelson 1970; DeRemer 1970; Voth 1970). Regarding crop response, Cole (1971) summarized his remarks by saying that "improvements in yield and quality and a shorter growing season emerge as general benefits associated with subsurface or trickle irrigation." Goldberg and Shmueli (1970) have reported dramatic yield increases with trickle irrigation but they did not give the water use data. All of the studies reviewed by Cole (1971) on water savings and crop response were conducted either on full-scale field plots or in greenhouses.

The purpose of this study was to compare water uses and efficiencies with various irrigation methods. The experiment reported here was conducted in a field lysimeter installation in which complete control of the soil water could be maintained.

Specific objectives were as follows:

(a) to compare water use efficiencies under well-watered conditions using both intensified and conventional water application methods; and (b) to evaluate effects of reduced irrigation amounts on crop yields when using trickle irrigation, i.e. to evaluate water use efficiencies with trickle irrigation applications designed to limit the availability of water.

The term "water use efficiency" has been defined in many ways in the literature. In this paper, it has been evaluated

in terms of both marketable yield per unit of applied water and marketable yield per unit of actual water use.

## DESCRIPTION OF EXPERIMENT

The experiment reported here was conducted in 1971 and 1972 utilizing field lysimeters of the percolative type. Eighteen lysimeters with undisturbed cores of Travis fine sandy loam were utilized in 1971 and nine of the same lysimeters were utilized in 1972. This soil consisted of a layer of fine sandy loam in the A horizon to a depth of 45 cm with an available water holding capacity of 0.12 cm per cm of depth and a red sandy clay soil in the B horizon with an available water holding capacity of 0.22 cm per cm of depth. The lysimeters were 90 cm in diameter and 180 cm in depth.

The experimental arrangement allowed three replications of each treatment. The area outside the lysimeters was used as a buffer area to simulate a field condition. A movable shelter, automatically actuated by rainfall, protected the lysimeters from rain. A detailed description of the installation has been given by Hiler (1969).

Wind speed, dry bulb temperature, dew point temperature and net radiation were measured above the crop canopy. Wind speed was measured by a totalizing 3-cup anemometer at a height of 200 cm above the ground. Dry bulb and wet bulb temperatures were measured at 100, 150 and 200 cm above the ground with aspirated psychrometers. Dew point temperature was measured at 150 cm above the ground with a lithium chloride dew point hygrometer. Net radiation was measured by a miniature net radiometer similar to that described by Fritschen (1965) at a height of 150 cm above the ground. These meteorological measurements were used to estimate the potential evapotranspiration from the crop with the Van Bavel (1966) equation with  $Z_0 = 2$  cm. Class A pan evaporation was measured in a nearby weather station.

The soil water pressure potential was

measured in each treatment at 15- and 30-cm depths with tensiometers. The soil water content in each lysimeter was determined by the neutron method (Van Bavel et al 1963) to a depth of 100 cm in 15-cm increments.

Grain sorghum (RS 671) was planted on April 16, 1971 and harvested on July 16, 1971 and grain sorghum (ORO) was planted on April 14, 1972 and harvested on July 25, 1972. The irrigation treatments were initiated on May 16 and May 1 during the 1971 and 1972 growing seasons, respectively.

Double rows 25 cm apart were planted across the center of each lysimeter.

The treatments used in 1971 were as follows:

- 1 Subsurface Irrigation
- 2 Trickle Irrigation
- 3 Subsurface plus Mist Irrigation
- 4 Trickle plus Mist Irrigation
- 5 Mist Irrigation
- 6 Surface Irrigation

The Subsurface and Trickle treatments were irrigated every third day. The irrigation amount was determined from the tensiometer reading and the soil water retention curve. The irrigation amount was calculated to bring the soil water content back to "field capacity." The subsurface and the trickle irrigation systems were identical except that the subsurface system was buried 20 cm below the soil surface while the trickle system was located at the soil surface. The irrigation lines were located across the centers of the lysimeters between the two rows of plants. The irrigation systems consisted of 1.58 cm (1/2 in. nominal) I.D. black polyethylene pipe with two Submatic\* insert orifices per lysimeter located 45 cm apart. The orifices were similar to those described by Whitney and Lo (1969), being 0.56 mm (0.022 in.) I.D. The system was operated at 0.09 bar (one psi) at the emitter and discharged approximately 50 cu cm per min (0.79 gph) per orifice. The system was purged with approximately one bar of pressure weekly to prevent orifice plugging. The irrigation water was municipal tap water which was filtered by a cartridge filter; the pressure was reduced by regulating valves. A timer was set to operate a solenoid valve on the irrigation system for each treatment to apply the calculated irrigation amount.

The mist irrigation systems were

\*Trade names are included for the benefit of the reader and do not infer any endorsement or preferential treatment of the product listed by the authors or the Texas Agricultural Experiment Station.

identical to those described by Howell et al (1971). All the mist treatments were mist irrigated when a 2 C average leaf temperature differential existed between the treatment and a control border area which was continually misted between 11 a.m. and 5 p.m. CDT. The mist irrigation systems used with the Subsurface plus Mist and Trickle plus Mist treatments operated on 5 min on and 10 min off-cycles. These systems were designed to reduce environmental evaporative demand only and did not add appreciably to the soil water supply. The Mist treatment was designed to "over mist" slightly so that the soil water pressure potential would be maintained between 0 and -0.7 bar. Infrared radiometers were utilized to determine leaf temperature differences.

The Surface treatment was irrigated when the soil water pressure potential in the root zone reached -0.7 bar. The irrigation amount was determined as 1.1 times the soil water depletion as measured with the neutron method in conjunction with surface soil sampling in the upper 10 cm.

The treatments used in 1972 were as follows:

- 1 Trickle (1.1)
- 2 Trickle (0.7)
- 3 Trickle (0.4)

Each treatment was irrigated three times a week (Monday, Wednesday and Friday). The irrigation amount for the Trickle (1.1) treatment was determined as 1.1 times the water depletion in that treatment as measured by the neutron method. The irrigation amount for the Trickle (0.7) treatment was 0.7 times the measured water depletion in the Trickle (1.1) treatment while that for the Trickle (0.4) treatment was 0.4 times the depletion in the Trickle (1.1) treatment. The irrigation systems used in 1972 consisted of 1.58 cm (1/2 in. nominal) I.D. black polyethylene pipe with two Triklon emitters per lysimeter. This emitter is a coiled microtube approximately 2.44 m in length with a 0.89 mm I.D. (0.035 in.) which discharged approximately 12.9 cu cm per min (0.20 gph) at 0.69 bar (10 psi). The irrigation water was tap water which was filtered by a cartridge filter; the pressure was reduced by regulating valves. A timer was set to operate a solenoid valve on the irrigation system for each treatment to apply the calculated irrigation amount. The system application rate per lysimeter was 0.24 cm per hr compared to the 1971 system application rate of 0.94 cm per hr. Reduced application rate was the reason for using

the Triklon emitters in 1972.

Crop height and leaf area index were used to describe the growth of the crop. Crop height was measured twice weekly in each lysimeter. Leaf area index was determined from weekly measurements of the leaf length and width of all the leaves on four plants in each lysimeter. From leaf samples taken throughout the season, leaf length times leaf width was statistically correlated to leaf area with a least-squares linear regression analysis.

Leaf temperature was measured daily with an infrared radiometer in both 1971 and 1972. Measurements of leaf temperature were taken on two well exposed leaves in each lysimeter at 1 p.m. CDT in 1972, leaf water potential was measured three times a week at 1 p.m. CDT using the pressure chamber method as described by Scholander et al (1965). Since this method is a destructive sampling technique, only one measurement per treatment was taken at any one time. Measurements were made only on the upper exposed leaves in the canopy (second to fifth leaf from top).

Total water use for all treatments in 1971 and 1972 was determined by the water balance method. Drainage was calculated from the amount of water pumped from the lysimeters at the bottom. Lysimeters were pumped on a weekly basis. Storage losses were determined from the change in water content profile between planting and harvesting. Irrigation amount was the total of all water added to the lysimeters between planting and harvest. The total water use was equal to irrigation amount plus storage losses minus drainage amount.

Grain yield was determined for each lysimeter by harvesting and threshing all heads in the lysimeter. The moisture content of the grain was determined and all yields were adjusted to 14-percent moisture content (wet basis). Test weights of the grain samples were also determined.

## RESULTS AND DISCUSSION

The 1971 grain sorghum yield and water use efficiency results are shown in Table 1. Analyses of variance were performed on the yields and both sets of water use efficiencies; in all cases, variance between treatments was significant at the one percent level and variance among replications was "not significant." Test weights of the grain were above 56 pounds per bushel for all treatments, but there were no significant differences between treatments.

Two points emerge from Table 1

TABLE 1. 1971 YIELD, WATER USE AND WATER USE EFFICIENCY RESULTS

Treatment	Yield, Y kg per ha	Irriga- tion, I, cm	Drainage, cm	Storage loss, cm	Total water use, TWU, cm	Water use efficiency, percent	
						Y/TWU	Y/I
Subsurface + mist	7,567 bc*	36.77	2.11	6.30	40.96	0.185 cd	0.206 b
Trickle + mist	9,110 a	38.07	0.42	6.37	44.02	0.207 c	0.239 b
Subsurface	8,391 ab	38.15	1.65	5.85	42.35	0.198 cd	0.220 b
Trickle	8,461 ab	29.23	0.64	6.28	34.87	0.243 a	0.289 a
Mist	7,781 bc	25.40	0.54	8.38	33.24	0.234 b	0.306 a
Surface	6,738 c	31.80	1.26	8.76	39.30	0.171 d	0.212 b

\* Letters signify 0.05 level of significance by Duncan's Test; means followed by same letter are not significantly different at the 0.05 level.

which warrant specific attention. First, the water use efficiencies for the Trickle and Mist treatments were the highest, regardless of the basis of calculation. The water use efficiency based on total water use was 42 percent greater for the Trickle treatment than for the Surface treatment. Second, when comparing the Trickle and Trickle plus Mist treatments, it is seen that the additional mist (applied to reduce evaporative demand and hence crop water deficit) resulted in a slightly increased yield; however, the water use efficiency was significantly reduced as a result of the added mist application.

Two values in Table 1 are suspect. They are the irrigation amount for the Subsurface treatment and the yield for the Subsurface plus Mist treatment. Even though the subsurface lines were purged weekly to prevent orifice plugging, it would appear that some plugging must have occurred in the Subsurface treatment when one compares the irrigation amount values for this treatment with those of the Subsurface plus Mist, Trickle, and Trickle plus Mist treatments. Thus it is believed that the actual amount of water applied in the Subsurface treatment was less than 38.15 cm; if this is true, the water use efficiencies would be higher for this treatment. No explanation is apparent for the relatively low yield in the Subsurface plus Mist treatment. A higher yield would be expected for this treatment than for the Subsurface treatment because of the reduced crop water deficit due to misting.

TABLE 2. MAXIMUM CROP HEIGHT AND LEAF AREA INDEX VALUES FOR THE 1971 GRAIN SORGHUM CROP

Treatment	Crop height, cm	Leaf area index
Subsurface plus Mist	126	3.9
Trickle plus Mist	121	3.7
Subsurface	128	3.8
Trickle	130	3.8
Mist	120	4.0
Surface	113	3.1

Both of these suspect values affect treatments involving subsurface irrigation; hence we are reluctant to draw specific conclusions concerning relative water use efficiencies using subsurface irrigation from the 1971 results.

Table 2 shows maximum grain sorghum height and leaf area index values for the 1971 season. It can be seen that all of the high-frequency water application treatments had larger plants both in terms of height and leaf area than did the Surface treatment. This increased crop size can be attributed to the more frequent water applications which likely reduced crop water deficits.

In 1972, intensive study was directed toward the trickle irrigation method for several reasons. Foremost was the fact that the Trickle and Mist treatments gave the highest efficiencies of water use in 1971 coupled with the fact that mist irrigation was the subject of previous intensive study by the authors (Howell et al 1971). Also, trickle irrigation is being adopted at a much faster rate than subsurface irrigation by irrigators in Australia, Israel, United States and other countries because of continuing problems with orifice plugging when using subsurface irrigation.

The 1972 grain sorghum yield and water use efficiency results are shown in Table 3. Analyses of variance on the yields and both sets of water use efficiencies indicated variance between yield treatments was significant at the five percent level while variance between water use efficiencies for the given treatments was significant at the one percent level. Variance among replica-

tions was "not significant" in all cases. As in 1971, test weights were above 56 lb per bu for all treatments with no significant differences between treatments.

The 1972 results shown in Table 3 illustrate that very significant increases in water use efficiency can be realized by applying sparing irrigation amounts on a frequent basis with the trickle method. The water use efficiency based on total water use was 50 percent greater for the Trickle (0.4) treatment than for the Trickle (1.1) treatment. The water use efficiency based on total water use is most representative of the increases to be expected because water use from storage in the soil profile was greater with the more sparing treatments. Yield per hectare is reduced, however, with the more sparing treatments.

Fig. 1 shows the leaf area index values for the three trickle treatments in 1972. Differences in leaf area are readily apparent between the three treatments during the last half of the growing season. The crop heights for the three treatments were nearly identical throughout the season reaching a maximum of approximately 115 cm.

The variation of soil water content at the 30-cm depth in the center lysimeter of each treatment is shown in Fig. 2. The soil water content at 30-cm was maintained near field capacity in the Trickle (1.1) treatment throughout the season. On the other hand, the Trickle (0.4) treatment had less than 50 percent available soil water at the 30-cm depth during the entire last half of the season.

Fig. 3 shows weekly averages of the daily water use rates from the three trickle treatments. These values were obtained from integrated differences in soil water contents throughout the soil profile. Considerable differences are evident between the three treatments. Weekly averages of daily potential evapotranspiration and pan evaporation rates are shown in Fig. 4. A comparison of Figs. 1, 3 and 4 shows that water use rates from the Trickle (1.1) treatment exceeded the potential rates after the peak leaf area was reached. The use rate from the Trickle (0.4) treatment was

TABLE 3. 1972 YIELD, WATER USE AND WATER USE EFFICIENCY RESULTS

Treatment	Yield, Y kg per ha	Irriga- tion, I, cm	Drainage, cm	Storage loss, cm	Total water use, TWU, cm	Water use efficiency, percent	
						Y/TWU	Y/I
Trickle (1.1)	9,209 a*	46.58	2.80	3.76	47.54 a	0.194 c	0.198 c
Trickle (0.7)	7,837 ab	28.24	3.53	7.09	31.80 b	0.246 b	0.278 b
Trickle (0.4)	6,743 b	16.93	3.18	9.35	23.10 c	0.292 a	0.398 a

\* Letters signify 0.05 level of significance by Duncan's Test; means followed by the same letter are not significantly different at the 0.05 level.

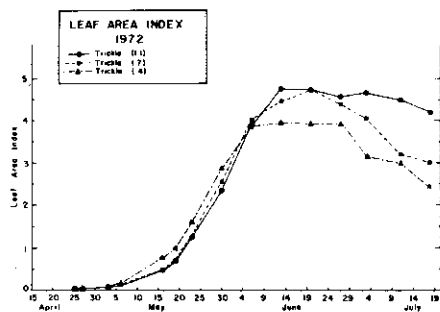


FIG. 1 Leaf area index values for the 1972 growing season.

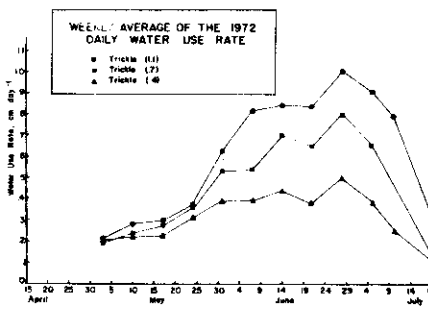


FIG. 3 Weekly average of the 1972 daily water use rate for grain sorghum grown at College Station, Texas.

considerably less than the potential rate throughout the entire growing season.

Irrigation application amounts of 0.6 to 0.7 times pan evaporation times percent cover are being recommended and used presently in Israel for citrus (Goldberg 1972); these values are also being used in the United States (Krupp 1972). Comparing again Figs. 1, 3 and 4 indicates that using this recommendation for grain sorghum (a row crop) would result in applications approximately equal to the Trickle (0.4) use rate after peak leaf area (full cover) is reached. Thus, based on our results, one could expect a high water use efficiency with grain sorghum using the "0.6-0.7 times pan evaporation" criterion; this criterion would not be good, however, if highest yields were desired.

Values of leaf water potential measured throughout the 1972 growing season at approximately solar noon for the three treatments are shown in Fig. 5. Considerable differences between the Trickle (1.1) and the Trickle (0.4) treatments are evident, particularly during the latter half of the season when differences in soil water contents, and hence soil water potentials, were greatest. Measurements were also made of leaf temperatures throughout the 1972 season; differences between the treatments oc-

curred at times but no definite trends were evident. Thus, if a plant indicator were to be used in timing trickle irrigations, our results indicate that leaf water potential would be a more sensitive indicator than leaf temperature.

#### SUMMARY AND CONCLUSIONS

Two irrigation methods which offer considerable promise for increased efficiency of water use are trickle and subsurface irrigation. The purposes of this paper were to compare water use efficiencies in a controlled-water experiment using both intensified and conventional irrigation methods and to evaluate effects of reduced irrigation amounts on crop yields when using trickle irrigation.

Grain sorghum was grown during 1971 and 1972 in a field lysimeter installation in which control of the soil water could be maintained. Undisturbed soil cores approximately one meter in diameter and two meters deep made up the lysimeters. Rainfall was kept off the lysimeters with an automated shelter system. Details of the lysimeter installation have been discussed previously.

Irrigation treatments during 1971 included Subsurface, Trickle, Subsurface plus Mist, Trickle plus Mist, Mist, and

Surface. All treatments involving subsurface and trickle irrigation were irrigated every third day in an amount calculated to bring the soil water content to "field capacity." The Mist treatment was "overmisted" slightly so that the soil water potential would be maintained between 0 and -0.7 bar. The Surface treatment was irrigated when the soil water potential in the root zone reached -0.7 bar in the amount of 1.1 times measured depletion.

Irrigation treatments during 1972 included Trickle (1.1), Trickle (0.7), and Trickle (0.4). All treatments were irrigated thrice weekly during the growing season. The irrigation amount for the Trickle (1.1) treatment was 1.1 times measured water depletion in that treatment. For the Trickle (0.7) treatment, the amount was 0.7 times depletion in the Trickle 1.1 treatment; the Trickle (0.4) irrigation amount was 0.4 times depletion in the Trickle (1.1) treatment.

Water measurements were made to determine irrigation amount, storage depletion, and drainage amount; hence total crop water use could be determined. Crop response measurements included quantity of marketable grain sorghum yield, test weight of grain, crop height, leaf area index, leaf water potential, and leaf temperature. Meteorological mea-

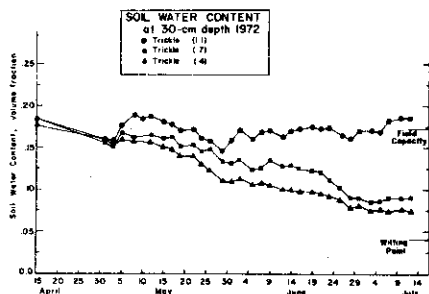


FIG. 2 Soil water content at 30-cm depth in the center lysimeter of each treatment during the 1972 growing season.

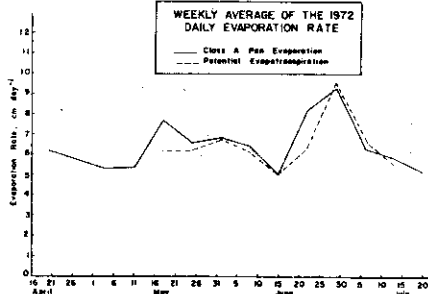


FIG. 4 Weekly average of the 1972 daily Class A pan evaporation and potential evapotranspiration for College Station, Texas.

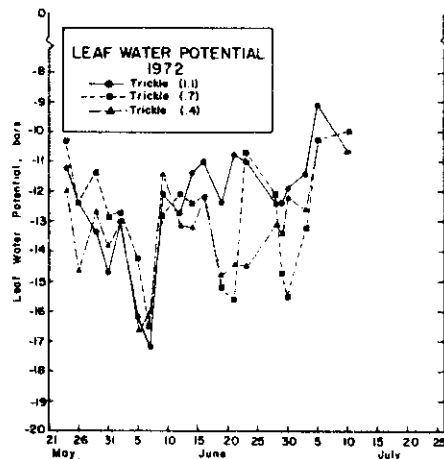


FIG. 5 Leaf water potential values for the 1972 growing season, measured at 1:00 p.m. CDT.

surements included those necessary to calculate potential evapotranspiration by the combination method, and pan evaporation.

As a result of this study, the following conclusions are indicated:

1 The Trickle and Mist treatments in 1971 resulted in the highest water use efficiencies; the increase in water use efficiency based on total water use was 42 percent for the Trickle treatment compared to the Surface treatment;

2 Grain sorghum growth as indicated by crop height and leaf area index was greater for all of the 1971 intensified treatments than for the Surface treatment; and

3 Comparison of the three levels of

trickle irrigation amounts in 1972 indicated that significant increases in water use efficiency can be realized by applying sparing amounts; the Trickle (0.4) treatment had a water use efficiency based on total water use which was 50 percent greater than that for the Trickle (1.1) treatment. Yield per hectare was reduced slightly with the more sparing treatments.

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**APPENDIX B**



## ABSTRACT

Optimization of Grain Sorghum Water Use Efficiency Under High  
Frequency Irrigation by System Simulation and Stochastic  
Dynamic Programming

Water deficits reduce plant growth and, subsequently, crop yields. Man has relied upon irrigation to overcome these crop water deficiencies. But since the present supplies of water are limited, more efficient irrigation application methods must be developed and utilized effectively. High frequency irrigation has been shown to be an efficient means for minimizing crop water deficits while maximizing irrigation application efficiency. This research evaluated the effects of high frequency irrigation on grain sorghum growth and yield and developed guidelines for the optimal utilization of a scarce resource -- water -- under high frequency irrigation.

An experiment was conducted in fully instrumented field lysimeters which had undisturbed soil cores. Rainfall was eliminated as a variable by an automated movable shelter which protected the lysimeters from rain. The field measurements that were made in each lysimeter were soil water content, leaf temperature, leaf resistance, leaf water potential, leaf area index, and crop height. Measurements of wind speed, air temperature, dew-point temperature, and net radiation were made above the crop.

The yield and water use efficiency of grain sorghum under high frequency irrigation was decreased primarily by water deficits occurring

during the boot-to-bloom growth period. Water use efficiency was increased when water deficits were carefully managed by applying small, frequent applications of water and avoiding large deficits during the boot-to-bloom period.

Yield models of the multiplicative- and additive-type were compared to the yield data. Only small differences between the models resulted, which were due primarily to the small set of data used to develop and test the models. However, within the range of the data, each model was an acceptable representation of the actual results of independent experiments.

An environmental model which used Monte Carlo methods to simulate temperature, rainfall, and potential evaporation was developed for Temple, Texas. This model was coupled to the Blackland soil water balance model to simulate the water use of grain sorghum under high frequency irrigation.

Stochastic dynamic programming was used to maximize the expected yield per unit of available irrigation water. The results indicated that irrigation requirements could be reduced by almost one-half without appreciable loss in yield if the irrigation water was supplied optimally throughout the season. Also, pre-irrigation (irrigation at or prior to germination) was preferred to using a like-amount of water, supplied optimally later in the season, if the soil water content was less than 150 mm.

This research demonstrated the potential of high frequency irrigation to improve water use efficiency. The application of

operations research techniques greatly improved the understanding of the interactions of a large number of components and enhanced the decision selection under uncertain outcomes.

APPENDIX C

TITLE:

Effects of Trickle Irrigation Frequency on Grain Sorghum Growth and Yield

OBJECTIVES:

The objective of this research is to determine if irrigation frequencies of 3, 2, and 1 irrigations per week will influence the growth and final yield of grain sorghum when irrigated at optimum levels.

LOCATION:

Agricultural Engineering Research Lysimeters, College Station, Texas.

TREATMENTS:

1. (W4) \* - Irrigated three times a week (Monday, Wednesday, Friday) in the amount of 1.1 times the measured evaporation losses as determined by the lysimeter water balance.
2. (W3) - Irrigated two times a week (Monday and Thursday).
3. (W2) - Irrigated only once a week (Monday).

Irrigation quantity in treatments 2 and 3 will be the same as in treatment 1 for each weekly period.

MEASUREMENTS:

1. Soil Water Balance: The lysimeters are protected from rainfall by the shelters and the runoff from the plot is routed around the lysimeter area to prevent runoff from entering the lysimeters; thus, both rainfall and runoff are eliminated from the water-balance equation. The primary purpose of the lysimeter is to define the geometry of the system such that both the drainage and evaporation components can be determined. The drainage is determined by the water extracted from the bottom of the lysimeter by vacuum pumping. The lysimeters evaporation can then be determined by the change in soil water

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\*Indicates lysimeter location with E or W referring to East or West lysimeter shelter and 1, 2, 3, and 4 referring to lysimeter row with 1 being the northern most lysimeter row and 4 being the southern most lysimeter row.

content over a specified time period. The lysimeters are vacuum pumped at weekly intervals and the electrical conductivity of the effluent is determined for each lysimeter to monitor any salinity change in the lysimeters. The soil water content in each lysimeter is determined to a depth of 1.3 meters in intervals of 15 centimeters three times a week (Monday, Wednesday, Friday and Thursday in Treatment 2 only). A neutron soil moisture meter is utilized to make this measurement.

2. Soil Water Potential: The soil water potential in each lysimeter will be determined with gage type tensiometers located at depths of 15 and 30 cm. The center lysimeter of each Treatment will have additional tensiometers at 60 and 90 cm and soil psychrometers at depths of 10 and 20 cm. The tensiometers are read daily and the psychrometers will be read weekly in each Treatment.
3. Plant Growth: Both plant height and leaf area index will be measured in each lysimeter. Each plant will be measured in height each Tuesday and Friday. The leaf length and width of each leaf on four of the plants in each lysimeter will be measured each Tuesday. Also, leaf samples will be taken from plants in the outside areas to determine a relationship between the product of leaf length and width to leaf area. Finally, yield measurements will be determined for each lysimeter by harvesting all the heads and plants in the lysimeter.
4. Plant Water Deficit: The plant water deficit or leaf water potential as measured by the "Pressure bomb" will be used to compare the plant water status of each Treatment. Afternoon (Approximately 1300 to 1400) readings will be taken in Treatments on Monday, Wednesday and Friday. Leaf temperature will be measured in each Treatment daily at 1300. The Barnes PRT-10 infrared radiometer will be used to make these measurements.
5. Meteorological: Solar radiation, reflected solar radiation, net radiation, dry bulb temperature, dew point temperature, and wind speed are measured over the crop canopy at the lysimeter site. All net radiation measurements are made at approximately 1.5 meters above the ground with cup anemometers. Dry bulb temperatures are determined at 1 and 2 meters above the ground by aspirated thermocouple sensors, and dew point temperatures are measured at 1 and 2 meters with dew-probes. The above data is recorded every 30 minutes by an automatic data acquisition system and the data are punched on paper tape for computer processing. Also, adjacent to the site a Class A weather station is maintained in which rainfall, solar radiation, maximum and minimum air temperature, relative humidity, 2 meter wind speed, and pan evaporation are recorded daily.

## 1974 GRAIN YIELD DATA

lysimeter	uncorrected grain weight g/lys.	Moisture Content (wet basis) percent	corrected <sup>1</sup> grain weight kg ha <sup>-1</sup>	Mean Weight kg ha <sup>-1</sup>
E1E	481.4	17.2	7286.0	
E1C	532.2	18.0	7977.0	7667.0 b*
E1W	502.8	15.8	7738.0	
E2E	706.7	15.8	10876.0	
E2C	722.6	14.8	11253.0	10982.0 a
E2W	674.6	14.7	10818.0	
E3E	719.4	15.3	11137.0	
E3C	704.7	14.9	10961.0	11015.0 a
E3W	715.7	16.3	10949.0	
E4E	487.6	15.8	7504.0	
E4C	520.5	15.5	8039.0	8120.0 b
E4W	566.8	14.9	8816.0	
W2E	715.5	15.1	11103.0	
W2C	688.0	14.6	10739.0	10655.0 a
W2W	650.9	14.9	10124.0	
W3E	726.5	14.4	11367.0	
W3C	706.7	14.9	10992.0	11057.0 a
W3W	660.0	14.5	10814.0	
W4E	724.6	14.6	11311.0	
W4C	757.9	15.4	11719.0	11348.0 a
W4W	645.3	15.1	11014.0	

<sup>1</sup>Corrected to 14 percent moisture content wet basis.

\*Letters signify 0.05 level of significance by Duncan's Test.

1974 Dry Matter and Grain Yield Component Data

Lysimeter	Number of Heads	Number of Plants	Total Dry Matter		Head Weight	Average	Weight per 1000 Seeds	Average	Test Weight	Average
			kg <sup>-1</sup>	kg <sup>-1</sup>						
E1E	18	18	16,799		38.98		34.02		0.734	
E1C	19	19	18,042	17,862b*	40.57	38.67b	31.68	31.67a	0.698	0.723a
E1W	20	20	18,745		36.47		29.30		0.738	
E2E	21	20	22,118		46.43		25.52		0.698	
E2C	21	20	23,126	22,378a	48.72	46.62a	27.42	26.32b	0.702	0.689ab
E2W	21	20	21,890		44.70		26.01		0.668	
E3E	21	20	23,283		47.53		25.47		0.681	
E3C	22	20	22,937	23,454a	45.19	46.48a	25.04	25.98b	0.668	0.684b
E3W	22	20	24,143		46.72		27.43		0.702	
E4E	20	20	16,805		34.91		31.31		0.708	
E4C	22	20	18,047	18,106b	36.11	36.66b	26.99	28.18ab	0.699	0.712ab
E4W	22	19	19,465		38.96		26.25		0.729	
W2E	20	20	25,080		50.67		26.35		0.727	
W2C	21	20	24,231	23,995a	48.31	49.23a	24.35	26.17a	0.736	0.726a
W2W	19	18	22,673		48.71		27.82		0.716	
W3E	20	20	23,978		50.02		24.63		0.722	
W3C	20	20	25,237	23,932a	51.42	49.79a	25.02	26.05a	0.694	0.708ab
W3W	19	20	22,580		47.92		28.50		0.708	
W4E	20	20	25,284		50.03		26.87		0.664	
W4C	21	20	26,570	25,825a	51.97	50.68a	27.38	27.73a	0.698	0.686b
W4W	20	20	25,622		50.05		28.92		0.695	

\*Letters signify significant differences at 0.05 level by Duncan's Test.



1974 Yield, Water Use and Water Use Efficiency

Results  
Trickle Irrigation Experiment

TREATMENT	Yield, y Kg ha <sup>-1</sup>	Irrigation, I cm	Drainage cm	Storage Loss cm	Rainfall cm	Total Water Use, TWU cm	Water Use Efficiency y/TWU, %
Trickle (W2) (once weekly)	10,655 a**	53.36	2.52	2.40	2.08*	55.32 a	0.193 a
Trickle (W3) (twice weekly)	11,057 a	54.06	1.77	2.68	2.08	57.05 a	0.194 a
Trickle (W4) (thrice weekly)	11,348 a	54.64	2.11	4.57	2.08	59.18 a	0.192 a

\*That amount felt on treatments due to shelter failure (7/15/74).

\*\*Letters signify .05 level of significance by Duncan's Test; means followed by same letter are not significantly different at the 0.05 level.

APPENDIX D

# Trickle Irrigation Lateral Design

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**T**RICKLE irrigation is the daily or frequent slow application of water at the soil surface to replenish water and/or nutrients which have been utilized by plants. This type of irrigation is normally accomplished using small-diameter plastic tubes with emitters at selected spacings. Trickle irrigation offers great agricultural potential to areas with limited and/or costly water supplies as well as areas with water supplies of high salt content (Cole 1971 and Black et al. 1970).

Precise design of trickle irrigation laterals is important because system pressure losses within which a trickle irrigation system must operate are extremely small when compared to "conventional" sprinkler irrigation system pressure losses. Careful consideration must be given to the lateral design to ensure that the consumptive use rate of the plants is met at a minimum system cost.

The purposes of this paper are (a) to develop design methods for trickle irrigation laterals with applications to orchard crops; and (b) to develop inputs necessary for precise engineering design based on experimental data. Two design methods are given; one is general in nature and involves a computer program while the other is a simplified procedure which is applicable when reduction coefficients to compensate for diverging flow along the lateral are known.

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## LATERAL DESIGN

The primary function of the lateral design is to determine the optimum pipe size and number of emitters per plant required to meet the consumptive use requirements of a crop within certain hydraulic uniformity constraints. In most irrigation systems, three elements — soil infiltration rate, peak consumptive use of the crop, and the irrigation system — have to be matched in order to achieve an adequate design. Since runoff is usually negligible due to the small application rate with trickle irrigation, only the trickle irrigation system itself and the consumptive use rate of the crop need be considered to achieve an adequate design. In rare instances where the emitter flow rate and the application amount are large, the soil

infiltration characteristics may be one of the limiting factors in the lateral design.

Many types of trickle emitters and systems are available, and generally the hydraulic operating characteristics of each individual emitter type are different. Fig. 1 shows the operating characteristics of three different trickle emitter types\*, insert orifice, labyrinth, and microtube. Davis and Nelson (1970) described 24 emitters available at that time while, three years later, Sneed (1973) estimated that greater than 50 different emitters were on the market. Each emitter to

\*Trade names included in this paper are presented only for the benefit of the reader and no endorsement or recommendation of the product is inferred by the authors or the Texas Agricultural Experiment Station.

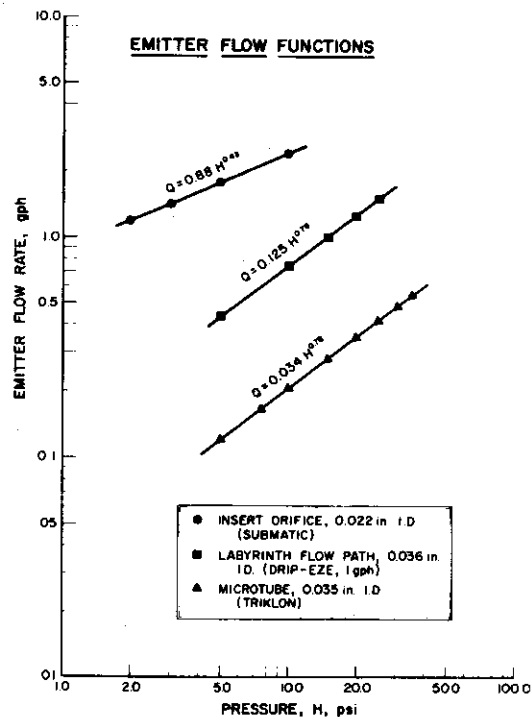


FIG. 1 Emitter flow functions.

some degree has its own operating characteristics. Two major groups of emitter types are generally acknowledged: (a) long flow path emitters and (b) orifice or nozzle emitters. Fig. 1 indicates that the emitter flow function (pressure-discharge curve) can be characterized over a desired range of flow by a linear plot on a log-log graph. This results in an equation of the form:

$$Q = KH^x \dots\dots\dots [1]$$

where

- Q = emitter flow rate, gallons per hour (gph)
- H = pressure at the emitter, pounds per sq in. (psi)
- K = emitter flow rate, gph, at a pressure of 1 psi
- x = slope of the line.

Data for emitter flow functions are readily available from manufacturers or can be determined by laboratory measurements. Extensive data for emitter flow functions for self-flushing emitters are given by Hanson (1973).

The peak consumptive use rate of the crop depends on the type of crop and the climate in which it is grown. Usually, the peak consumptive use rate occurs only for a short time period during the early fruiting stage. The most economical system would be designed for continuous operation at peak capacity during this period. Peak water requirements have not been adequately defined for trickle irrigation, by either research or experience, to be used with confidence in the lateral design. The design application rate can be estimated by reducing the peak consumptive use rate for sprinkler and surface irrigation by an empirical coverage factor as follows:

$$R = 0.623EAP \dots\dots\dots [2]$$

where

- R = the design application rate per tree, gallons per day (gpd)
- E = the peak consumptive use rate for sprinkler or surface irrigation, in. per day
- A = the tree space area (row spacing x plant spacing within the row, sq ft).
- P = the coverage factor (fraction of tree space area covered by the crop).

Equation [2] is only an estimation method to be used until more specific crop water use data can be obtained for trickle irrigation. Note that equa-

tion [2] is based on daily irrigation, and if less frequent applications are desired, then E will be the product of the daily consumptive use times the length of the irrigation interval in days. Values of E can be obtained from most sprinkler irrigation handbooks; 0.7 of the maximum mean monthly evaporation from a Class A evaporation pan reduced to daily values has been suggested as an appropriate value of E for arid climates (Goldberg 1972). However, this "rule of thumb" has yet to be documented or proven. Hiler and Howell (1973) found that applications of 0.6 to 0.7 of Class A pan evaporation were desirable from a water use efficiency viewpoint but would not produce a maximum yield in a row crop like grain sorghum.

The number of emitters per tree and the average lateral pressure can be determined from the design application rate, R, and the emitter flow function, equation [1]. The required emitter flow rate, Q, in gph can be determined for selected values of the number of emitters per tree, N, as follows:

$$Q = \frac{R}{TN} \dots\dots\dots [3]$$

where

T = time to apply the irrigation, hours (hr) per day.

As stated previously the most economical system would require T to be approximately 24 hr but for operator convenience, recovery time in case of system breakdown, system automation, or irrigation set size limitation, T may be reduced to any desired lower value. Also from a plant response viewpoint, continuous irrigation may not be desirable; therefore the irrigation time is recommended not to exceed 20 hr per day. By substituting equation [1] into equation [3] and rearranging, the required average lateral pressure, H, is given as follows:

$$H = \left( \frac{R}{KTN} \right)^{1/x} \dots\dots\dots [4]$$

H must be maintained in the operating range for the specific emitter type. The number of emitters per tree may have to be increased to allow for adequate distribution to the root zone or to allow lateral pressure to be

decreased to a lower value. In the specific case of a young orchard, R may need to be increased to allow for future irrigation requirements as the crop grows. If by the above adjustments, the application rate per tree (NQ) is increased (as could be the case when N is increased to the next integer value and Q is a minimum for a specific emitter operating range), the time, T, to apply the irrigation can be determined by equation [3].

If N is greater than one, the distance between emitters (emitter spacing) at a tree can be determined from a trial application at the field site or from prior experience based on the soil type. Generally when saline water is used for trickle irrigation, the wetting patterns should overlap sufficiently to avoid salt accumulation in the crop root zone.

#### Design Method Using Computer Program

A FORTRAN computer program was developed on the IBM 360/65 digital computer to calculate the pipe friction loss, emitter friction loss, emitter flow ratio (ratio of the minimum emitter flow to the maximum emitter flow for a given lateral), and the total flow in the lateral as a function of pipe size (inside pipe diameter), tree spacing, number of emitters per tree, emitter spacing (the spacing between emitters if more than one emitter per tree was used), pressure at the end of the lateral, slope (field slope in percent), and lateral length. A flow chart of the program is shown in Fig. 2, and a list of the input data and output data is shown in Table 1. The program is similar to but more comprehensive than that of Zetzsche and Newman (1968). Copies of the program are available upon request from the authors.

The pressure loss due to pipe friction was computed by the Hazen-Williams equation:

$$H_F = 4.551 \frac{LQ'^{1.852}}{C^{1.852} D^{4.871}} \dots\dots\dots [5]$$

where

- H<sub>F</sub> = pressure loss due to pipe friction, psi
- C = Hazen-Williams roughness coefficient
- L = pipe length, ft
- D = inside pipe diameter, inches (in.)
- Q' = lateral flow rate, gallons per minute (gpm)

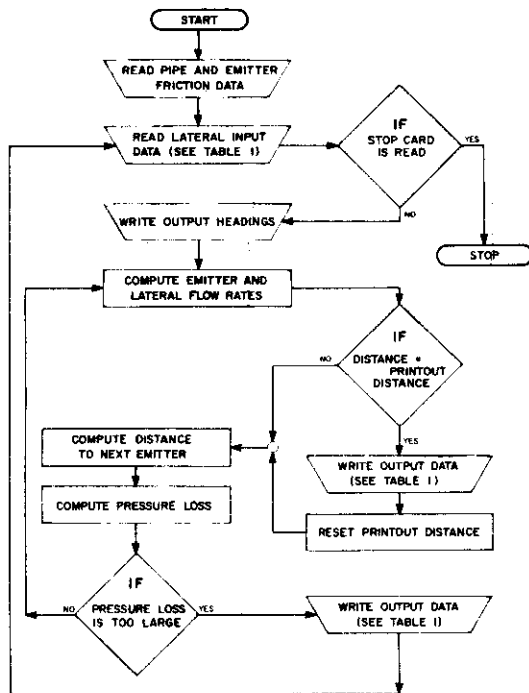


FIG. 2 Flow chart for lateral design computer program.

For smooth, straight polyvinyl chloride (PVC) pipe,  $C$  is assumed to be 150 in general practice, and for polyethylene pipe,  $C$  is generally assumed to be 140 (Sneed 1973). However Hanson (1973) found  $C$  values for laboratory trickle lines to vary from 98 to 136 depending on the specific emitter type.

The emitter design can greatly influence the pipe roughness. An in-line emitter which is directly inserted into a cut end of the pipe can cause significant pressure loss due to the flow restriction caused by the emitter. This pressure loss can be as large as 0.038 psi per emitter with a through flow of 0.5 gpm (Drip-eze Tech Manual 1972). In our program, an equation similar to equation [1] fitted to empirical data is utilized to calculate the emitter friction loss as a function of flow rate.

When designing low pressure distribution systems, elevation can become an important design parameter. A single value of the field slope in the direction of the lateral is used to compute the head loss or gain caused by a change in elevation.

The computer program begins calculations at the downstream end of the lateral and approaches the mainline

junction in incremental units of emitter spacing until the emitter flow ratio is unacceptable or the pressure drop is too large for the required lateral length. Pressure loss in the lateral is usually limited to 20 percent ( $\pm 10$  percent) of the average emitter operating pressure, and the emitter flow ratio is maintained above 0.83. These criteria will usually maintain a lateral uniformity coefficient of at least 95 percent as suggested by Wu and Gitlin (1974).

The program is written in a general nature and can accommodate any number of additional features which may be desired. With small modifications the program could be used to determine microtube lengths (Kenworthy 1972), emitter or orifice sizes (Meyers and Bucks 1972), or emitter spacings (Wilke 1971) required to maintain even flow rates along the lateral. For a given set of design inputs, the program can be used to determine if the given pipe size will be adequate to limit the pressure loss and the flow variation along the lateral limits acceptable for the design lateral length.

#### Determination of F-Values

The computer program was used to

TABLE 1. LIST OF INPUT AND OUTPUT DATA FOR LATERAL DESIGN COMPUTER PROGRAM

Input	Output
$K$ - emitter flow coefficient	$L$ - lateral distance, ft.
$x$ - emitter flow exponent	$Q$ - emitter flow rate, gph
$C$ - Hazen-Williams roughness coefficient	Emitter flow ratio
$D$ - inside pipe diameter, in.	$Q'$ - lateral flow rate, gpm
$H_0$ - downstream lateral pressure, psi	$H_F$ - pipe pressure loss, psi
$N$ - number of emitters per tree	$H_L$ - lateral pressure loss, psi
Plant spacing, ft	$H_e$ - elevation pressure loss or gain, psi
Printout interval, ft	$F$ - reduction coefficient
Emitter friction data, psi per emitter per gpm	$H$ - lateral pressure, psi
Lateral slope, percent	Number of emitters

determine  $F$  values (reduction coefficients to compensate for diverging flow along the lateral, see Christiansen 1942) for various number of emitters.  $F$  was calculated as the ratio of the actual pressure drop determined by discrete steps to the friction loss calculated for the total lateral flow at that point and distance. Fig. 3 shows  $F$  as a function of numbers of emitters and emitter spacing for  $\frac{1}{2}$ -in. lateral with an end pressure of 10 psi and no emitter friction. A similar relationship exists between  $F$ , number of emitters, and the lateral pressure for a constant spacing. Fig. 4 shows  $F$  as a function of number of emitters and emitter spacing for a  $\frac{1}{2}$ -in. lateral with an end pressure of 10 psi and emitter friction data taken from Drip-eze Tech Manual (1972). The increased magnitude of the  $F$  values in Fig. 4 compared to those in Fig. 3 occurs because at certain lateral flow rates the emitter friction can be as large or even larger than the pipe friction between emitters. In these cases, it is imperative that emitter friction not be neglected in the design method, as can be seen in Fig. 4. The data indicate that at a flow rate of 0.5 gpm the emitter friction is equivalent to 2.5 ft of  $\frac{1}{2}$ -in. polyethylene pipe at that flow rate. For trickle lines with between 20 and 70 emitters *without emitter friction*,  $F$  can be assumed to be 0.36 for most circumstances, as was the conclusion of Keller and Karmeli (1973).

#### Design Method Using Known F-Values

When  $F$ -values are known, the design calculations can be greatly simplified without loss of accuracy. This section presents design procedures when appropriate  $F$ -values are known. The lateral pressure loss  $H_L$  is a product of  $F$  and the total pipe friction loss,  $H_F$ , for the given lateral length and total flow rate,  $Q'$ .  $Q'$  is assumed to be the average emitter flow rate

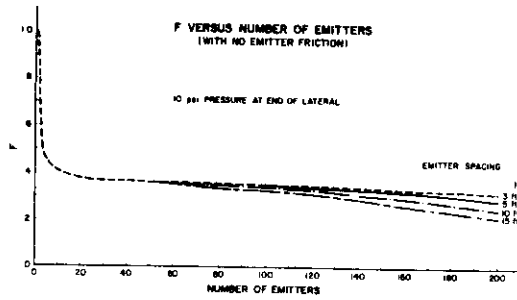


FIG. 3 F values for different numbers of emitters and emitter spacings for Drip-eze DH 1-580 emitters (1 gph) and DH 580 pipe (0.580 in. I.D.) with an end pressure of 10 psi and no emitter friction.

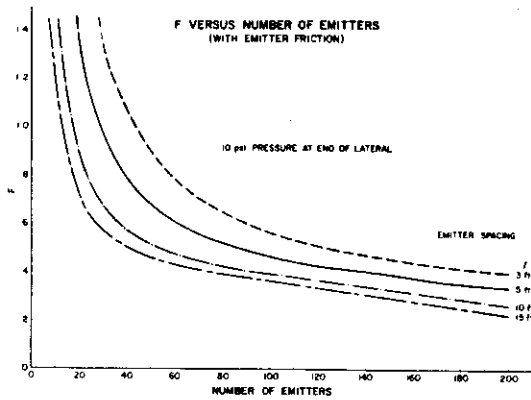


FIG. 4 F values for different numbers of emitters and emitter spacings for Drip-eze DH 1-580 emitters (1 gph) and DH 580 pipe (0.580 in. I.D.) with an end pressure of 10 psi and emitter friction.

times the number of emitters. Thus the actual lateral pressure loss can be calculated independent of the computer method.

Following Christiansen (1942), the pressure at the end of the lateral,  $H_0$ , and the pressure at the head of the lateral,  $H_n$ , can approximately be calculated as follows:

$$H_0 = H - 0.25H_f \pm 0.50H_e \quad [7]$$

$$H_n = H_0 + H_f \pm H_e \quad [8]$$

where

$H$  = the average lateral pressure, psi, and

$H_e$  = the change in elevation, psi.

The emitter flow ratio can now be approximately calculated by

$$\frac{Q_{min}}{Q_{max}} = \left( \frac{H_0}{H_n} \right)^x \quad [9]$$

where

$Q_{min}$  = minimum lateral emitter flow, gph

$Q_{max}$  = maximum lateral emitter flow, gph

$x$  = emitter flow exponent in equation [1]

The design can then be evaluated based on the minimum acceptable emitter flow ratio and adjustments made if necessary.

#### LABORATORY STUDIES

Laboratory studies were undertaken to determine specific emitter flow functions and appropriate values of  $C$  for  $\frac{1}{2}$ -in. polyethylene pipe. To test the validity of the computer solutions, pressure distributions were measured in a model lateral and compared with

those predicted from the computer program.

Three emitter types were selected for testing: (a) insert orifice, 0.022-in. I.D. (Submatic), (b) labyrinth flow path, 0.036-in. I.D. (Drip-eze DE 1-580), and (c) microtube, 0.035-in. I.D. (TriKLon). Each emitter type was installed into a 2.0-ft long section of  $\frac{1}{2}$ -in. polyethylene pipe equipped with a precision pressure gauge ( $\frac{1}{4}$  of 1 percent accuracy) and a pressure regulating valve. Pressures were manually set, and flow rate measurements were taken with a graduated cylinder for 5-min time periods as measured with a stop watch. Water temperature was also measured by a thermometer to account for viscosity changes. Five emitters from each emitter type were tested.

The pipe roughness coefficient,  $C$ , was determined for 100-ft sections of  $\frac{1}{2}$ -in. (0.622-in. I.D.) polyethylene pipe and Drip-eze DH 580 (0.580-in. I.D.) polyethylene pipe. A 20-ft section of pipe was provided at the head and tail end of the test pipe. At the head end, the water entered through a flow meter, pressure reducing valve, and pressure gauge. A precision metering valve was located at the end of the pipe. The 100-ft test section was carefully selected to avoid any irregularities in the pipe. Tees were placed at each end of the test pipe and connected differentially to an inclined mercury manometer. The valve on the end of the pipe was used to regulate the flow rate. Flow rates were determined by volumetric catchment as well as by the flow meter. Flow rates were set and the corresponding pressure drop was read from the manometer after equilibrium. Water

temperature was also measured to correct for changes in viscosity. Tests were repeated 3 times. Then the test pipes were coiled into three 8-ft diameter circles, and the same tests were repeated.

Pressure distributions were determined in a model lateral 500 ft long of Drip-eze DH 580 (0.580-in. I.D.) polyethylene pipe with Drip-eze 1-580 emitters spaced 2-ft apart. Pressure taps were located every 50-ft, and the pressures were measured on a series of mercury manometers. The head was arranged as previously described, and the tail end was plugged with a pressure gauge. Emitter flow rates were measured next to each pressure tap. Test runs were made at 9.5, 15.0 and 19.2 psi pressures at the plugged end.

Figs. 1, 5, and 6 show the experimental results. Fig. 1 gives the emitter flow functions as well as the regression equations. All correlation coefficients were above 0.98. Both Drip-eze and TriKLon exhibited laminar flow characteristics. The Submatic orifice did not strictly follow the theoretical orifice equation where flow is directly proportional to the square-root of the pressure. However, Karmeli (1970) reported that some perforated orifices did follow closely the theoretical orifice equation.

The friction loss in  $\frac{1}{2}$ -in. (0.622-in. I.D.) polyethylene pipe versus flow rate is shown in Fig. 5. The  $C$  value of the polyethylene pipe was determined by regression analysis to be 130, while for Drip-eze DH 580 pipe  $C$  was determined to be 128. The results for Drip-eze pipe were not shown but were quite similar to those for  $\frac{1}{2}$ -in. polyethylene pipe. The effects of the loops

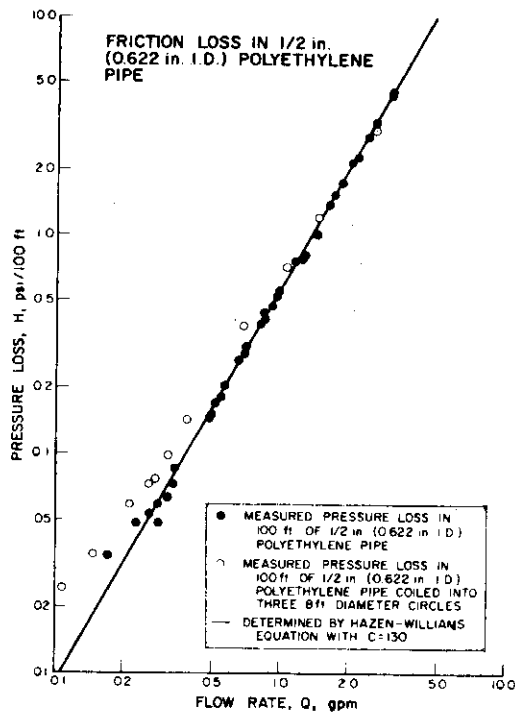


FIG. 5 Pressure loss in 1/2 in. (0.622 in. I.D.) polyethylene pipe.

in the pipe were significant only at flow rates below 1 gpm. For design purposes, a value of 130 for C would be more appropriate than the commonly used 150 or 140 based upon these results and those of Hanson (1973).

The pressure distributions in the model lateral are shown in Fig. 6. The pressure drop ratio is the fraction of the pressure drop from the inlet to total pressure drop, and the distance ratio is the fraction of the distance from the inlet to the entire lateral length. These results agree well with the computer generated curve also shown in Fig. 6. An emitter friction loss was included in the computer program which utilized data given in Drip-eze Tech Manual (1972). The emitter friction loss was determined as a function of flow rate through the emitter. The emitter friction caused the dimensionless curve in Fig. 6 to be slightly below that predicted by Wu and Gitlin (1973, 1974). When emitter friction was deleted from the program, the results matched those of Wu and Gitlin (1973, 1974). Roughly 53 percent of the lateral friction drop occurred in the first 20 percent of the lateral length.

The experimental results appeared

to verify the computer program. These results along with the other hydraulic considerations were combined to produce the following design procedure for trickle irrigation laterals.

#### DESIGN PROCEDURE AND EXAMPLE

##### Procedure

##### Step 1

Determine the tree spacing, row spacing, lateral slope, peak consumptive use of the crop, coverage factor, required lateral length, desired operation time, and select the maximum allowable pressure variation along the lateral.

##### Step 2

Determine the design application rate from equation [2].

##### Step 3

Determine the number of emitters, the average emitter flow rate, and the required average pressure from equations [3] and [4]. Determine emitter spacing (the distance between emitters at a tree) if N is greater than one.

##### Step 4

Determine the system operating time required to apply the design amount from equation [3].

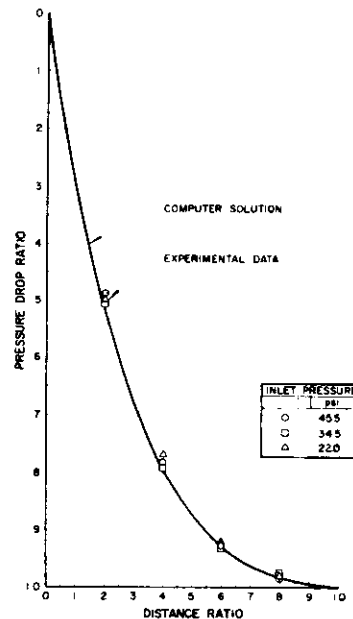


FIG. 6 Comparison of experimental trickle lateral pressure distribution to that predicted by computer solution.

##### Step 5

Choose an initial lateral pipe size.

##### Step 6

(Design method using known F-values) Determine the lateral pressure drop by use of equation [5] and the appropriate F-value to calculate  $H_f$ , equations [7] and [8] to calculate  $H_o$  and  $H_n$ , respectively, and equation [9] to calculate the emitter flow ratio.

##### or Step 6A

(Design method using computer program) Determine the lateral pressure drop and emitter flow ratio at the required lateral length from the lateral design computer program.

##### Step 7

If the pressure variation or emitter flow ratio is unacceptable, the lateral length will have to be shortened, lateral flow rate reduced or return to Step 5 and select another pipe size.

##### Example

A trickle irrigation system is being considered for a citrus orchard which is located in the Lower Rio Grande Valley of Texas. The required lateral length is 900 ft. The tree spacing is 15 ft along the row, and the row spacing is 25 ft. The field is presently being border irrigated and has been leveled to approximately zero slope in the lateral direction. The peak consump-

tive use of the crop is taken as 0.20 in. per day, and the crop cover factor is 0.40. For this example problem, Drip-eze emitters (DH 1-580, 1 gph) and pipe (DH 580, 0.580 in. I.D.) will be used. A minimum uniformity coefficient of emitter flow in the lateral line of 0.95 (emitter flow ratio = 0.83) is desired.

**Step 1**

Tree spacing = 15 ft  
 Row spacing = 25 ft  
 Lateral slope = 0.0 percent  
 E = 0.20 in. per day  
 P = 0.40

Lateral Length = 900 ft  
 Desired Operation time = 24.0 hr  
 Allowable pressure variation along lateral = 20 percent of the emitter operating pressure.  
 $A = 15 \times 25 = 375 \text{ sq ft}$

**Step 2**

$R = 0.623(0.20)(375)(0.40) = 18.7 \text{ gpd}$

**Step 3**

Try  $N = 1$   
 $Q = 18.7 / (24.0)(1) = 0.78 \text{ gph}$

$$H = \left[ \frac{18.7}{(0.125)(24.0)(1.0)} \right]^{1/0.78} = 10.4 \text{ psi}$$

The desired operating pressure of this particular emitter is 15.0 psi, so H must be increased from 10.4 psi to 15 psi, and Q will now be 1.0 gph as shown by Fig. 1.

$N = 1$   
 $Q = 1.0 \text{ gph}$   
 $H = 15.0 \text{ psi}$   
 Emitter spacing = 0.0, since  $N = 1$   
 $Q' = (60)(1.0) = 60 \text{ gpm} = 1 \text{ gpm}$

**Step 4**

$T = 18.7 / (1.0)(1.0) = 18.7 \text{ hr}$

**Step 5**

$D = 0.580 \text{ in.}$

**Step 6**

Design method using known F-values

$$H_f = (0.41)(4.551)(900) \left( \frac{1.0}{130} \right)^{1.852} (0.580)^{-4.871}$$

$H_f = 2.90 \text{ psi}$

$H_o = 15.0 - (0.25)(2.90) = 14.27 \text{ psi}$

$H_n = 14.27 + 2.90 = 17.17 \text{ psi}$

$$\frac{Q_{\min}}{Q_{\max}} = \left( \frac{14.27}{17.17} \right)^{0.78} = 0.865$$

**or Step 6A**

Design method using computer program.

The computer program calculated the lateral pressure loss as 2.94 psi, the end pressure as 14.27 psi, the inlet pressure as 17.21 psi and the

TABLE 2. COMPUTER OUTPUT FOR LATERAL DESIGN EXAMPLE

Distance, ft	Pressure, psi	Emitter flow rate, gph	Lateral flow rate, gpm	Total pressure loss, psi	Emitter flow ratio	F
0	14.27	0.99	0.02	0.00	1.00	--
105	14.28	0.99	0.12	0.01	0.99	0.99
210	14.34	0.99	0.23	0.07	0.99	0.65
300	14.44	1.00	0.33	0.17	0.99	0.55
405	14.65	1.01	0.45	0.35	0.98	0.49
510	14.91	1.03	0.57	0.64	0.97	0.45
600	15.25	1.04	0.67	0.98	0.95	0.43
705	18.28	1.07	0.79	1.50	0.93	0.41
810	16.46	1.11	0.92	2.19	0.89	0.40
900	17.21	1.15	1.03	2.94	0.86	0.39
1005	18.28	1.21	1.17	4.01	0.82	0.38

emitter flow ratio as 0.864. Table 2 shows the computer output for this example.

**Step 7**

The actual lateral pressure drop of 2.94 psi is less than the allowable pressure loss of 3.00 psi (0.20 x 15.0); in terms of emitter flow ratio, the actual value of 0.86 is greater than the minimum acceptable value of 0.83. Therefore, the selected pipe size is acceptable for a 900 ft lateral with 1 gph emitters 15 ft apart.

Additional alternate design approaches are given by Howell and Hiler (1972).

**DISCUSSION**

Trickle irrigation system design based on peak consumptive use, as this term has been defined and measured in relation to sprinkler and surface irrigation, may lead to an overdesigned system. Many researchers, see Cole (1971), have found a 40 to 50 percent water savings by using trickle or subsurface irrigation in comparison to the more conventional systems. More fundamental research is needed in this area to account for these differences. The method proposed by equation [2] appears to give reasonable working estimates for the design application

rate.

Several assumptions were required in this analysis. The emitter presence in the lateral was assumed to act as a flow restriction causing a pressure loss which is a function of the emitter design and flow rate through the emitter. Figs. 3 and 4 demonstrate the degree to which the hydraulics of a lateral can be affected. This so-called "emitter friction" will have to be considered in design of laterals using in-line emitters.

The pressure gain caused by the di-

viding flow in the lateral was neglected in this paper. In most instances, the ratio of the emitter flow path diameter to the lateral diameter is small. Also, the emitter flow path does not make a smooth, perpendicular exit from the lateral. Generally at points in the lateral where the ratio of emitter flow to the pipe is large, the flow velocity is small. Thus for most laterals the pressure gain caused by the dividing flow can be safely neglected.

A single value of the lateral slope was utilized by the computer program. In some extreme cases, individual elevation readings could be input to the program to accurately calculate the pressure at each point in the lateral.

A general expression for F has not been determined. F appears to be generally constant for the number of emitters but also depends upon the emitter spacing and downstream lateral pressure. This work assumed that F will not depend upon the specific emitter type. Large errors in F can result if emitter friction is neglected when using in-line emitters.

**SUMMARY AND CONCLUSIONS**

This paper presents a design method for determining the pressure loss and emitter flow ratio for trickle irrigation laterals. The design method is based upon known principles of fluid mechanics. A computer program was written to determine the lateral pressure loss and emitter flow ratio at a given design length as function of pipe size, tree spacing, number of emitters per tree, emitter spacing (spacing between emitters when more than one emitter per tree is used), downstream lateral pressure, and lateral slope (Fig. 2). For a given set of design inputs, the program can be used to determine if the given pipe size will be adequate to limit the pressure loss and flow variation along the lateral to limits acceptable for the design lateral length.



The program was used to compute F values (Figs. 3 and 4) to be used in the design method. Design equations are given which can be used with known F-values to determine the lateral pressure loss and flow variation along the lateral for a given pipe size. Thus the computer solution method can be obviated when accurate F-values are available.

Experimental data are given which show the emitter flow function for three emitter types, friction loss in 1/2-in. polyethylene pipe, and the pressure distribution in a model lateral. The data indicate that the emitter flow function can be represented by a power-type equation with the constants determined by the empirical data (Fig. 1). The Hazen-Williams roughness coefficient was computed to be approximately 130 for 1/2-in. (0.622-in. I.D.) and Drip-eze DH 580 (0.580-in. I.D.) polyethylene pipe (Fig. 5). The pressure distribution in the model lateral was in close agreement with the pressure distribution predicted by the computer program for the lateral (Fig. 6). Approximately 50 percent of the lateral pressure drop occurred in the first 20 percent of the lateral distance.

As a result of this study, the following conclusions are indicated:

1 In-line emitters which are directly

inserted into a cut end of the pipe can cause significant pressure loss due to the flow path restriction caused by the emitter. This pressure loss must be considered for precise engineering design of trickle irrigation laterals.

2 The Hazen-Williams roughness coefficient was determined to be approximately 130 for 1/2-in. polyethylene pipe.

3 F values were dependent upon the emitter friction to a large extent, and upon emitter spacing and lateral pressure to a lesser extent. When using in-line emitters, F must be determined with care, or large errors can result.

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APPENDIX E

# JOURNAL OF THE IRRIGATION AND DRAINAGE DIVISION

## DESIGNING TRICKLE IRRIGATION LATERALS FOR UNIFORMITY

By Terry A. Howell<sup>1</sup> and Edward A. Hiler<sup>2</sup>

### INTRODUCTION

The trickle irrigation method is rapidly gaining importance in the United States especially in areas with short or expensive, or both, water supplies. Current estimates show that approx 100,000 acres ( $4.1 \times 10^8 \text{ m}^2$ ) in the western United States are being trickle irrigated and the future potential could be as large as several million acres. Trickle irrigation has a wide range of applications from orchards to greenhouses and also has future potential for row crops. Trickle irrigation potentials and problems are presented by Cole (3) and Black, et al. (1).

Trickle irrigation is a method of watering plants frequently and with volumes of water approaching the consumptive use of the plants thereby minimizing such "conventional" losses as deep percolation, runoff, and soil water evaporation. This irrigation method is accomplished by using small-diameter plastic lateral lines with devices called "emitters" or "drippers" at selected spacings to deliver water to the soil surface near the base of the plants.

Trickle irrigation emitters vary from elaborate variable flow rate types to simple orifices or even punched, drilled, or burned holes in the pipe. In general, the flow rate through the emitter is controlled by the hydraulic pressure at the emitter and the flow path dimensions of the emitter. Since water flowing through the lateral pipe loses energy due to friction, a pressure variation will exist along the pipe length. If the emitter geometry is fixed, then a corresponding flow rate distribution proportional to the pressure distribution will exist along the pipe length. Even uniformity of flow from each emitter is possible only if the emitter size is changed [orifice diameter, Meyers and Bucks (8), or microtube

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length, Kenworthy (7)]. Meyers and Bucks (8) used a graphical technique to determine emitter size while the writers (5) suggested a computer method that could be used for either case. However, in general practice the emitter characteristics are usually fixed, and the flow rate is determined by pressure alone.

The purposes of this paper are to: (1) Develop design equations for determining trickle irrigation lateral lengths for a selected flow uniformity; and (2) illustrate the use of these equations for trickle irrigation design through application examples. The design equations are developed from principles of fluid mechanics and are dependent on hydraulic characteristics of the emitter and lateral line.

#### PREVIOUS WORK

Recently, several researchers have presented design data and procedures for trickle irrigation laterals. Keller and Karmeli (6) presented design equations and data to determine irrigation interval, emitter spacing and flow rates, and hydraulic characteristics of the system. Also, they proposed important new concepts of emission uniformity and system efficiency.

Wu and Gitlin (9,10) developed a graphical method for determining the lateral uniformity as a function of lateral length, inlet pressure, lateral flow rate, and lateral slope. In addition, they presented dimensionless curves for the pressure drop ratio versus length ratio and lateral uniformity versus maximum to minimum emitter flow ratio.

The writers (4) and Zetzsche and Newman (11) suggested a computer solution method for determining lateral lengths for selected uniformities subject to emitter spacing and downstream pressure. The writers (5) modified their previous work to allow calculation of the design lateral length without the use of the computer. They also presented computer-derived curves of  $F$  (reduction coefficient for dividing flow and emitter friction) versus number of emitters and emitter spacing.

One of the major problems in lateral design is the determination of the application rate and frequency. Keller and Karmeli (6) and the writers (5) presented methods to estimate the design application rate.

#### DESIGN CONSIDERATIONS

The emitter flow function can be given as

$$q = kH^x \dots \dots \dots (1)$$

in which  $q$  = emitter flow rate, in gallons per hour (cubic decimeters per hour);  $H$  = pressure at the emitter, in pounds per square inch (kilonewtons per square meter);  $k$  = emitter flow rate, in gallons per hour (cubic decimeters per hour), at a pressure of 1 psi (6.9 kN/m<sup>2</sup>); and  $x$  = slope of the line on a log-log plot and is characterized by the flow regime of the emitter. Fig. 1 shows the emitter flow functions for three specific emitter types. (Trade names included in this paper are presented only for the benefit of the reader and no endorsement or recommendation of the product is inferred by the writers or the Texas Agricultural Experiment Station.) Data for emitter flow functions are readily available from manufacturers or can be determined by laboratory measurements.

The design emitter flow rate,  $q$ , in gallons per hour (cubic decimeters per hour), depends on the peak consumptive use rate, the number of emitters per

tree, irrigation frequency, and the time to apply the irrigation; it can be determined using the method given by the writers (5). Then by Eq. 1 the inlet pressure,  $H_n$ , is

$$H_n = \left[ \frac{q}{k} \left( 1 + \frac{P}{100} \right) \right]^{1/x} \dots \dots \dots (2)$$

in which  $P$  = flow variation allowed in the lateral, as a percentage, e.g.,  $\pm 10\%$  from  $q$  equals a  $P$  of 10%; and the downstream pressure,  $H_o$ , is

$$H_o = \left[ \frac{q}{k} \left( 1 - \frac{P}{100} \right) \right]^{1/x} \dots \dots \dots (3)$$

The value of  $P$  is determined by the desired uniformity coefficient as given in Fig. 2. The data for Fig. 2 were from Wu and Gitlin (10), and the uniformity

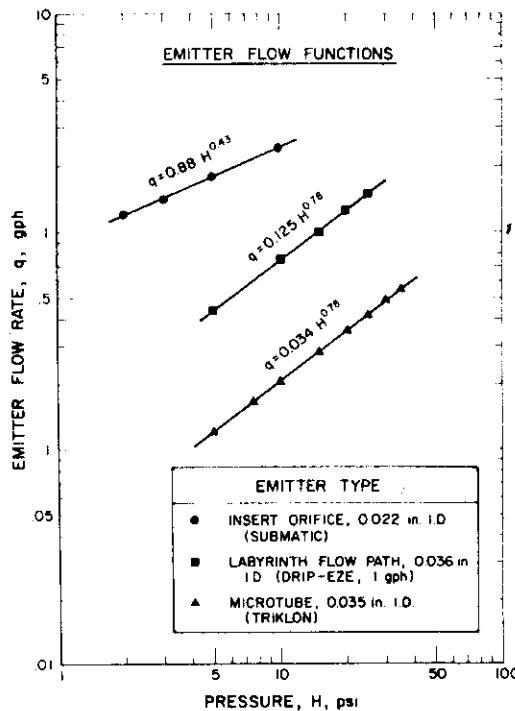


FIG. 1.—Emitter Flow Functions (1 in. = 25.4 mm; 1 gph = 3.8 dm<sup>3</sup>/hr; 1 psi = 6.9 kN/m<sup>2</sup>)

coefficient was defined by Christiansen (2). In general, the uniformity coefficient should always be maintained above 0.90 and a value of 0.95 or larger is desirable.

The allowable pressure loss due to pipe friction in the lateral for the desired uniformity is

$$H_f = H_n - H_o \pm H_e \dots \dots \dots (4)$$

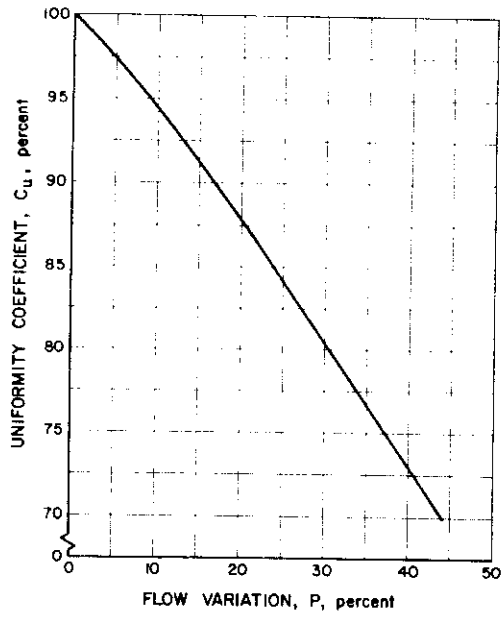


FIG. 2.—Comparison of Flow Variation to Uniformity Coefficient

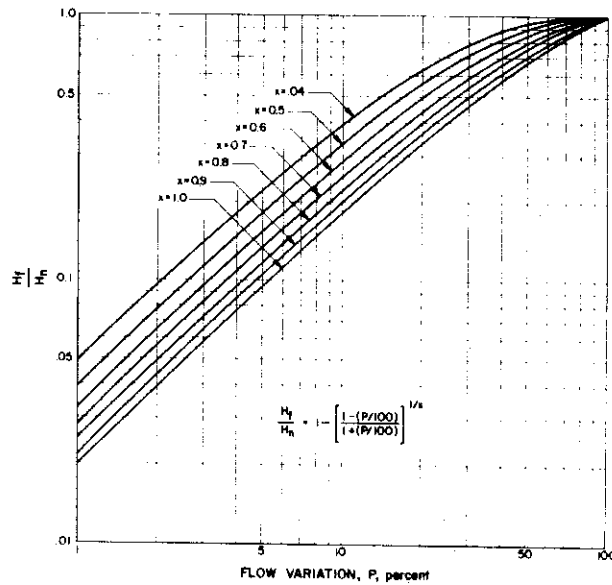


FIG. 3.—Ratio of Allowable Friction Loss to Inlet Pressure as Function of Flow Variation for Different Emitter Characteristics for Level Laterals

in which  $H_f$  = lateral friction pressure loss, in pounds per square inch (kilonewtons per square meter); and  $H_e$  = the total elevation change along the lateral, in pounds per square inch (kilonewtons per square meter) with a + meaning the lateral runs downslope and - meaning the lateral runs upslope. Assuming no elevation change, a dimensionless ratio of  $H_f$  to  $H_n$  becomes

$$\frac{H_f}{H_n} = 1 - \left[ \frac{\left(1 - \frac{P}{100}\right)}{\left(1 + \frac{P}{100}\right)} \right]^{1/x} \dots \dots \dots (5)$$

Fig. 3 shows a dimensionless graph of  $H_f/H_n$  versus  $P$  for various values of  $x$ .

Data from the writers' (5) computer programs show that the average emitter flow rate,  $\bar{q}$ , for the lateral occurred at 40% of lateral length from the inlet. Following Christiansen (2), the average lateral pressure,  $\bar{H}$ , is

$$\bar{H} = H_n - \frac{3}{4} H_f \pm \frac{1}{2} H_e \dots \dots \dots (6)$$

Therefore substitution of Eq. 6 into Eq. 1, the average emitter flow rate becomes

$$\bar{q} = K \left( H_n - \frac{3}{4} H_f \pm \frac{1}{2} H_e \right)^x \dots \dots \dots (7)$$

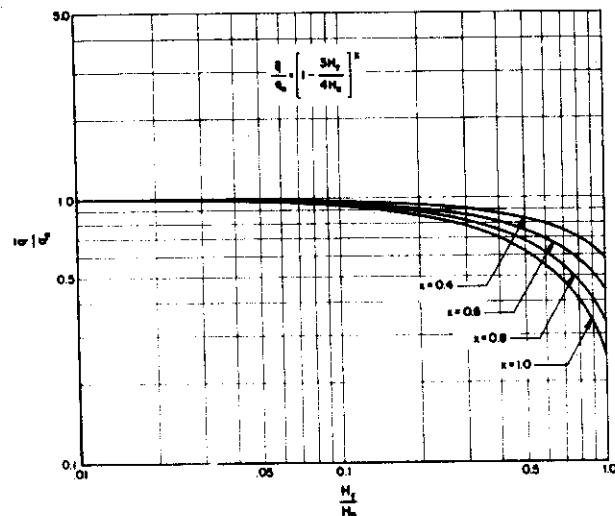


FIG. 4.—Ratio of Average Emitter Flow to Emitter Flow Rate at Inlet as Function of Ratio of Allowable Friction Loss to Inlet Pressure for Different Emitter Characteristics for Level Laterals

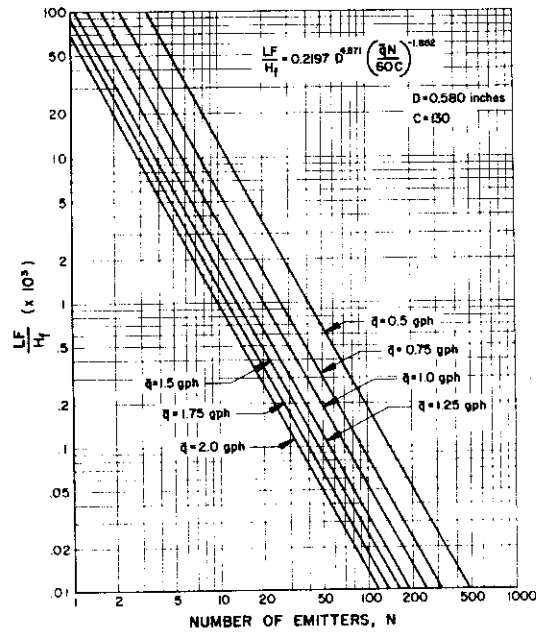


FIG. 5.— $LF/H_f$  as Function of Number of Emitters for Different Emitter Flow Rates (1 in. = 25.4 mm; 1 gph = 3.8 dm<sup>3</sup>/hr)

A dimensionless ratio of  $\bar{q}$  to  $q_n$ , the inlet emitter flow rate, is given as follows, assuming no elevation change:

$$\frac{\bar{q}}{q_n} = \left[ 1 - \frac{3}{4} \left( \frac{H_f}{H_n} \right) \right]^x \dots \dots \dots (8)$$

Fig. 4 shows a dimensionless graph of  $\bar{q}/q_n$  versus  $H_f/H_n$  for various values of  $x$ .

The allowable pressure loss in the lateral can be determined using the Hazen-Williams equation and accounting for the reduction coefficient for dividing flow and emitter friction, as follows:

$$H_f = F 4.551 D^{-4.871} \left( \frac{\bar{q} N}{60 C} \right)^{1.852} L \dots \dots \dots (9)$$

in which  $D$  = the inside pipe diameter, in inches (millimeters);  $N$  = the number of emitters;  $C$  = the Hazen-Williams roughness coefficient [ $C = 130$  for 1/2 in. (12.7 mm) polyethylene pipe, (5)];  $L$  = the lateral length, in feet (meters); and  $F$  = the reduction coefficient for dividing flow and emitter friction. Eq. 9 is the Hazen-Williams equation times the  $F$  factor. Rearranging Eq. 9 and solving for  $LF/H_f$  yields

$$\frac{LF}{H_f} = 0.220 D^{4.871} \left( \frac{\bar{q} N}{60 C} \right)^{-1.852} \dots \dots \dots (10)$$



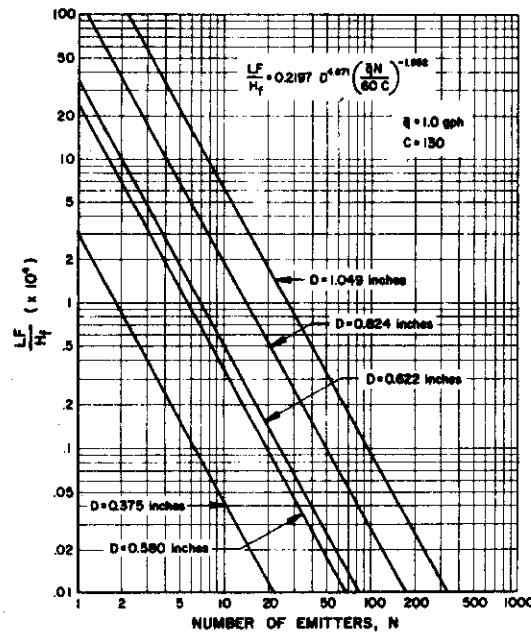


FIG. 6.— $LF/H_f$  as Function of Number of Emitters and Different Pipe Sizes (1 in. = 25.4 mm; 1 gph = 3.8 dm<sup>3</sup>/hr)

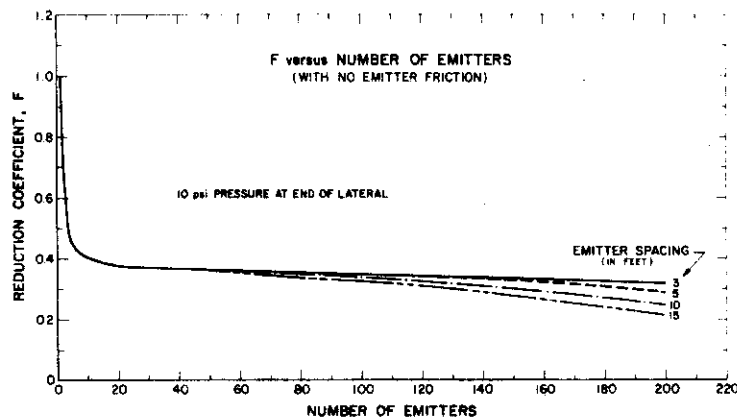


FIG. 7.— $F$  Values for Different Numbers of Emitters and Emitter Spacing (1 ft = 0.305 m) for Drip-Eze DH 1-580 Emitters (1 gph = 3.8 dm<sup>3</sup>/hr) and DH 580 Pipe [0.580 in. (14.73 mm) ID] with End Pressure of 10 psi (69 kN/m<sup>2</sup>) and No Emitter Friction

Fig. 5 shows  $LF/H_f$  versus  $N$  for various values of  $\bar{q}$  with  $D = 0.58$  in. (15 mm) and  $C = 130$ . Fig. 6 shows  $LF/H_f$  versus  $N$  for various values of  $D$  with  $\bar{q} = 1.0$  gph (3.8 dm<sup>3</sup>/hr) and  $C = 130$ . Substitution of  $L/S$  for  $N$  in Eq. 10 and solving for  $L$ , it follows that

$$L = 0.588 D^{1.708} F^{-0.351} H_f^{0.351} \left( \frac{60CS}{\bar{q}} \right)^{0.650} \dots \dots \dots (11)$$

in which  $S =$  the average emitter spacing, in feet (meters).

Assuming  $F$  is constant over a selected range of  $N$ , Eqs. 10 and 11 show that for level laterals the maximum lateral length for a selected uniformity is a linear (log-log) function of either  $N$  or  $S$ , respectively. The slope of this line is strictly a function of the flow rate exponent in the pipe friction equation.

If the elevation change is known, Eqs. 10 and 11 can be solved by using  $H_f$  determined by Eq. 4. Where the lateral slope,  $s$ , as a percentage, is known, the allowable pipe friction loss (Eq. 4) becomes

$$H_f = H_n - H_o + \frac{sL}{231} \dots \dots \dots (12)$$

If only the lateral slope is known,  $L$  can be determined by an iterative solution since two unknowns are then present in Eqs. 11 and 12. The solution generally converges well after three or four iterations. However, the emitter spacing,  $S$ , can be determined explicitly from Eqs. 11 and 12 as a function of  $L$ . The solution of  $L$  versus either  $N$  or  $S$  is not linear on a log-log scale if the lateral is not level.

The writers (5) presented computer-derived curves for  $F$  versus  $N$ . The value of  $F$  also depended upon emitter friction, emitter spacing, and downstream lateral pressure. Fig. 7 shows  $F$  versus  $N$  for selected emitter spacings with a downstream pressure of 10 psi (69 kN/m<sup>2</sup>) and no emitter friction.

**APPLICATION EXAMPLES**

**Example I.**—A trickle irrigation equipment manufacturer would like a graph or table of lateral lengths versus emitter spacing for two uniformity coefficients (95% and 90%) with  $q$  equal to 1 gph (3.8 dm<sup>3</sup>/hr) to distribute to dealers to assist them in lateral design. The emitter flow function is given as  $Q = 0.25H^{0.70}$ . The pipe size is a 0.622-in. (16-mm) ID polyethylene pipe with  $C = 130$ .

From Fig. 2,  $P = 9\%$  and  $17\%$  for 95% and 90% uniformity, respectively. From Fig. 3,  $H_f/H_n = 0.23$  and  $0.39$ , respectively. By Eq. 2,  $H_n = 8.20$  psi (57 kN/m<sup>2</sup>) and  $9.07$  psi (62.6 kN/m<sup>2</sup>), respectively. From Fig. 4, or by Eq. 8,  $\bar{q}/q_n = 0.88$  and  $0.79$ , respectively, and by Eq. 1,  $q_n = 1.09$  gph (4.1 dm<sup>3</sup>/hr) and  $1.17$  gph (4.5 dm<sup>3</sup>/hr), respectively. Therefore,  $H_f = 1.84$  psi (12.7 kN/m<sup>2</sup>) and  $3.20$  psi (22 kN/m<sup>2</sup>), respectively, while  $\bar{q} = 0.96$  gph (3.6 dm<sup>3</sup>/hr) and  $0.92$  gph (3.5 dm<sup>3</sup>/hr), respectively. From Fig. 7,  $F = 0.35$ . Eq. 11 can now be used directly with the respective data to calculate the lateral length versus emitter spacing for 95% and 90% uniformity. The results can be plotted on a log-log scale as shown in Fig. 8.

**Example II.** —A trickle irrigation lateral is to be designed for an orchard with

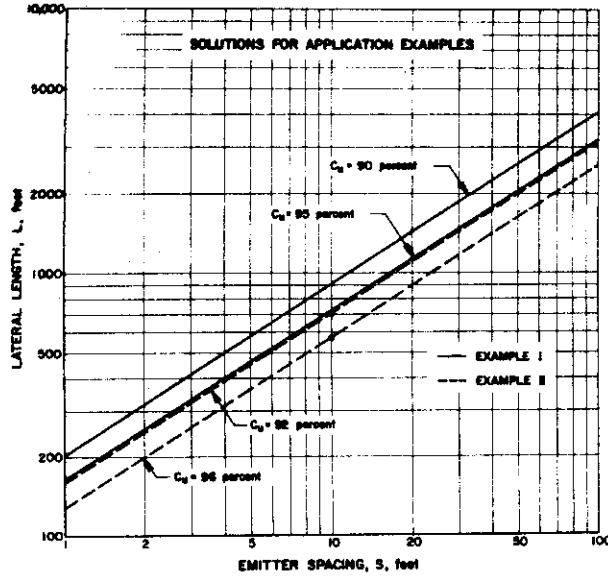


FIG. 8.—Solutions for Application Examples (1 ft = 0.305 m)

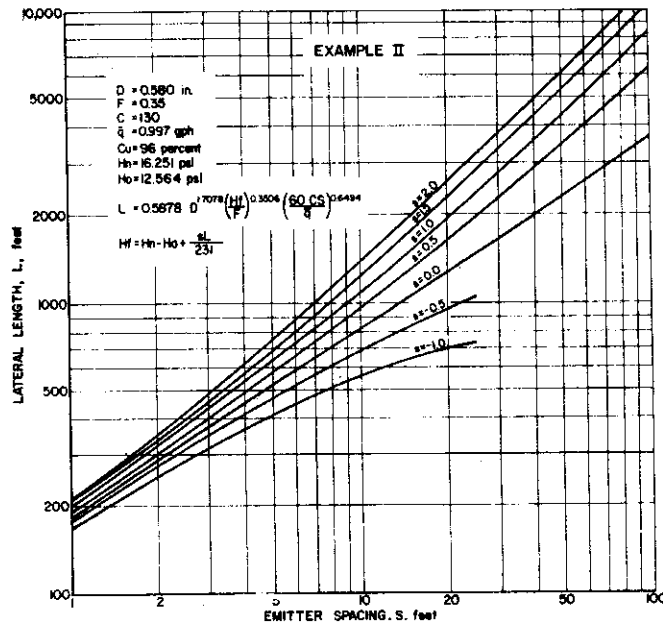


FIG. 9.—Solution for Application Example II for Various Up and Down-Hill Values of Land Slope at Various Emitter Spacings (1 ft = 0.305 m; 1 in. = 25.4 mm; 1 gph = 3.8 dm<sup>3</sup>/hr; 1 psi = 6.9 kN/m<sup>2</sup>)

700-ft (210-m) rows, a 10-ft (3.1-m) tree spacing, and an application rate of 1 gph (3.8 dm<sup>3</sup>/hr) per tree. The lateral must be laid uphill with a 5.5-ft [2.39-psi (16.5-kN/m<sup>2</sup>)] elevation change. The pipe size is a 0.58-in. (14.7-mm) ID polyethylene pipe ( $C = 130$ ) with emitters which have a flow function of  $q = 0.125 H^{0.78}$ . A lateral uniformity of 96% is desired.

From Fig. 2,  $P = 10\%$ , and by Eqs. 2 and 3,  $H_n$  and  $H_o = 16.25$  psi (112.1 kN/m<sup>2</sup>) and 12.56 psi (86.7 kN/m<sup>2</sup>), respectively. By Eq. 4,  $H_f = 1.31$  psi (9.0 kN/m<sup>2</sup>) since  $H_e = 2.38$  psi (16.5 kN/m<sup>2</sup>). By Eq. 6,  $\bar{H} = 14.08$  psi (97.1 kN/m<sup>2</sup>), by Eq. 1,  $\bar{q} = 0.99$  gph (3.8 dm<sup>3</sup>/hr), and from Fig. 7,  $F = 0.35$ .

By Eq. 11, the maximum allowable lateral length equals 553.6 ft (169 m). Since for the given pipe size and uniformity constraints the design lateral length of 700 ft (210 m) cannot be met, either the pipe size will have to be increased or the length divided into irrigation sets. The 700-ft (210-m) design lateral length can also be met by reducing the uniformity coefficient to 92%. Fig. 8 shows the results for this example. Fig. 9 shows this example solved for various up and down-hill land slope values and their effect on the solution for various emitter spacings.

#### SUMMARY AND CONCLUSIONS

Design equations are presented that allow the length of a trickle irrigation lateral to be designed to meet specific uniformity criteria. The emitter flow function (Eq. 1 or Fig. 1) is utilized to determine the allowable pressure loss to meet the uniformity standards. The emitter flow variation of the lateral (increase or decrease as compared to the design flow rate) is a function of the uniformity coefficient (Fig. 2). Thus, by knowing the emitter flow function, elevation change, and design uniformity, the allowable pipe friction loss can be computed by Eq. 4. Then taking the pipe size, pipe roughness coefficient (Hazen-Williams), reduction coefficient for dividing flow, average emitter flow rate, allowable pipe friction loss determined previously, and either the number of emitters per lateral,  $N$ , or the average emitter spacing,  $S$ , into account, the lateral length,  $L$ , can be determined by Eqs. 10 or 11, respectively. The solution for a given value of uniformity is a log-linear line (log  $N$  versus log  $L$  or log  $S$  versus log  $L$ ) with a slope that depends only on the flow rate exponent in the pipe friction loss equation for level laterals.

Design input data include the emitter flow function and reduction coefficient for dividing flow and emitter friction  $F$ . These data can be determined experimentally, obtained from manufacturers, or taken from existing literature. Keller and Karmeli (6) and the writers (5) presented information on the design input data.

Dimensionless graphs are presented that can assist in the design of trickle irrigation laterals. If inlet lateral pressure  $H_n$ , emitter flow rate exponent  $x$ , uniformity  $C_u$ , and reduction coefficient  $F$  are known, the dimensionless graphs can be used to determine the design lateral length as a function of the number of emitters per lateral.

Two application examples are given to demonstrate the design method. The method could possibly be simplified further into a design nomograph if desired. In addition this method could be applied to sprinkler irrigation laterals where

the only required input would be the sprinkler flow function.

#### ACKNOWLEDGMENT

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#### APPENDIX II.—NOTATION

The following symbols are used in this paper:

- $C$  = desired emitter flow rate, in gallons per hour (cubic decimeters per hour);
- $C_u$  = uniformity coefficient, as a percentage;
- $D$  = inside pipe diameter, in inches (millimeters);
- $F$  = reduction coefficient for dividing flow and emitter friction;
- $H$  = pressure, in pounds per square inch (kilonewtons per square meter);
- $\bar{H}$  = average pressure, in pounds per square inch (kilonewtons per square meter);
- $H_e$  = elevation pressure change, in pounds per square inch (kilonewtons per square meter);

- $H_f$  = allowable lateral friction pressure loss, in pounds per square inch (kilonewtons per square meter);
- $H_n$  = inlet pressure, in pounds per square inch (kilonewtons per square meter);
- $H_o$  = downstream pressure, in pounds per square inch (kilonewtons per square meter);
- $k$  = intercept of emitter flow function;
- $L$  = lateral length, in feet (meters);
- $N$  = number of emitters;
- $P$  = flow variation, as a percentage;
- $q$  = desired emitter flow rate, in gallons per hour (cubic decimeters per hour);
- $\bar{q}$  = average emitter flow rate, in gallons per hour (cubic decimeters per hour);
- $q_n$  = emitter flow rate at inlet, in gallons per hour (cubic decimeters per hour);
- $S$  = average emitter spacing, in feet (meters);
- $s$  = lateral slope, as a percentage; and
- $x$  = slope of emitter flow function.

APPENDIX F

Documentation for TRICKLE IRRIGATION LATERAL DESIGN Program

by

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This program will calculate the pressure and emitter flow rate distributions along a lateral as functions of beginning pressure (pressure at the distal end of the lateral), emitter spacing, slope, pipe size, and emitter characteristics. The program was written to aid in the hydraulic design of trickle irrigation laterals.

The program begins calculations at the downstream end of the lateral and approaches the mainline junction in incremental units of emitter spacing until the pressure drop exceeds the preselected maximum value. Figure 1 shows a flow chart for the program. Table 1 gives the input and output data list. Figure 2 shows the deck set-up and data input formats.

The program incorporates two main options:

OPTION (1) - This option is the selection of pipe friction loss equation. Either the Darcy equation utilizing friction factors for smooth pipe or the Hazen-Williams equation may be selected. However, in the laminar range the program uses the Darcy equation. The friction factor equations were taken from work by Wu and Fangmeier (1974).

Darcy Equation

$$H_f = f \frac{V^2 L}{2g D}$$

$$f = 64.4/R_n \text{ for } R_n < 2,000$$

$$f = 3.42 \times 10^{-5} R_n^{0.85} \text{ for } 2,000 \leq R_n \leq 4,000$$

$$f = 0.316 R_n^{-0.25} \text{ for } R_n > 4,000$$



Hazen-Williams Equation

$$H_f = 4.5512 LD^{-4.871} \left(\frac{Q}{C}\right)^{1.852}$$

where  $H_f$  = pipe friction in ft in Darcy equation and in psi in Hazen-Williams,

$f$  = Darcy friction factor,

$C$  = Hazen-Williams roughness coefficient,

$R_n$  = Reynolds number -  $VD/\nu$ ,

$g$  = acceleration of gravity = 32.2 ft/sec<sup>2</sup>,

$V$  = flow velocity in fps,

$L$  = pipe length in ft,

$D$  = inside pipe diameter in ft in Darcy equation and in. in Hazen-Williams, and

$Q$  = flow rate in gpm.

OPTION (2) - This option is for determining the emitter friction caused by water flowing through an in-line emitter. The option is whether to read in emitter friction data or to read in no data and consider the emitter as frictionless. If data is provided, the emitter friction is calculated by linear interpolation between flow rate and emitter friction loss. See the Drip-eze Tech Manual (1972) for an example of this type of data.

The program is designed for orchard applications with the emitter spacing determined by the tree spacing in ft (TSPACE), number of emitters per tree (EPERT), and the emitter spacing in ft if multiple emitters per tree are used. ESPACE is the minimum emitter spacing allowed; therefore

$$TSPACE - (EPERT - 1.0) (ESPACE) \geq ESPACE.$$

or the program will stop. Figure 3 shows an emitter spacing example.

The program uses an emitter flow function which is simply a log-log regression function as shown here

$$q = KH^x$$

where  $q$  = emitter flow rate in gph,

$K$  = value of  $q$  at  $H = 1$  psi,

$H$  = pressure in psi, and

$x$  = slope of the plot and is characterized by the emitter flow regime.

Figure 4 shows the emitter flow functions for three specific emitter types. Data for emitter flow functions are readily available from manufacturers or can be determined by laboratory measurements.

A single value of the field slope in the direction of the lateral is used to compute the head loss or gain caused by a change in elevation. A positive slope is taken as meaning that water is flowing downhill while a negative slope means that water is flowing uphill.

Two measures of flow uniformity are incorporated in the program. The emitter flow ratio ( $q_{\min}/q_{\max}$ ) of Zetsche and Newman (1968) and the uniformity coefficient of Christiansen (1942) are calculated in the program. For efficient lateral operation a coefficient of uniformity greater than 95 percent or an emitter flow ratio greater than 82 percent is recommended.

The program is written in a general nature and can accommodate any number of additional features which may be desired. With small modifications the program could be used to determine micro-tube lengths (Kenworthy, 1972), emitter or orifice sizes (Meyers and Bucks, 1972), or emitter spacings (Wilke, 1971) required to maintain even flow rates along the lateral. For a given set of design inputs, the program can be used to determine if the given pipe size will be adequate to limit the pressure loss and the flow variation along the lateral to limits acceptable for the design lateral length.

The following references may be helpful in understanding the program.

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61

/\*

BLANK (STOP CARD)

... DITTO ... (AS MANY AS NEEDED)

FLWTAB, EFTAB, FLWTAB, EFTAB, ETC. (NO FORMAT)

C	EMITK	EMITX	KFL*	KEFL*	NP* (3F10.4, 3I10)	*RIGHT JUSTIFY	
SHEAD	PIPE	TSPACE	EPERT	ESPACE	SLOPE	PDMAX	PRINT

TITLE (20A4)

//\$ DATA

DECK

C

/\*WATFIV

/\* PASSWORD

JOB

oS/360

JOB CARD

ATM

Figure 2. Deck Set-up.



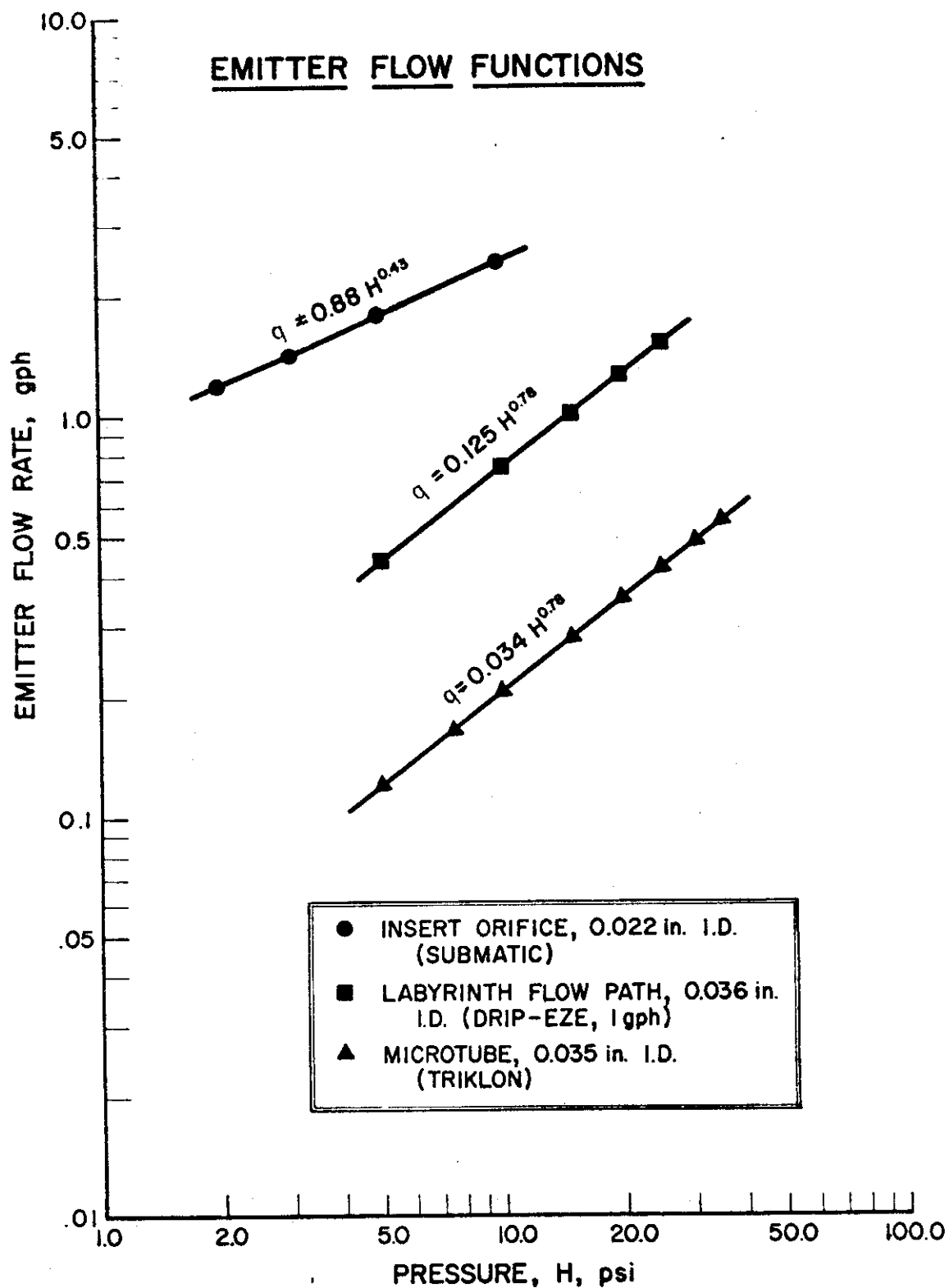


Figure 4. Emitter flow functions.

Table 1. Input and Output Data List

	<u>INPUT</u>
TITLE	Problem name,
SHEAD	Starting head in psi,
PIPE	Inside pipe diameter in inches,
TSPACE	Tree spacing in ft,
EPERT	Number of emitters per tree,
ESPACE	Emitter spacing in ft,
SLOPE	Lateral slope in percent,
PDMAX	Maximum allowable pressure drop in psi,
PRINT	Output interval in ft,
C	Hazen-Williams roughness coefficient,
EMITK	Intercept of emitter flow function in gph,
EMITX	Slope of emitter flow function,
KFL	Friction equation option,
KEFL	Emitter friction option,
NP	Number of data pairs for KEFL,
FLWTAB	Flow rate table in gph,
EFTAB	Emitter friction in psi.
	<u>OUTPUT</u>
DIST	Lateral length in ft,
RATIO	Minimum to maximum emitter flow ratio in percent,
CU	Uniformity coefficient in percent,
HEAD	Pressure in psi,
PDROP	Total pressure loss in psi,
FLOW	Total lateral flow rate in gph,
Q(I)	Emitter flow rate in gph,
RELEV	Elevation change in psi,
SUMHL	Pipe friction loss in psi,
SUMHF	Emitter friction loss in psi.



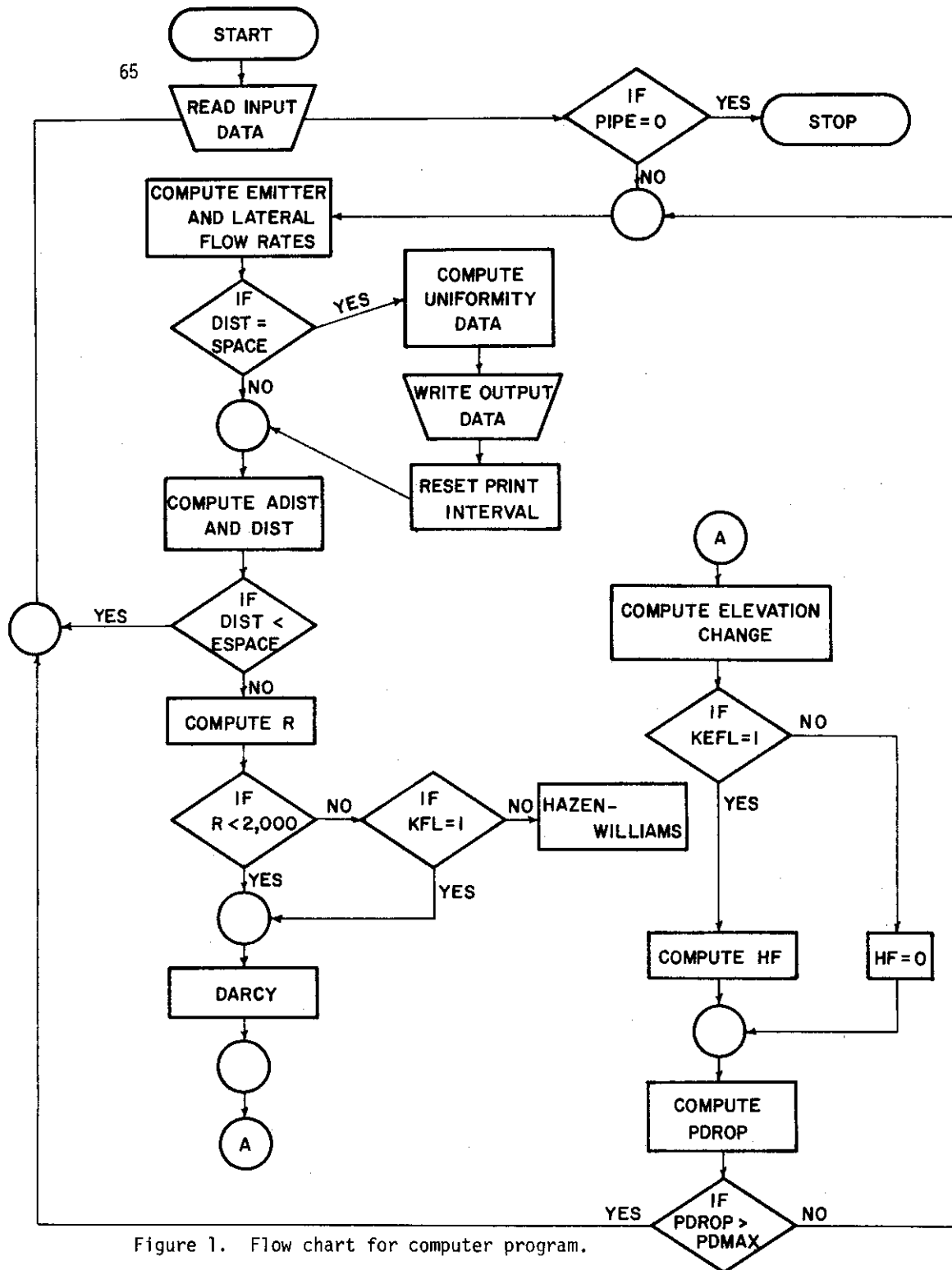


Figure 1. Flow chart for computer program.





```

C      *      FLWTAB = TABLE OF FLOW RATES
C      *      EFTAB = TABLE OF EMITTER FRICTION
C
C      READ, (FLWTAB(I), EFTAB(I), I=1, NP)
C      WRITE(6, 54)
54     FORMAT(/10X, 'FLOW RATE EMITTER FRICTION', /10X, ' GPH
1     PSI', /10X, 26(1H-))
C      WRITE(6, 112) (FLWTAB(I), EFTAB(I), I=1, NP)
112    FORMAT(13X, F4.0, 10X, F7.5)
56     CONTINUE
C      IF (PIPE.EQ.0.0) GO TO 101
C      WRITE(6, 20)
20     FORMAT(1H1, 9X, 'PIPE SIZE', 3X, 'STARTING HEAD', 3X, 'TREE SPACING',
3X, 'EMITTERS PER', 3X, 'EMITTER SPACING', 4X, 'SLOPE', /14X, 'IN',
10X, 'PSI', 14X, 'FT', 11X, 'TREE', 14X, 'FT', 10X, 'PER CENT', /10X,
84(1H-))
28     WRITE(6, 28) PIPE, HEAD, TSPACE, EPERT, ESPACE, SLOPE
C      FORMAT( //11X, F6.4, 9X, F5.2, 10X, F5.2, 9X, F5.2, 13X, F5.2, 9X, F5.2)
C ***** ZERO VARIABLES *****
C
C      Z = 1.0
C      ADIST = 0.0
C      DIST = 0.0
C      FLOW = 0.0
C      QMIN = 1.0
C      QMAX = 0.0
C      RELEV = 0.0
C      SUMHL = 0.0
C      SUMHF = 0.0
C      SPACE = 0.0
C      HF = 0.0
C      I = 1.
C      WRITE(6, 29)
29     FORMAT(//// 5X, 'DISTANCE', 3X, 'RATIO', 3X, 'UNIFORMITY', 3X, 'HEAD', 3X,
1 'PRESSURE DROP', 3X, 'FLOW', 3X, 'EMITTER FLOW', 3X, 'ELEVATION', 3X, 'PIP
2E FRICTION', 3X, 'EMITTER FRICTION' / 8X, 'FT', 28X, 'PSI', 9X, 'PSI', 8
3X, 'GPH', 9X, 'GPH', 10X, 'PSI', 11X, 'PSI', 12X, 'PSI', / 5X, 121(1H-))
C
C ***** SPECIFIC EMITTER FLOW FUNCTION *****
C
C      17 Q(I) = EMITK*HEAD**EMITX

```

```

3 IF(Q(I)-QMIN) 3,4,4
4 QMIN = Q(I)
5 IF(Q(I)-QMAX) 6,6,5
6 QMAX = Q(I)
AFLO = FLOW
6 FLOW = FLOW + Q(I)
C
C***** CALCULATE DISTANCE TO NEXT EMITTER *****
C
14 IF(DIST-SPACE) 14,15,15
999 IF(Z.EQ.EPERT) GO TO 40
IF(EPERT.EQ.1.0) DIST = DIST + TSPACE
IF(EPERT.EQ.1.0) ADIST = TSPACE
88 IF(EPERT.EQ.1.0) GO TO 41
DIST = DIST + ESPACE
ADIST = ESPACE
40 IF(Z.NE.EPERT) GO TO 41
DIST = DIST + (TSPACE - ((EPERT - 1.0)*ESPACE))
41 ADIST = TSPACE - ((EPERT - 1.0)*ESPACE)
Z = Z + 1.
IF(Z.EQ.EPERT + 1.0) Z = 1.0
C
C***** CALCULATE PIPE FRICTION LOSS *****
C
VEL = FLOW*0.00003713/(3.1416*PIPE*PIPE/144.0/4.0)
R = VEL*PIPE/12.0/0.00001
IF(R.LT.2000.0) GO TO 111
IF(R.GT.2000.0) GO TO 122
111 FACT=64.4/R
GO TO 115
122 IF(KFL.EQ.2) GO TO 22
IF (R-4000.0) 113,113,114
113 FACT=(0.0000342)*R**0.85
GO TO 115
114 FACT=0.316/R**0.25
115 CONTINUE
HLOSS = (FACT*ADIST*12.0/PIPE)*(VEL*VEL/64.4)*0.4335
SUMHL = SUMHL + HLOSS
GO TO 19
22 HLOSS = 4.5512*ADIST*(FLOW/60.0/C)**1.852/(PIPE**4.871)
SUMHL = SUMHL + HLOSS

```

```

C
C***** ELEVATION *****
C
19  ELEV = SLOPE*ADIST/100.0
    RELEV=RELEV-ELEV*0.4335
    HELEV=ELEV*0.4335
C
C*****   CALCULATE EMITTER FRICTION FROM INPUT DATA   *****
C
    IF(KEFL.EQ.2.0) GO TO 91
    CALL INTPL (AFLO,FLWTAB,EFTAB,HF,NP)
91  CONTINUE
    SUMHF = SUMHF + HF
C
C*****   PRESSURE DROP   *****
C
    HEAD=HEAD+HLOSS+HF-HELEV
    PDROP=HEAD-SHEAD
    IF(PDROP.GT.PDMAX) GO TO 99
    IF(PDROP.LT.PDMAX) GO TO 95
99  WRITE(6,98) PDMAX
98  FORMAT(/'/10X,'PRESSURE DROP IS GREATER THAN MAXIMUM ALLOWABLE',F5.
11,' PSI')
    IF(PDROP.GT.PDMAX) GO TO 100
95  CONTINUE
    I = I + 1.
    GO TO 17
C
C*****   CALCULATE EMITTER FLOW RATIO   *****
C
15  RATIO = (QMIN/QMAX)*100.0
    IF(DIST.EQ.0.0) GO TO 55
    GO TO 60
55  HLOSS=0.0
    PDROP=0.0
    F=1.0
    ELEV = 0.0

```

```

        DIST = 0.0
60 CONTINUE

C*****  CALCULATE EMITTER FLOW UNIFORMITY  *****
C
C      CALL UNFC(Q,I,CU)
C
C*****  WRITE OUTPUT DATA  *****
50  WRITE(6,50) DIST,RATIO, CU, HEAD, PDROP, FLOW, Q(I), RELEV, SUMHL, SUMHF
    FORMAT(7X,F5.0,5X,F5.1,5X,F5.1,5X,F5.2,8X,F5.2,5X,F6.2,7X,F5.2,7X,
    1F6.2,9X,F5.2,10X,F5.2)
    SPACE = SPACE + PRINT
    GO TO 14
100 CONTINUE
    GO TO 61
101 STOP
    END
    SUBROUTINE UNFC(X,N,CU)

C*****  CALCULATES THE UNIFORMITY COEFFICIENT  *****
C
C      DIMENSION X(N)
C      SUMX = 0.0
C      SUMXP = 0.0
C      DO 1010 I = 1,N
1010 SUMX = SUMX + X(I)
C      XBAR = SUMX/N
C      DO 1011 I = 1,N
1011 SUMXP = SUMXP + ABS(X(I)-XBAR)
C      XPBAR = SUMXP/N
C      CU = 100.0*(1.0-(XPBAR/XBAR))
C      RETURN
C      END
C      SUBROUTINE INTPL(X, ARG, VAL, Y, NDIM)
C      DIMENSION ARG(NDIM), VAL(NDIM)

C*****  CALCULATES THE LINEAR INTERPOLATED VALUE FROM TWO DATA SETS *
C

```

```
Y=VAL(I)
IF(X.LE.ARG(I)) GO TO 101
Y=VAL(NDIM)
IF(X.GE.ARG(NDIM)) GO TO 101
DO 10I=2,NDIM
N=I
IF(X.LT.ARG(I)) GO TO 50
IF(X.EQ.ARG(I)) GO TO 100
10 CONTINUE
50 Y=VAL(N-1)+ABS((X-ARG(N-1))/(ARG(N)-ARG(N-1)))*(VAL(N)-VAL(N-1))
GO TO 101
100 Y=VAL(I)
101 RETURN
END
```



APPENDIX G

# Trickle Irrigation with Water of Different Salinity Levels

W. J. Seifert, Jr., E. A. Hiler, T. A. Howell  
ASSOC. MEMBER    MEMBER    ASSOC. MEMBER  
ASAE                ASAE                ASAE

**I**N the world today the question of an adequate water supply to meet the present and future demands of irrigated agriculture is of utmost importance. With the increasing demand for American-grown food commodities, our water supply must be used judiciously. The use of irrigation water which is now considered of inferior quality for present irrigation methods would increase the supply of usable water.

Trickle irrigation has resulted in considerable increases in water use efficiency (yield per unit of water applied) over furrow and sprinkler irrigation (Cole 1971, Hiler and Howell 1973, Bernstein and Francois 1973, and Cho et al. 1974). Trickle irrigation research has been conducted irrigating sandy soils with water of marginal quality (Goldberg and Shmueli 1969, Bernstein and Francois 1973, and Cho and Yamamoto 1973). There is considerable potential for water and energy savings with trickle irrigation; also, the possibility exists for use of lower quality water which is generally considered unacceptable with conventional irrigation methods.

In an experiment conducted on sandy soil, Goldberg and Shmueli (1969) found that trickle irrigation with water of a high electrolyte concentration produced three salinity zones. The upper zone near the soil's surface had a high salt concentration that increased toward the soil surface and the trickle emitters. A broad intermediate zone had a low to moderate salt concentration, while the lower zone possessed an increasing salt concentration as the distance increased from the emitter.

Voth (1970) conducted an experi-

ment in which strawberries were grown using trickle and furrow irrigation. The irrigation water contained 1,000 to 1,100 ppm total dissolved solids. During the growing season, the electrical conductivity of the soil in the trickle irrigated beds decreased from 4.22 to 1.86 mmhos/cm, while the electrical conductivity of the furrow irrigated beds increased from 4.63 to 5.64 mmhos/cm. Composite soil samples from 0 to 15 cm deep were used for the electrical conductivity measurements. Total water application was 67 cm for the furrow irrigated plots compared to 29 cm for trickle irrigated plots.

Tscheschke (1973) irrigated tomatoes with water having an electrical conductivity of 5.5 mmhos/cm. The salinity level of the irrigation water was obtained by adding calcium chloride to tap water. The four irrigation treatments were: (a) at a level equal to the crop evapotranspiration (ET), (b) at a level 20 percent less than crop ET, (c) on alternate days at the crop ET level, and (d) on alternate days at 20 percent above the measured crop ET. Results indicated that by irrigating at a level 20 percent above the consumptive use, approximately 1/4 of the root zone was maintained at a soil water potential greater than -3 bars. This irrigation treatment provided the most desirable root zone water potential of the four treatments tested, particularly in cases where salt sensitive crops were trickle irrigated.

Bernstein and Francois (1973) compared trickle, furrow, and sprinkler irrigation of bell peppers in a small-plot study on a sandy loam soil using water having salt concentrations of 450 mg/l and 2450 mg/l water. Using the same amount of low-salinity water, the trickle-irrigated plots outyielded the furrow and sprinkler plots by 50 percent. High salinity water (2450 mg/l) resulted in only a 14 percent reduction in yield compared to low salinity water (450 mg/l) with trickle irrigation; 54 and 94 percent reductions resulted for furrow- and sprinkler-irrigated plots, respectively. When irrigation amount was con-

sidered as a variable, trickle irrigation required 1/3 less water than furrow irrigation for maximum yield.

Cho and Yamamoto (1973) studied effects of the trickle irrigation method on salinity damage of crops in a greenhouse experiment using a sand culture. By comparison with the sprinkler method using saline water, cotton yield was 50 percent higher with 6000-mg/l water and tomato yield was 7 percent higher with 4000-mg/l water. It was noted that salts concentrate and increase on the sand surface with sprinkler irrigation. With the trickle method, salinity decreased in the cones of wetting, but increased in the outer cones. To our knowledge, no research has been reported on effects of trickle irrigating with high-salinity water on medium- to heavy-textured soils.

The primary objective of this research was to determine the effects of three different concentrations of saline water on grain sorghum growth and yield and on the environment of a silt loam soil using trickle irrigation. An additional objective was to compare the effects of irrigation water at one electrolyte concentration on grain sorghum using both surface and trickle irrigation.

## PROCEDURE

This experiment was conducted during the growing seasons of 1972 and 1973. In mid-April of both years, grain sorghum (*Sorghum bicolor* (L.) Moench, cv. 'Oro') was planted in double rows 25 cm apart in lysimeters. Approximately 100 to 110 days after each planting, the mature grain was harvested.

Fifteen lysimeters were constructed by excavating five areas 330 cm x 110 cm x 61 cm. Each excavated area was divided into three sub-areas 110 cm x 110 cm with galvanized sheet metal used for the construction of all lysimeter walls. Norwood silt loam soil was placed in all lysimeters to a depth of 60 cm and to a uniform bulk density. The soil below 60 cm was the B-horizon of Lufkin fine sandy loam, which is a highly compacted, very slowly permeable clay. The effect of rainfall on the

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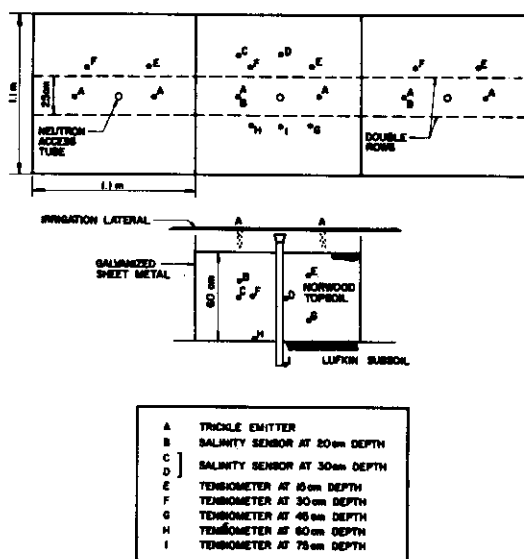


FIG. 1 Experimental layout of lysimeters.

experiment was eliminated by movable shelters which covered the lysimeters when actuated by rainfall. Details of the lysimeters and instrumentation locations are given in Fig. 1. The lysimeters were described in detail by Seifert (1973) with the lysimeter area and installation given by Hiler (1969).

Five treatments were used with three replications of each treatment. Treatment I was trickle irrigated with water having an electrolyte concentration of 800 ppm. Treatment II was trickle irrigated with water having an electrolyte concentration of 1,600 ppm. Treatment III was trickle irrigated with water having an electrolyte concentration of 2,400 ppm. The control, Treatment IV, was trickle irrigated with tap water having an electrolyte concentration of 450 ppm. Treatment V was surface irrigated with water having an electrolyte concentration of 1,600 ppm. This treatment was irrigated when the soil-water potential at a depth of 15 cm reached -0.7 bar in the amount of 1.1 times the measured soil-water losses in the 60-cm profile. Treatments I, II, III, and IV were trickle irrigated every Monday, Wednesday, and Friday during the growing season in the amount of 1.1 times the measured soil-water losses. Prescribed electrolyte concentrations were achieved in Treatments I, II, III, and V by adding NaCl, CaCl<sub>2</sub>, and MgSO<sub>4</sub> to tap water in proper proportions to obtain a sodium adsorption ratio (SAR) of 15. Treatment IV was irrigated with tap water having a SAR of approximately

40. The irrigation system had an application rate of 0.25 per hr and is similar to the system described by Hiler and Howell (1973).

A description of the meteorological instrumentation used in this experiment was given by Hiler and Howell (1973). Wind speed, dry-bulb temperature, wet-bulb temperature, dew-point temperature, incoming solar radiation, and net radiation were measured above the crop canopy. All of these measurements were recorded every 6 min on a 30-channel data acquisition system. The meteorological data were averaged over 30-min intervals to provide an estimate of potential evapotranspiration (Van Bavel 1966). Details of this aspect of the study are given by Seifert (1973).

Soil water losses were determined by the neutron method with measurements taken to a 60-cm depth at 15-cm intervals. Each lysimeter had an access tube extending to a depth of 65 cm. Gravimetric samples were taken to characterize water losses in the top 15 cm. The soil-water matric potential was measured at depths of 15, 30, and 60 cm with tensiometers located as shown in Fig. 1. In 1973, an additional tensiometer was placed at 75 cm to provide data for characterizing any downward water flux below the lysimeters. The tensiometers were serviced daily. The total soil-water potential was measured with soil psychrometers used in conjunction with a psychrometric microvolt meter, as described by Brown (1970).

Soil salinity was measured *in situ*

with soil salinity sensors and a salinity bridge using principles described by Richards (1966). In 1972 salinity sensors were buried between the double rows at a depth of 20 cm in the center lysimeter of each treatment and in one other lysimeter of each trickle treatment. A salinity sensor was also placed 30 cm laterally outward from the double row centerline at a depth of 30 cm in the center lysimeter of Treatments I, II, III. Locations of the salinity sensors used in 1973 are shown in Fig. 1. Salinity sensor readings were taken twice weekly during the two growing seasons.

Twice weekly, crop height was measured in each lysimeter. Leaf-area index, the ratio of the plant leaf area to its subtended land area, was determined twice a week during the early part of the growing season and then weekly the remainder of the season. Leaf area was determined by measuring leaf length and width and then multiplying their product by 0.7, an empirically determined constant (Van Bavel et al. 1971).

Leaf temperature was measured with an infrared radiometer. Leaf temperature readings were taken every afternoon at 1:00 P.M. CDT on four representative plants in each lysimeter. Leaf-water potential was measured by the pressure chamber method (Scholander et al. 1965). The pressure chamber method is a destructive technique; therefore, only one leaf from each lysimeter was taken at any sampling time. The leaf midrib was used to make leaf-water potential measurements and was found to provide reproducible results (De Roo 1969).

At the end of each summer growing season, grain sorghum yields were determined and adjusted to 14 percent moisture content (wet basis). Following the summer 1973 growing season, the plants were harvested and aboveground dry matter yield was determined for each lysimeter.

Each year after the crop was harvested a composite soil sample was taken in the plant root zone at a depth range of 15-30 cm in the center lysimeter of each treatment. To help determine the salinity pattern, soil samples were taken from 15 different locations in the center lysimeter of each treatment. Details concerning the soil salinity monitoring procedures are given by Seifert (1973).

## RESULTS AND DISCUSSION

At the beginning of the experiment in 1972, soil salinities in all treatments were nearly identical. Thus since the

**TABLE 1. GRAIN YIELDS, DRY MATTER PRODUCTION, WATER USE, AND WATER USE EFFICIENCIES.**

Treatment	Grain yield, kg/ha		1973 dry matter production, kg/ha	Water use†, cm		Water use efficiency‡, percent	
	1972	1973		1972	1973	1972	1973
I, Trickle, 800 ppm.	6994ab*	6808a	11 737a	42.6a	42.7bc	0.17a	0.16ab
II, Trickle, 1600 ppm.	7502a	6437ab	11 302ab	46.7a	36.2c	0.16a	0.18a
III, Trickle, 2400 ppm.	6946ab	4973d	7814c	47.0a	50.9a	0.15ab	0.10d
IV, Trickle, Tap Water	6431bc	5731bc	9367b	49.1a	46.1ab	0.13b	0.13c
V, Surface, 1600 ppm.	5786c	5350cd	8915bc	43.3a	37.8c	0.13b	0.14bc

\*Means followed by the same letter are not significantly different at the 0.05 level of significance, as determined by the Duncan multiple range test.

†Includes water applied plus use from storage.

‡Grain yield per unit of water use.

crop was past the critical seedling stage before major differences in soil salinity occurred, crop growth and yields were not greatly different between the treatments in 1972. Major differences did occur in 1973, however, following the variable salinity increases during the 1972 season. Treatments III (Trickle, 2400 ppm) and V (Surface, 1600 ppm) had to be replanted twice at the beginning of the 1973 season to obtain acceptable stands.

**Effects on Crop Growth and Yield**

Table 1 shows the grain yields for the 1972 and 1973 seasons and aboveground dry matter production for 1973. Statistical analyses indicated, in all cases, that the treatment effect was significant at the 0.05 level while the difference between replications was not significant. Grain yield and aboveground

dry matter production in Treatment III (Trickle, 2400 ppm) were reduced very substantially compared to Treatments I and II (Trickle, 800 and 1600 ppm). A comparison of Treatments II and V (Trickle, 1600 ppm, and Surface, 1600 ppm) indicates significantly higher yields were obtained in both 1972 and 1973 with trickle irrigation than with surface irrigation when using 1600 ppm water. This comparison was made to evaluate salinity effects when using "standard" management practices with the two irrigation methods; however, it is recognized that these yield differences are likely affected by the differences in irrigation frequency and matric potential at irrigation time. The reduced yield in Treatment IV (tap water) is not readily explainable; it could be due to fertility deficiencies although fertilizer was added using recommended rates and

procedures as determined by soil analyses prior to the beginning of each season. Because of the higher SAR of Treatment IV irrigation water, the reduced yield could be due to a Ca or Mg deficiency. Aboveground dry matter production and grain yield values followed remarkably similar patterns in 1973.

Water use and water use efficiency values are also given in Table 1. The water use efficiency results followed approximately the same pattern as the yield results. The high water use in 1973 in Treatment III cannot be explained unless there was deep seepage in this treatment. However, the tensiometer readings (Fig. 1) in conjunction with hydraulic conductivities of the surface layer and sublayer indicated negligible downward water flux in all treatments.

Crop growth during the season was characterized by crop height and leaf area index. Values of leaf area index for Treatments II, III, and IV for 1973 are shown in Fig. 2. Curves for Treatments I and V were similar to that shown for Treatment II. In general, leaf area index decreased with increasing electrolyte concentrations of the irrigation water. Crop height results followed a similar pattern with Treatment III (the shortest) being 10 to 25 cm shorter than Treatment I (the tallest) throughout the 1973 growing season. All treatments reached maximum crop heights at the end of the rapid vegetative growth stage. Differences in growth during 1972 followed similar patterns to those in 1973 but were not as pronounced (Seifert, 1973).

Leaf water potentials decreased (became more negative) in each treatment as the 1973 growing season progressed. The average leaf water potentials for each treatment during the 1973 growing season were as follows: I, -12.8 bars; II, -12.9 bars; III, -13.4 bars; IV, -12.3 bars;

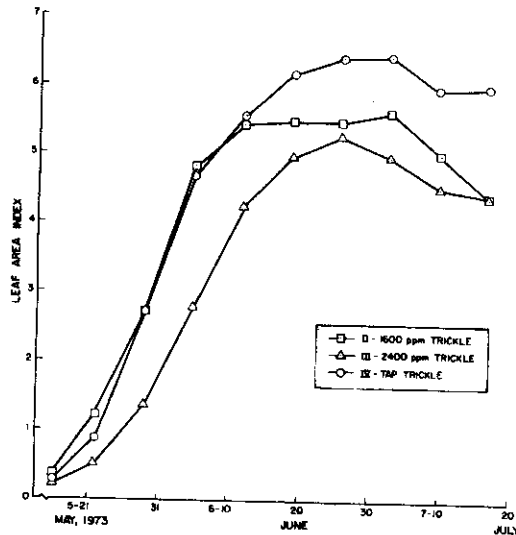


FIG. 2 Leaf area index values for three treatments during 1973.

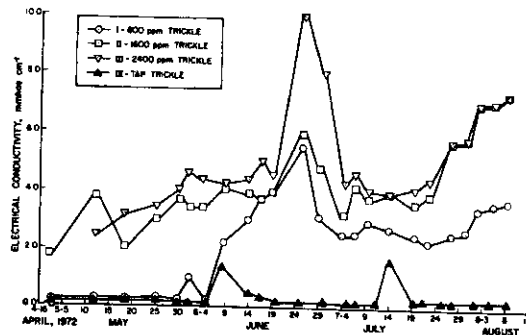


FIG. 3 Electrical conductivities at position B (midway between double row at 20-cm depth) throughout the 1972 growing season.

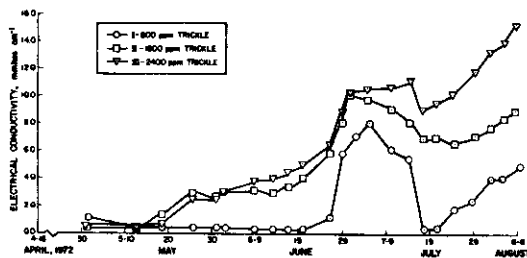


FIG. 4 Electrical conductivities at position C (30 cm outward from double-row centerline at 30 cm depth) throughout the 1972 growing season.

and V, -12.9 bars. As with leaf area index, the leaf water potentials decreased with increasing salinity level of the irrigation water. Leaf temperatures were similar in all treatments. Detailed data for the 1972 season for both leaf water potential and leaf temperature are given by Seifert (1973).

#### Effects on Soil Salinity

Soil salinity measured with *in situ* salinity sensors is given in Figs. 3 and 4 for the 1972 growing season and Figs. 5 and 6 for the 1973 season. Fig. 3 shows soil salinity for Treatments I, II, III, and IV in 1972 at Position B (Fig. 1) which is located immediately below a trickle emitter between the double rows at a depth of 20 cm. Fig. 4 shows soil salinity for Treatments I, II, and III in 1972 at Position C (Fig. 1) which is 30 cm deep and 30 cm laterally outward from the double row centerline. Figs. 5 and 6 show soil salinities at Position B and C for the 1973 season. These results indicated a direct relation between soil salinity and electrolyte concentration of the irrigation water, as would be expected. By comparing Figs. 3 and 5, it can be seen that the soil salinities were

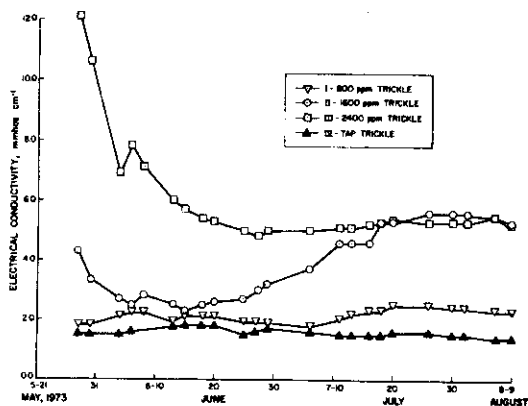


FIG. 6 Electrical conductivities at position C (30 cm outward from double-row centerline at 30 cm depth) during the 1973 season.

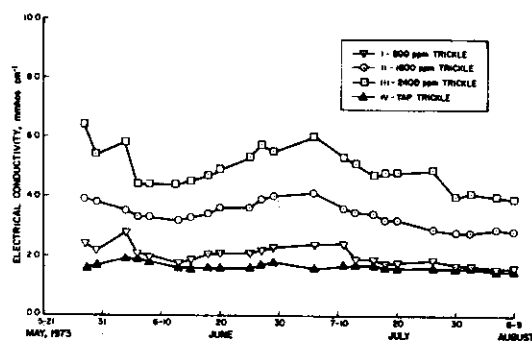


FIG. 5 Electrical conductivities at position B (midway between double row at 20 cm depth) during the 1973 season.

much higher in Treatment III at Position B early in the 1973 season than they were early in the 1972 season. This accounts for the difficulty in getting an acceptable stand in 1973 in Treatment III. Soil salinities in Treatment V (not shown) indicated very large fluctuations throughout 1972 and 1973 seasons but were generally higher at both Positions B and C than any of the trickle treatments (Seifert 1973). The sharp decline in soil salinity in Treatment III at Position C in 1973 (Fig. 6) was likely a re-

sult of movement of the wetting front beyond the salinity sensor thus leaching accumulated salts further away from the sensor.

Profiles of soil salinity based on saturation extract results are shown in Figs. 7 and 8. These measurements were made following the 1972 and 1973 growing seasons, respectively. In Treatment V, the soil in the lysimeters was bedded up and water was applied outside the double rows to simulate furrow irrigation. In Treatments I through IV,

Treatment I						
B		A		B		Surface
2.7 mmhos/cm	2.3	.8	3.4	7.4	7.5 cm	
3.1	1.0	.7	1.3	1.9	15 cm	
2.1	2.0	1.7	2.5	2.6	15 cm	
	15 cm		15 cm		15 cm	
Treatment II						
B		A		B		
1.8	2.8	2.4	2.9	4.2		
2.8	2.4	.7	2.7	1.8		
3.9	1.9	1.2	4.0	3.6		
Treatment III						
B		A		B		
6.8	2.8	1.5	1.6	2.3		
4.5	3.4	2.9	2.5	4.8		
5.0	5.0	1.4	4.2	6.7		
Treatment IV						
B		A		B		
1.2	.9	.9	1.0	1.5		
.7	.7	.7	.7	.9		
1.0	.7	.8	.7	.8		
Treatment V						
B		B		B		
1.7	1.6	2.1	1.9	1.2		
1.6	4.8	4.8	3.7	1.8		
1.9	2.9	4.4	3.6	3.2		

FIG. 7 Conductivity of saturation extracts of soil samples taken at the end of the 1972 growing season, with [A] emitter line and [B] plant row locations.

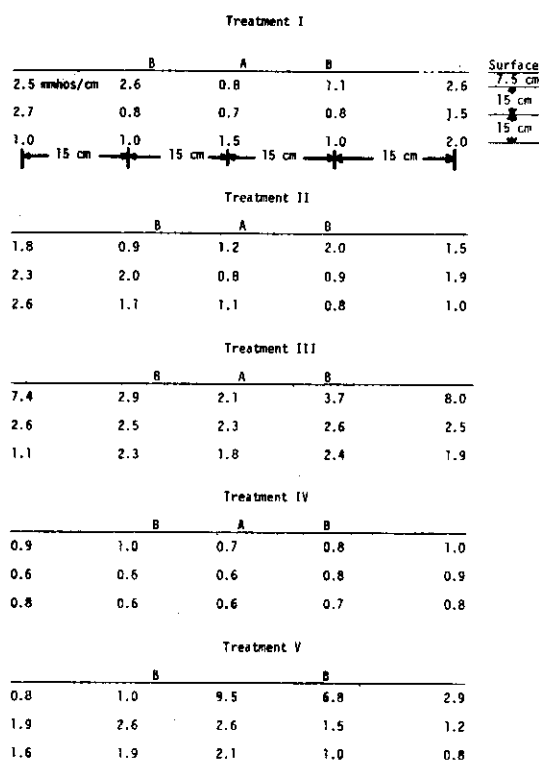


FIG. 8 Conductivity of saturation extracts of soil samples taken at the end of the 1973 growing season, with [A] emitter line and [B] plant row locations.

water was applied between the double rows as shown. By comparing Treatments II (trickle, 1600 ppm) and V (surface, 1600 ppm) at the end of both seasons, it can be seen that the area directly beneath and between the double rows had lower soil salinity for the trickle irrigated Treatment II than for the furrow irrigated Treatment V. In the trickle irrigated treatments, the salt was forced away from the crop root zone, while in the furrow irrigated treatment, salt was forced toward the crop root zone. Thus, based on these results, the

yield results shown in Table 1 for Treatments II and V are expected. In both Treatments III (trickle, 2400 ppm) and V (surface, 1600 ppm), it is seen that sizable increases in soil salinity occurred in the crop root zone.

Results of salinity analyses conducted on composite soil samples (15 to 30 cm depth) taken before and after harvest in 1972 and after harvest in 1973 are shown in Table 2. Most notable changes in soil chemistry from the beginning to the end of the experiment were increases in electrical conductivity,

sodium, chlorides, sulfates and sodium adsorption ratio. Treatments III and V indicated most pronounced increases in the zone from which these samples were taken. The ion concentration increases are expected because these ions were used in the makeup water.

#### SUMMARY AND CONCLUSIONS

Objectives of this study were (a) to determine effects of different concentrations of saline water on grain sorghum production and soil environment using trickle irrigation, and (b) to evaluate effects of irrigation water at one electrolyte concentration with both surface and trickle irrigation. The study was conducted in a sheltered lysimeter installation during two successive seasons. A Norwood silt loam soil was utilized in the lysimeters. Salts were purposely not leached between seasons so that salinity buildup effects could be evaluated. Numerous crop, soil and meteorological parameters were measured and evaluated to quantify effects of various treatments on the crop and soil.

Treatments I, II, III and IV were trickle irrigated thrice weekly to replenish water use with water having electrolyte concentrations of 800 ppm, 1600 ppm, 2400 ppm, and tap water at approximately 450 ppm, respectively. Treatment V was surface irrigated to replenish water use with 1600-ppm water when the soil matric potential reached -0.7 bar at 15.25 cm depth.

For the conditions of this study, the following conclusions are indicated:

1 With trickle irrigation, significant reductions in growth, yield, dry matter production, and water use efficiency occurred in Treatment III (2400 ppm) compared to Treatments I (800 ppm) and II (1600 ppm) during the second season;

2 When using 1600-ppm water, the trickle-irrigated Treatment II resulted in

TABLE 2. SOIL SALINITY RESULTS BEFORE PLANTING, 1972. AFTER HARVEST, 1972 AND AFTER HARVEST, 1973.

Sampling date	Treatment	pH	EC x 10 <sup>3</sup>	Cations - meq/l				Anions - meq/l				Sodium adsorption ratio
				Ca	Mg	K	Na	CO <sub>3</sub>	HCO <sub>3</sub>	SO <sub>4</sub>	Cl	
3-31-72	Composite of all treatments	8.2	0.70	4.45	0.65	0.18	1.45	-	2.91	0.54	2.06	0.91
8-09-72	I	8.4	2.81	5.18	0.66	0.33	22.5	0.78	3.11	5.90	19.94	13.21
8-09-72	II	8.7	3.26	3.11	0.20	0.53	30.9	1.94	5.83	6.83	20.48	24.02
8-09-72	III	8.3	3.61	4.14	0.24	0.21	32.1	0.78	3.50	7.42	24.98	21.64
8-09-72	IV	8.6	0.96	1.71	0.18	0.16	7.7	0.31	3.89	1.45	4.90	7.92
8-09-72	V	8.5	1.68	2.18	0.25	0.16	13.6	0.31	3.11	1.18	11.57	12.34
9-11-73	I	8.4	1.68	1.66	0.40	0.15	16.10	1.25	5.99	2.87	7.99	15.86
9-11-73	II	8.3	1.55	1.38	0.01	0.10	14.90	-	5.80	2.15	8.92	17.88
9-11-73	III	8.4	2.81	2.65	0.69	0.15	26.00	2.50	4.62	3.66	17.07	20.12
9-11-73	IV	8.6	1.12	1.77	0.29	0.14	11.00	2.50	5.55	2.15	4.66	10.84
9-11-73	V	7.8	6.12	21.57	2.33	0.55	46.60	-	5.93	21.19	31.82	13.48

significantly higher yields, dry matter production and water use efficiencies than the surface-irrigated Treatment V; it should be noted that this is a comparison of systems (application method plus management practice), not application method alone;

3 Replanting was necessary to achieve acceptable stands in Treatments III (Trickle, 2400 ppm) and V (Surface, 1600 ppm) during the second season; this indicates the need for leaching prior to next planting when using high-salinity water; the reduced seedling vigor in Treatments III and V was likely a major cause for the results indicated in 1. and 2.;

4 Plant growth, dry matter production, and average leaf water potentials decreased with increasing electrolyte concentration of the irrigation water; and

5 For 1600-ppm irrigation water, the soil directly beneath and between the double rows had lower salinity levels (based on saturation-extract conductivities) for the trickle-irrigated treatment (II) than for the surface-irrigated treatment (V).

More research is needed in the area of trickle irrigation with high-salinity water. Consideration of irrigation amount as a variable (in addition to salinity level) is a logical next step. Also work is needed to ascertain practical leaching approaches when trickle irrigating with high-salinity water.

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