This is to certify that the

dissertation entitled

Characterizing Irrigation Environmental Efficiency
Based on Distribution Uniformity
and Irrigation Management

presented by

Neba M. Ambe

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Agricultural Technology and Systems Management

Major professor

Date 2-2-96

# CHARACTERIZING IRRIGATION ENVIRONMENTAL EFFICIENCY BASED ON DISTRIBUTION UNIFORMITY AND IRRIGATION MANAGEMENT

By

Neba M. AMBE

A DISSERTATION

*Submitted to*
*Michigan State University*
*in partial fulfilment of the requirements*
*for the degree of*

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

1995

UMI Number: 9631224

# ABSTRACT

## CHARACTERIZING IRRIGATION ENVIRONMENTAL EFFICIENCY BASED ON DISTRIBUTION UNIFORMITY AND IRRIGATION MANAGEMENT

By

Neba M. AMBE

Managing irrigation systems in an environmentally sound manner is a major challenge to irrigation mangers. Two common performance measures are often used: statistical uniformity - a measure of variation in the system's applied water. and application efficiency - a management parameter which is indicative of how much of the applied water is in the root zone. Both system performance and management strategies have an impact on the irrigated farm's environment. but neither of these measures quantifies that impact. This study was undertaken to answer the following research questions. Can an environmental efficiency performance measure for irrigation management be formulated? How does application efficiency (AE) vary with the application depth under an imposed areal distribution?

A definition of irrigation environmental efficiency is proposed. An equation for determining its variance was formulated using system science and the propagation of error theories. Irrigation data from center pivot irrigation systems with statistical uniformities from 40 to 98% were simulated using mean and standard deviations from data in the literature and actual data from St. Joseph County. MI. Application efficiencies for selected depths (0.4 to 1.2 of the average applied depth) and statistical distributions were determined

for each system. The results were then used to determine irrigation environmental efficiency.

The results show that: 1) the statistical distribution of application efficiency for various minimum application ratios (MAR - required depth divided by the mean applied depth) can be described by a family of curves whose slopes slightly increase with the statistical uniformity of the system: 2) application efficiency increases with MAR: the increasing rates are a function of the system uniformity; and 3) irrigation environmental efficiency ($E_{IE}$) is a function of the irrigation system and management.

Regression equations relating application efficiency to the minimum application ratio, charts that relate irrigation environmental efficiency to application efficiency, statistical uniformity, and the fractional area fully irrigated are presented. $E_{IE}$ has been used to show and compare the statistical distribution of various center pivot systems, from two geographical regions in the United States, and to evaluate five Michigan farms using data from actual irrigation schedules.

## DEDICATION

*To*
*my family members*
*Living and Dead*

and

*To all*
*who seek protection*
*of the environment.*

## ACKNOWLEDGMENTS

*My indebted thanks to my program directors: Professor V. F. Bralts for conceiving this research idea. his motivation and encouragement to undertake this project. and Professor R. D. von Bernuth for his insight and guidance in the course of this study. Their careful direction and supervision led to the timely completion of this work. Special thanks to Professors T. H. Burkhardt. E. Dersch and W. H. Shayya for serving as members of my advisory committee. Their individual and collective inputs led to the integrated approach taken in this study.*

*I express gratitude to John Barkley and Tim Russet of the National Resources Conservation Service. St. Joseph County. MI for their time. effort and assistance in locating the necessary data for this project. Sincere thanks go to Dr. A. Go. Ms. L. Arganian and P. Gardner for providing the necessary assistance and a hospitable atmosphere in accomplishing this task.*

*Acclaim and benediction to my mother. Lum Regina and grandmother. Nchang Monica on whose farms I developed an interest in agricultural science. and above all for providing me the education they never got. My heartfelt gratitude to all my family who have always been supportive of my educational goals and despite the long years of absence never gave up. Although all of them have not lived to see the end result. their images remain fresh in my mind as I write these lines.*

*And finally I owe a significant debt to my Lansing-Cameroon family and all my friends for their moral. spiritual and material support. The list is quite a long one. so omission of any names is unintentional.*

# PREFACE

My love and curiosity for the agricultural sciences came from assisting my mother and grandmother with routine farm activities. Interest in agricultural research must have begun when I asked my grandmother, out of frustration from the tedious labor, if there was a less tiring and time saving means of planting corn. Over the years, and drawing from my association with the farm and its produce, I have come to realize that a farm is not just part of the soil or *dirt*, that a farmer is not just one who sows seeds, and that plants don't grow just because a seed is sown. There is a complex mutual association of these entities, perhaps not realized or understood by many. How this symbiotic relationship can be maintained provided an interesting deliberation and has been the mental requirement to pursue the work reported in these leaves.

This work is the child of a casual conversation with Professor Bralts who emphatically said: *I believe distribution efficiency and application efficiency can be combined to get environmental efficiency, and somebody ought to do it*. At first I found no interest in the subject and he might have given up trying to convince me. An absurdity, it sounded to me, primarily because I thought that was too abstract, far from reality and therefore a difficult goal to pursue. But in the deep belief of my personal philosophy - nothing without hands can challenge a human being with hands and a brain - I decided to take on the task. What at first sounded abstract and undoable has materialized into a dissertation, presented here in six sections.

The first section contains introductory information on the nature, problem, scope and objectives of the research. Section II contains the relevant literature reviewed. It covers a historical perspective of the relationship between irrigation management and the environment, the application of systems theory to irrigation management; and a discussion of the various irrigation performance measures in current use.

Research procedures, results and discussion are presented in section III. These are reported as two independent papers in conformity with the publishing format of the *Transactions of the ASAE* scientific journal. Each paper contains an abstract, specific objectives, investigation procedure, results, discussion and conclusion.

Section IV is a general conclusion on the nature of the research findings, application and relation to past works. Recommendations based on the experience and results from this work are presented in section V. Unless indicated as a footnote, full citations on all referenced works in the text are given in Section VI - References. Finally, details of material that could not be included in the text can be found in the Appendices.

*Neba M. AMBE*
*1 December 1995*
*Michigan State University*

## TABLE OF CONTENTS


LIST OF TABLES .......... x

LIST OF FIGURES .......... xi

**I. Introduction** .......... 1

A. Problem statement .......... 3

B. Scope and objectives .......... 4

**II. Literature Review** .......... 5

A. Irrigation management and the environment .......... 5

1. Historical systems .......... 5

2. Irrigation disasters: lessons from the past .......... 6

3. Irrigation and resource development .......... 8

B. Systems theory and irrigation management .......... 9

1. System concepts .......... 10

2. Systems theory and approach .......... 11

3. Rationale for application to irrigation management .......... 19

4. Application to irrigation management .......... 20

C. Irrigation performance measures .......... 21

1. Irrigation uniformity .......... 22

2. Irrigation efficiency .......... 29

D. Summary and discussion .......... 40

**III. Research Procedure, Results and Discussion** .................................. 42
A. Estimating irrigation application efficiency and its statistical distribution ........ 43
1. Abstract ................................................ 43
2. Introduction ............................................ 43
3. Theoretical development .................................. 45
4. Procedure ............................................... 47
5. Results and discussion ..................................... 50
6. Conclusions ............................................. 61
B. An environmental efficiency performance measure for irrigation management .... 62
1. Abstract ................................................ 62
2. Introduction ............................................ 62
3. Theoretical development .................................. 65
4. Procedures ............................................. 70
5. Results and discussion ..................................... 72
6. Conclusions ............................................. 82

**IV. General Conclusion** ............................................ 83

**V. Recommendations** ............................................ 85

**VI. References** ................................................ 87

**Appendices** ................................................... 95
Appendix 1. QuickBasic Program Listing ............................ 95
Appendix 2. Detailed Program Output ............................... 98
Appendix 3. Regression Coefficients ............................... 102
Appendix 4. SCS-Scheduler Output: Soil Water Content ............... 103
Appendix 5. Center Pivot Evaluation Data for St. Joseph, MI ............ 108

## List of Tables


Table 1. Definitions of efficiency ........ 30
Table 2. Selected data from Heermann et al. (1992). ........ 48
Table 3. An example of a generated matrix from equation [26] ........ 49
Table 4. Validity of AE results from the procedure of Equation [25] ........ 51
Table 5. Irrigation measures and suggested $E_{IE}$ classification values. ........ 77

## List of Figures


Figure 1. Systems approach to problem solving (adapted from Manetsch and Park, 1993) ... 12

Figure 2. System modeling procedure (adapted from Manetsch and Park, 1993) .......... 16

Figure 3. Natural resource system .......... 20

Figure 4. Application efficiency definition sketch .......... 32

Figure 5. Infiltrated soil water variability .......... 46

Figure 6. AE frequency distributions for selected systems .......... 52

Figure 7. Cumulative frequency distributions from Figure 6 .......... 53

Figure 8. Application efficiency as a function of MAR and $U_S$ .......... 55

Figure 9. Relating application uniformity to application efficiency and leached fraction .... 57

Figure 10. Relationship between AE, $U_S$ and fully irrigated area .......... 58

Figure 11. Estimating application uniformity from AE and $U_S$ for an example problem ..... 60

Figure 12. Estimating the fractional area adequately irrigated for an example problem ..... 60

Figure 13. Bridging the gap between the physical and management aspects of irrigation .... 63

Figure 14. Irrigation environmental efficiency related to MAR, $U_S$ and AE .......... 73

Figure 15. Irrigation environmental efficiency related to MAR, $U_S$ and irrigated area ....... 74

Figure 16. Estimating $E_{IE}$ from AE, $U_S$ and MAR for two example problems .......... 76

Figure 17. Estimating $E_{IE}$ fractional area adequately irrigated, MAR and $U_S$ for two example problems .......... 76

Figure 18. $E_{IE}$ distribution of center pivot systems from Michigan and Colorado .......... 78

Figure 19. Seasonal variation of $E_{IE}$ for selected Michigan farms .......... 80

# I. Introduction

*If I were a tree among trees, a cat among animals,*
*... this problem would not arise.*[1]
*- Albert Camus -*

*A river flowed from Eden to water the garden*[2]. ... Generations have, and will continue to depend on water. Throughout the entire history of the human race, irrigation - the artificial supply of water to meet plant needs - has always been indispensable to agriculture. Irrigation is one of the basic measures for raising world agricultural production. FAO predicts 300 million hectares of land will be under irrigation by 2000. The principal objective of irrigation is to adequately and efficiently fill the root zone with required soil water using either subsurface, surface, sprinkler or drip method. The driving force behind the development of each system or a shift from one system to another is the desire for more efficient water use, higher economic returns and environmental protection. Efficiency depends on several factors including distribution uniformity of the applied water, irrigation scheduling and plant-soil-water relations.

Irrigation managers and farmers are concerned with the system's efficiency throughout the growing season. An ideal system would be 100% efficient. Unfortunately each irrigation system poses some degree of non-uniformity which can be attributed to system

---

[1] An absurd reasoning. *The Myth of Sisyphus*, p. 38, 1955.

[2] *The river split into four streams, two of which are the familiar Tigris and Euphrates (Genesis, 2:10, 14).*

design and operation, soil properties and climatic factors. The result is the coexistence of under- and over-irrigated spots in the same field. Under-irrigation results in yield losses. Over-irrigation produces deep percolation losses of water and plant nutrients. Percolated nutrients pose an environmental hazard, in addition to increased cost of pumping excess water. The farmer is often forced to make trade offs between conflicting environmental and economic goals.

The climate of an area determines the amount of precipitation, which in turn affects the amount of irrigation water to meet plant needs. Topography and soil type dictate the irrigation method selected. Economic conditions specify the complexity of the irrigation system and affect its distribution uniformity. Socio-economic (and most recently environmental) conditions bias the farmers' goals, decisions and consequently management practices. These in turn affect the efficiency and economic outcome of the system. Environmental pollution may be a consequence of the overall system efficiency.

The above describes a closed system in which energy and material flow to and fro. From the law of conservation of flow, every system with input has an output: desired and undesired. Too often we have focused on the desired outputs with little or no attention to the undesired ones. Agricultural production inevitably depletes resources and may pollute the environment. In analyzing system profits, the undesired output that ends up in the environment is given zero dollar value and the long term effects are ignored. This is because external accountability across the system boundary is limited to those outputs that bring income. We know, for example, how much corn leaves the farm, its net returns and where it goes. However, the quantity of leached nitrates (e.g. 120 kg per hectare; Martin, 1992) or the amounts of soil loss from erosion are rarely considered. Vital questions are often ignored. What is the cost of cleaning up? What are the long term ramifications, and how long will it take before we see these effects? There is an urgent need to pay attention to system outputs that end up in the environment.

The ever increasing demand for water and the continuous depletion and pollution of resources clearly suggests the need for greater stewardship. *Agriculture must move toward more efficient, productive and environmentally sound practices.* The work described here examines how improved irrigation management can help assure an agricultural system that is economically and environmentally sustainable.

### A. Problem statement

Application efficiency is indicative of how the system is managed while distribution uniformity is used to evaluate system performance. Both an irrigator's management practices and the performance of an irrigation system can have a significant impact on the environment. For a given efficient management practice and system performance, can the potential effect of their combined output to the environment be characterized? No. As of now, there is no performance measure for the potential of environmental degradation resulting from the combined performance and management of an irrigation system.

**B. Scope and objectives**

The work reported here contains a literature review with respect to irrigation management and the environment, systems theory and irrigation management, and irrigation performance measures, and research findings on methods of estimating application and environmental efficiency in irrigation management. Use is made of the integrated concept of the soil-plant-water-management system in which irrigation performance measures, systems theory and statistical concepts are used to develop an index for characterizing the potential environmental effects of irrigation management. The concept of irrigation environmental efficiency is proposed and applied to selected irrigation systems.

The overall goal of this research is to develop a performance measure for environmental efficiency of irrigation management practices. The following are the specific objectives:

1. To assess the statistical distribution of application efficiency.
2. To develop an environmental performance measure for irrigation systems.
3. To evaluate selected center pivot systems and some Michigan irrigated farms using the new parameter.

# II. Literature Review

*Irrigation, of necessity, involves a trade-off between production, and some environmental value; ... irrigation is a social contract to sacrifice some environmental values ...*[1]
*- Jan van Schilfgaarde -*

## A. Irrigation management and the environment

### 1. Historical systems

Irrigation is one of the oldest agricultural practices in the world. Its origin can be traced to that of the human race (Genesis, 2:10). Irrigation has been practiced on the banks and delta of the river Nile for about 8000 years - making it the longest period of continuous large scale irrigation (van Schilfgaarde, 1994). Historical accounts reviewed by Jensen (1980) indicate technological developments in irrigation agriculture on the river Nile about 6,000 B.C., drained canals in Mesopotamia in 4,000 B.C. and the use of flooding waters on the Indus river about 2,500 B.C. Irrigation practices were in place along the Yellow river in 2,627 B.C. and in Peru about 1,000 B.C.

The dependence of early civilizations on irrigation earned them the name *hydraulic societies* (James et al., 1982). These societies with government directed water control originated in the Near East, Egypt and Mesopotamia thousands of years before the Christian era and continued in India, Persia, Central Asia, parts of Southeast Asia and ancient Hawaii (Kappel, 1974). Such societies in the Western Hemisphere, Kappel continues, flourished

[1] Water management in semiarid environments. *Journal of Soil & Water* Conservation, 50(5):420-421, 1995.

in Andean Zone, Mesoamerica (region of the Lake Mexico), Southwestern United States in Arizona and New Mexico among the Pueblo Indians prior to the Spanish conquest. Remains of ancient canals are still evident on both sides of the Salt River, Arizona (Taylor and Ashcroft, 1972).

Ancient irrigation systems required highly organized societies to maintain them. Sri Lanka (Ceylon) at the turn of the century had irrigation structures as old as 2,500 years. In the last 900 years the government built 1,420 new tanks (dams) and 534 canals; at the same time 2,355 tanks and 3,621 canals were repaired (James et al., 1982).

It has often been debated and is still unclear whether social institutions brought about irrigation or irrigation established them (Adams, 1974; James et al., 1982; Kappel, 1974). It is believed that the Sumerian Empire, whose bread basket was Mesopotamia, perished because of the collapse of the irrigation system; one school of thought has it that the irrigation system collapsed because of a detoriation in the empire's social structure (van Schilfgaarde, 1994). One thing is clear: societies have disappeared and ecological disasters have taken a toll when irrigation systems failed.

## 2. Irrigation disasters: lessons from the past

The history of civilization contains a litany of self-destructive irrigation developments. Failure of the Syrian and Babylonian societies of the Near East and North Africa (Carthage) were attributed to waterlogging and a rise in the soil water table in irrigated lands (Taylor and Ashcroft, 1972). Salt deposition in the root zone resulted to poor or no crop growth.

Seeped waters from earthen canals into adjacent lands, waterlogged lands and annual malaria epidemics in the Middle East are all examples of human misery blamed on poorly planned and managed systems (Gulhati and Smith, 1967). A change in irrigation practices following the construction of the Aswan Dam in Egypt caused waterlogging of the Nile Delta leading to the 1902 cotton crop failure. In Pakistan, it took 568 tube wells, 2,370 wells and 1.790 kilometers of installed drains to reclaim 1,040,000 ha of land. Prior to this initiative, an estimated 20,000 to 40,000 hectares went out of production annually as a result of salinity and water logging (White House, 1964; Cantor, 1970).

Within a few decades of irrigation in the San Joaquin and Imperial valleys (California) 121,000 hectares of land became unproductive. Salt accumulation was to blame (Harris, 1920). Other areas included the Great Basin, Colorado, Rio Grande River and Columbia River basins. Taylor and Aschroft (1972) cited increased salinity, low permeability (infiltration) rates and soil structure deterioration in the Salt River Valley of Arizona as an ancient evidence of unsatisfactory methods of water application.

The few cited examples clearly portray what can go wrong with poorly managed systems. The Punjab irrigation system (Falcon and Gotsch, 1971) where poor management led to increased soil salinity stands out as one of the modern examples. In Idaho, Carter (1980) estimated the total quantity of salt leached from a five meter deep Portneuf silt loam at 70 metric tons/ha; the first 14 cm of water passing out of the bottom of the soil carried 38 metric tons/ha of soluble salt into ground water over a two year period. Concern for the environment has prompted van Schilfgaarde (1994) a prominent irrigation scientist to write:

> *Irrigation has made major contributions in the past, continuing through this day, to feeding the world and to rationalizing the use of limited natural resources for the common wealth: but in the process, warts have arisen and inequities have appeared*

*and unneeded insults to the environment havz occurred.*

Every rose has a thorn, but the careful harvester never gets hurt. Irrigation should and ought not to be self destructive. Society's inability to control management practices can render irrigation systems destructive.

### 3. Irrigation and resource development

Irrigation relates to water resource development. James et al. (1982) have noted that "rarely is one farm an independent unit of irrigation" since bringing water to the farm and/or draining the excess from the farm requires cooperation that begins with the farmer, community and then extends to the river basin. Depending on the size and location of the irrigated area, this can extend to national and international levels. Examples include the Colorado River flowing through a vast irrigated land in the United States into Mexico and the Nile river rising from Ethiopia through Sudan and Egypt.

In a given irrigation system, withdrawal rates that exceed recharge rates, according to Hillel (1987), eventually deplete the source and even deprive the crop of water when it is in most need. An irrigation system without proper drainage may become unsustainable. Excess drainage is a potential environmental hazard. Consequently, proper irrigation control should begin at the source: groundwater, river or lake.

Irrigation is an integral part of resource development and it is a human exercise and social endeavor (in communal systems) rather than an academic exercise. Hillel (1987) in this regard considers irrigation projects as a place for a community of people to work together while leading healthy and harmonious lives. This requires designing a system beyond the purpose of crop production; it takes food and a clean environment to live a healthy life.

Human beings, with their intelligence, creativity and initiative, are an important resource in development. Hillel (1987) notes with regret that irrigation managers in communal systems tend to be authoritative, and often neglect the real players of the game. Most systems in North Africa and Asia are designed and operated by engineers for the convenience of engineers with limited attention to the needs and desires of the farmers (van Schilfgaarde, 1994). The same can be said of the economic and agronomic aspects of irrigation management. An essential resource is wasted if humans are deprived of the ability to use their senses in their work. Hillel points out that people tend to cherish, and are more careful with the products of their initiatives or where they are participants.

## B. Systems theory and irrigation management

Irrigation is not an end in itself; it needs coordinated management of economic and environmental problems. The complexity of the irrigation-farm-environment system, in addition to uncertainties in a political and socio-economic situation call for a systems theory application to irrigation management. Systems theory and analysis have been used extensively in the physical sciences; its application in agriculture, particularly irrigation, is a new and rapidly developing investigative tool (ICID, 1980; Carruthers and Clark, 1981; Holy, 1981).

**1. System concepts**

A system is a hierarchical structure with a defined boundary consisting of inter-related components (single functioning units) that act together to achieve a specified objective (Ogata, 1978). Its overall behavior is influenced by changes in any system component. The boundary can either be natural or artificially fixed by the investigator in conformity with system objectives (ICID, 1980) and the magnitude of complexity the investigator is willing to tolerate. A system boundary, according to Rountree (1977), should not be regarded as rigid lines; rather, as grey bands whose factors have diminishing effects on system behaviour. The system concept can be extended to various phenomena (Ogata, 1978) including irrigation management (Vang and Barney, 1994; Carruthers and Clark, 1981; Holy, 1981).

Every system has input(s) and output(s). A system input is that factor which stimulates a change in system behaviour. Two types of inputs are recognized. The first type, exogenous or environmental input is determined by factors completely independent of, or external to the system. Weather is an example of an exogenous input in a farming system. The second type, endogenous or controllable input is used as a means of altering system behaviour in a desirable direction. For example, the number of seeds per hectare, or volume of water in a given period.

System output is a factor caused by a given system. It can either be used as an input into another system or used as a performance measure of the system. A system can produce desired and undesired outputs. The desired output is a means of satisfying a system goal whereas the undesired output is that unwanted side effect produced by a system in the cause of satisfying intended goals. The most challenging practice for managers and farmers is to balance between the two in a profitable manner.

A system can be characterized as dynamic or static (Ogata, 1978). In a dynamic system, variables change with time as a result of changes in inputs and interactions among system elements. Manetsch and Park (1993) refer to such, as a system with memory because its outputs depend on previous values of input variables. The output of a dynamic system changes with time if it is not in a state of equilibrium (Ogata, 1978). A static system has no memory i.e. its output is independent of previous input variables and remains constant if its input does change.

**2. Systems theory and approach**

Systems theory provides a problem solving tool in which the inter-relationships of each part of the problem in a component is considered as well as the inter-relationships among objectives, and the means of realizing them (ICID, 1980). This, according to Chestnut (1966), involves the overall consideration of various methods of accomplishing desired objectives as an *integrated whole* where each component is designed to achieve a common goal. Thus, a complex problem can be composed of a series of precise and specified component tasks for solution while maintaining the unity of the system.

Manetsch and Park (1993) define systems approach as:

> *a problem solving methodology which begins with tentatively identified set of needs which are acceptable or "good" in light of trade-offs among needs and the resource limitations that are accepted as constraints in the given setting.*

This approach overtly seeks to include all factors which are important in arriving at a "good" solution to the given problem. It also makes use of quantitative models. Most often, simulations of these models assist in making rational decisions. Simulation involves the use of a computer program or the functioning model of a system on which different design and management strategies are tried.

Figure 1 is a summary of the systems approach as a problem solving methodology. Each of the boxes represents a major phase of the approach. Although the arrows are unidirectional, it is important to note that each phase is an interactive decision making process and is composed of sub-phases. A global view of these phases will be discussed followed by a detail look of the modeling phase. The discussion is based on the six major phases of systems approached identified by Manetsch and Park (1993).

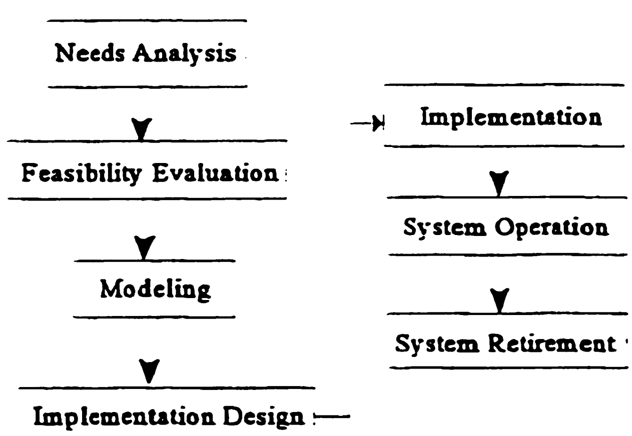



Figure 1. Systems approach to problem solving (adapted from Manetsch and Park, 1993).

The approach begins with a ***needs analysis*** which takes into consideration the needs of every one as well as institutions which will be involved with the proposed system. It involves interactions with policy/decision makers, managers or operators responsible for the performance of the system. Needs analysis can be accomplished through surveys, polls, expert opinions and evaluation of working systems similar to that under study. If a need exists, an explicit statement is made and this forms the basis of feasibility evaluation.

In the ***feasibility evaluation*** phase a set of feasible system configurations or management strategies capable of satisfying identified needs are generated. It is important at this stage to differentiate between needs and wants. A careful analyst should question: do these needs, in fact, exist? If they do, can they be stated in an operational form? This phase formulates an explicit statement of the problem to be solved based on the identified needs.

***Modeling*** is based on the specifications for system design or management strategy from feasibility evaluation. In the modeling phase, mathematical models of the system alternatives are constructed, if possible. Models are usually implemented on computers[4] and validated (See *System modeling* below). These models are used to explore possible trade-offs among performance criteria, assist decision and policy makers in arriving at normative judgments about what is good or best (Manetsch and Park, 1993). This eventually leads to the creative synthesis of better system design and/or management strategies.

***Implementation design*** specifies the details of the system and/or the management strategy designed in the modeling phase. Manetsch and Park stress a "complete" specification of the details i.e. developing a complete set of instructions that will lead to the operation of the desired real system. This phase also involves the complete specification of

[4] *Mathematical/computer models may not be possible in some cases.*

the system structure, required data, statistical analysis, communication channels to decision makers, etc.

The ***implementation*** phase gives physical existence to the desired system in which management designs are brought into existence. Deficiencies and errors of implementation design are detected and corrected through repetition of implementation design.

System adequacy is tested or determined in the ***system operation*** phase. In most cases, operation reveals additional deficiencies that were undetected in the previous phases. It also involves an on-line management control since it is here that management strategies developed in the earlier phases are implemented. System theory requires that this phase be periodically reviewed and improved upon by repeating previous phases of the systems methodology.

The last phase of systems methodology is ***system retirement***. This is often ignored in most system analyses (Manetsch, personal communication). It is important to realize and include this phase in all systems analysis. This phase requires answers to such questions as: what happens to system components when the system is dysfunctional or has reached the end of its economic life? Will the retired components or replaced parts pose an environmental hazard? How long can the system operate before it is retired, and would it have made any beneficial economic returns? Such questions are an aid to defining the structure of the system.

*a. System modeling*

System modeling involves the representation of a given situation. It consists of developing a mathematical model of a system suitable for operation on a computer. Dent (1975) regards modeling as a technique with which to apply and extend *systems thinking*. In its development, Wright (1975) advises that the starting point should be a very simple input-output model which can later on be expanded in detail with the following identifications: major subsystems, important components and relationships within each subsystem, links between subsystems, important environmental variables and control points. A resulting conceptual model provides the basis for identifying the type and form of data required.

The modeling task takes on two approaches. The first is called *the black box*[5] approach (Manetsch and Park, 1993) where inputs and outputs can be observed and measured, but the process of transforming inputs to outputs remains unknown or is of less importance to the user. This approach seeks to identify a system model from data that describes the behaviour of the system. Using various mathematical relations and statistical techniques a model is derived as the *best fit* to the operational data. Most of the work done in various engineering disciplines employs the black box approach.

The second is the structural approach which begins with a careful examination of system structure and theory to determine basic system components and linkages. An overall system

---

[5] *Wright uses the term Black Box to refer to an unknown, though stable and independent grouping of detail.*

model is thus developed by modeling the characteristics of the system components and the constraints imposed by its components. The structural approach has been used in the design and control of both physical and non-physical systems (Mintzberg, 1976; Manetsch and Park, 1993). Both approaches are complementary to each other and models developed from both approaches generally give better results (Manetsch and Park, 1993).

Application of models in systems research can be distinguished into two categories: descriptive and normative (Wright, 1975). The model, when used for descriptive purposes becomes a framework for identifying system components and relationships as well as determining the satisfactory functional relationships. The normative application requires some objective function to evaluate different decision rules. Such functions are often concerned with profits or utility.

### b. *Modeling procedure*

Six major steps (boxed) can be identified in system modeling (Figure 2). The input of a modeling phase comes from feasibility evaluation. A selected concept is modeled in the form of equations, block diagrams, flow charts, etc.

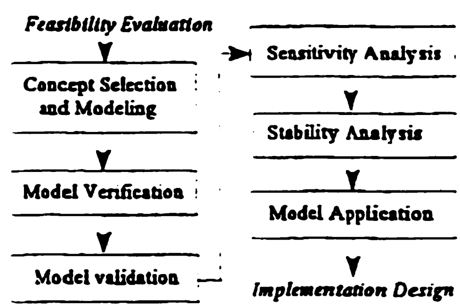



Figure 2. System modeling procedure (adapted from Manetsch and Park, 1993).

and implemented on a computer. This phase involves important decisions that affect the accuracy of computer solutions, operational costs, coding language, model compatibility with available computers and other software applications, specification of model inputs, etc. Once the model is implemented and the input-output formats are designed, the next step is to verify that the model does indeed simulate the underlying situation. To verify means to establish the truth, accuracy or reality of something. Thus, a model is verified in relation to absolute truth. Although one may not establish a fact with absolute certainty, hypotheses can be tested in terms of the probability that they are true (Naylor and Finger, 1967). The process of verification includes cross checking model results with hand calculated results, and numerical with analytical results for agreement.

Validation is often a link to an iterative loop that leads to successive tests and refinement in a model. If the model describes a controllable system, validation must demonstrate that the model exhibits behaviour that characterizes the system (Manetsch and Park, 1993). This is achieved through reproducing past system behaviour or independent data that were not used in constructing the model. Neter et al. (1990) state two ways of validating a model:

1. use new independent data to check model and predictive ability.
2. compare results with theoretical expectations, earlier empirical and simulation results.

For non-existent systems, e.g. using a model to design a new system, the validity of developed model relies on the validity of the various theories and assumptions which determined the structural form of the equations of the model (Manetsch and Park, 1993) and the values assigned to model parameters. It also relies heavily on subjective judgement, preferably involving the decision maker. Validation can lead to further information gathering, data collection, improved estimates of coefficients and refined models. A crucial question to answer in validation is whether the model leads to better decisions than can be obtained from using other techniques.

Sensitivity is defined as the rate of change in one factor with respect to another (McCuen, 1973; Wyseure, 1986) or the change in an objective function due to perturbations in the value of a parameter (Beck and Kenneth, 1977). Sensitivity analysis determines which decision variables (design parameters and controllable inputs) are important and worth including in model applications. Knowledge of model parameters of lesser importance in affecting system performance can provide additional freedom to satisfy the necessary constraints which may apply to inputs and parameters.

Stability analysis identifies the stability boundaries of the system such that critical parameters will not be unknowingly set at values which could lead to unstable behaviour over time as system structure or environment changes. Stability analyses employs analytical studies based on stability theory and use of repeated simulated runs to explore stability boundaries.

Model implementation, also referred to as experimentation, has the purpose of comparing various treatments under exactly identical conditions. Wright gives four objectives of model application: i) compare alternative courses of action, ii) estimate system response to changes in the level of single inputs, iii) explore the response surface generated for different combinations of input levels, and iv) estimate the input combination required for an optimal or minimal level of output.

**3. Rationale for application to irrigation management**

ICID (1980) offers the following justification for employing systems theory and analysis in irrigation management.

1. It is useful when required data for solving a problem cannot be obtained directly by observation.
2. It permits the combination of strictly scientific approaches with common sense, subjective opinions, evaluations, intuition and experience for decision making. Manetsch and Park (1993) have used this concept in developing a systems problem solving procedure.
3. Manipulating individual components can achieve maximum effectiveness for the whole system.
4. It's an excellent decision tool in the phase of uncertainty where the decision or policy maker can choose a line of action based on desired objectives and quantitative comparisons of alternative solutions.

The fourth justification finds application in a natural resource system (Figure 3) where farmers attempt to control the soil water content in an uncertain environmental and economic condition to achieve high yields while striving to minimize environmental degradation. Harding (1968) recognized the conflict between environmental and economic goals and wrote:

> *The great challenge facing us now is to invent the corrective feedbacks that are needed to keep custodians honest. We must find ways to legitimate the authority of both the custodians and the corrective feedbacks.*

In light of the above statement, one is tempted to call for an immediate and abrupt change in our goal philosophies. But this is unlikely to happen over night. Thus, Street (1990) has suggested developing transition strategies based on the laws of thermodynamics and entropy. This can be done through systems analysis.

#### 4. Application to irrigation management

A typical natural resource system comprises the environment, management, soil and irrigation system (Figure 3). The environment provides conditions for existence and survival. The soil provides the basis for agricultural production. Management controls the produce from the farm, irrigation and the soil through tillage and the use of soil conditioners. It is important to note that there is no control over the pollutants, yet they enter the environment which is the major input source for the soil and irrigation. In our current thinking, management practices and economic analyses are confined to the components above the broken line. Our ultimate desire is to erase the line and have direct control over the pollutants in the system (i.e., redirect the arrow that links management and produce such that management can control *both* produce and pollutants).

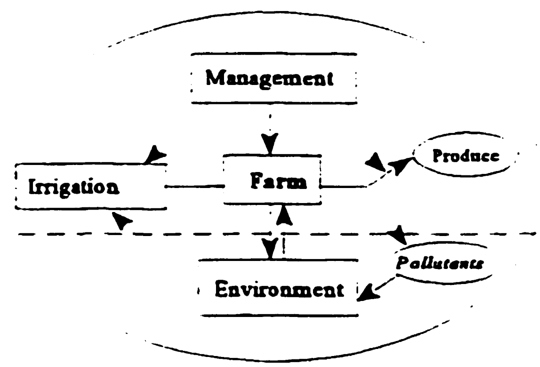



Figure 3. Natural resource system

Figure 3 shows the management and environmental components as a dynamic function of goals, information feedback and control. It can be considered an open system because of the constant exchange of material, energy and information. Information provides the manager with the *state of the system* based on observed inputs and outputs. The goals in combination with these observations provide a framework for decision making i.e. system control. The result is a set of formulated decision rules for system operation which constitutes a management policy that is tactical or strategic (Wright, 1975). One advantage of the systems approach is that the irrigator can have both tactical and strategic goals (soil water levels, salt contents, groundwater quality, etc.) for managing irrigation, soil and the environment. In addition, solution sets that are feasible and efficient according to technical and economic criteria are identified for the decision maker to compare and pass judgement. Suffice to note that farmers' practical applications of recommended practices tend to be governed by financial cost considerations.

The ellipse in Figure 3 tells us that nothing leaves or enters the system. Thus, we have to be careful in pursuit of our production goals. Serious long term implications can result in pursuit of short term economic goals. Doyle (1990) cites a Punjab irrigation study (Falcon and Gotsch, 1971) where such pursuits have led to increasing soil salinity.

## C. Irrigation performance measures

Irrigation water distribution in the field can either be measured directly or inferred from overlapped sprinkler patterns (Hart and Heermann, 1976) using distribution functions. Various functions for such inference have been presented (Heermann et al., 1992; Warrick, 1983; Elliot et al., 1980; Hart and Heermann, 1976). Most of these functions require knowledge of the mean application depth, its standard deviation and the shape of the distribution.

Irrigation performance measures are a way of characterizing system behaviour from several estimates of irrigation depths at various locations. These measures determine the degree of water replenishment in the root zone at each irrigation, the amount of runoff and/or deep percolation and the uniformity of the applied water during irrigation (Rauschkolb and Hornsby, 1994). There are at least five performance measures in the literature (Kruse, 1978; Shearer, 1978). This review focuses on distribution uniformity and application efficiency as measures of irrigation uniformity and efficiency.

### 1. Irrigation uniformity

Irrigation uniformity refers to the variation in the amounts of water applied to locations within an irrigated field. Ideally, an irrigation system should apply water such that all parts receive equal amounts. The absence of an ideal system means that some parts of the irrigated field receive more water than others. On one hand, if the field is irrigated such that all parts receive the required or desired amount, then some parts will be over irrigated. On the other hand, if only part of the field receives the most irrigated water to meet the required depth, then under-irrigation will occur in some areas. Irrigation uniformity is therefore a measure of the degree to which water is uniformly distributed to the field. There are at least eight proposed ways of characterizing uniformity in the literature (see *Uniformity measures* *and coefficient* below). Subsurface (Hart, 1972), local and global (Solomon, 1983, 1985) uniformities have been described.

Local uniformity as stated by Solomon, is limited to portions of an irrigated area in a field (e.g. the area between four sprinklers; the area of a furrow or border strip (for surface irrigation) or a lateral (for trickle irrigation). Global uniformity involves full field scale factors that are often not included in local uniformity studies (e.g. field wide pressure differences and edge effects in sprinkler irrigation). Hill and Keller (1980) estimated that differences in field wide pressures and sprinkler edge effects account for twenty percent reduction in the uniformity coefficient.

The areal distribution and uniformity of water application has been used to characterize uniformity of soil water in the root zone. Hart (1972) compared the uniformity of applied soil water and concluded that sub-surface redistribution (horizontal) approached a final value (85%) with time. Cohen and Bresler (1967) attribute subsurface redistribution to horizontal matric gradients that are established in non-uniform distributions to compensate for areas with less water. However, Sinai and Zaslavsky (1977) found that both surface and sub-soil characteristics can cause non-uniform sub-surface redistribution.

*a. Influencing factors*

Soil characteristics influence water flow over the soil surface and its infiltration into the root zone thus, affecting uniformity. Brakensiek et al. (1981) reported variability of soil infiltration characteristics even within a given textural class. In furrow irrigation, Hill and Keller (1980) have observed differences between wheel and non-wheel furrows. Ley and

Chyma (1981) reported a range of 5 - 15% standard deviation of the mean flow in furrow flow rates. Pressure variations within a pipe or resulting from field elevation differences and hydraulic characteristics of emitters also contribute to irrigation non-uniformity.

Initial soil water content plays a significant role in subsurface uniformity. Redistribution is most rapid at high water content gradients. Uniformity however, approaches a limit which would not be exceeded in a reasonable length of time (Hart, 1972). In one study Hart showed that two systems with surface distributions of 60 and 70% attained a subsurface distribution uniformity of 85%. The time taken to attain the final value was shorter in the 70% than in the 60% system. The author then concluded that the ultimate useful distribution might be high irrespective of the initial surface distribution.

### *b. Uniformity measure and coefficient*

All irrigation systems possess some non-uniformity in water application. Since 100% uniformity is economically unfeasible, irrigators must accept less than ideal uniformity in operating their systems. This calls for a performance measure - uniformity coefficient - for assessing the uniformity of water application in irrigation systems. A review of some of the measures follows.

Christiansen (1942) defined and used the first uniformity for sprinkler irrigation as:

$$U_C = \left(1 - \frac{\Sigma|x_i - \mu|}{N\,\mu}\right) 100 \qquad [1]$$

where $U_C$ is the Christiansen uniformity coefficient; $\Sigma|x_i - \mu|$ is the sum of the absolute difference between each measured value ($x_i$) and the mean ($\mu$); N is the number of observations. The author selected 84% as the minimum acceptable level of water distribution for any particular irrigation method.

Dabbous (1962) cited a second coefficient developed in 1955 based on a range of estimated water depths. The mathematical representation is given by [2]

$$U_R = \frac{2(H - L)}{H + L} \qquad [2]$$

where H and L are the highest and lowest values of irrigation depths respectively. The coefficient uses the mid point of the range as a measure of central tendency. Solomon (1983) reported a modification of equation [2] given by Rainbird Sprinkler Manufacturers as:

$$U_R = \frac{H - L}{\mu} \qquad [3]$$

where $\mu$ is the mean applied depth and H and L as previously defined.

A third uniformity measure came into the literature in 1947 (Wilcox and Swailes) as

$$U_W = 1 - \frac{\sigma}{\mu} = 1 - cv \qquad [4]$$

where $\sigma$ is the standard deviation from the mean applied depth, $\mu$, and cv, the coefficient of variation. This coefficient has also been referred to as the Wilcox-Swailes uniformity (Su, 1979) or the statistical uniformity (Bralts et al., 1981). The measure found application in the development of combined statistical uniformity measures or variance equations in drip and surface irrigation (Bralts et al., 1981; Jaynes and Clemmens, 1986; Clemmens, 1991).

Another uniformity coefficient which makes use of the standard deviation but based on a normal distribution of irrigated depths introduced in 1965 (Hart and Reynolds) is

$$U_H = 1 - 0.798\ cv \qquad [5]$$

Solomon (1983) lists two advantages of equation [5]: (i) it makes use of the standard deviation of the data in the same way as equation [4] and (ii) its numerical value in most instances is similar to Christiansen's uniformity coefficient, equation [1]. The two equations are numerically equivalent for normally distributed irrigation depths. $U_H$ has also been referred to as the Hawaiian Sugar Planters Association uniformity coefficient.

In 1964, Benami and Hore proposed the "A" coefficient and defined it as

$$A = 1.66 \frac{M_b - MD_b}{M_a - MD_a} \qquad [6]$$

where $M_a$ and $M_b$ are respectively the mean depths above and below the mean application depth, and the MDs their respective mean deviations. According to Solomon (1983) the significance of [6] has not been recognized and its later use in the literature is limited to those works reviewing it or comparing it to other measures. Hart and Heermann (1976) see "no particular advantage" of using equation [6] in place of "other established distribution parameters", probably because of the complicated use of the absolute deviations.

Karmeli (1977, 1978); Karmeli et al. (1978) formulated a uniformity coefficient similar to Christiansen's but based on the linear cumulative distribution function for sprinkler irrigation depths, equation [7].

$$U_E = 1 - 0.256\ \beta \qquad [7]$$

where $\beta$ is the slope of the cumulative distribution line. This measure has been used in optimal irrigation scheduling to minimize deep percolation.

The Soil Conservation Service (Dabbous, 1962) proposed pattern efficiency (PE) as a measure of uniformity defined as the ratio of the mean of the low quarter irrigated depth to the mean depth. The term efficiency may be misleading as this measure does not assume a management scheme. Hart and Reynolds (1965) suggested a statistical version of PE as

$$DU = 1 - 1.27\ cv \qquad [8]$$

where cv is the irrigation system's coefficient of variation. For a normal distribution, the mean of the low quarter is approximately 1.27 times away from the standard deviation below the mean (Solomon, 1983). Thus the numerical value from the SCS definition and [8] are equal so long as the irrigated depths are normally distributed. PE has been referred to as distribution uniformity (Kruse, 1978) or trickle emission uniformity (Hill and Keller, 1980; Keller and Karmeli, 1974a).

Keller and Karmeli (1974b) further suggested an "absolute emission uniformity", equation that includes the average ratios of maximum and minimum emitter flow rates.

$$EU_a = \frac{1}{2}\left(\frac{q_n}{q_a} + \frac{q_a}{q_x}\right) 100 \qquad [9]$$

where $q_n$ = average of lowest one-quarter of emitter flow rates; $q_a$ = average of all emitter flow rates and $q_x$ = average of highest one-eight of emitter flow rates. The authors recommended a design EU greater than 90%.

The On Farm Irrigation Committee (Kruse, 1978) recommended distribution uniformity (DU, equation [8]) and Christiansen's uniformity ($U_C$, equation [1]) as uniformity measures.

### c. *Uniformity interrelationships*

Warrick (1983) presented analytic relationships between Christiansen's uniformity [1], distribution uniformity, [4], and the coefficient of variation for six statistical distributions. These were generalized as:

$$U_W = 1.13\ cv\ ; \qquad cv < 0.25 \tag{10}$$

$$U_C = 1 - 0.8\ cv\ ; \qquad cv < 0.5 \tag{11}$$

$$DU = -0.6 + 1.6\ U_C\ ; \qquad cv < 0.25 \tag{12}$$

In addition, the author tabulated exact analytical relationships between cv, equations [1] and [8] for the normal, log-normal, uniform, specialized, beta and gamma functions. Other relationships include:

$$U_E = 0.985\ U_C + 0.011 \tag{13}$$

$$U_C = 0.958\ U_H + 0.030 \tag{14}$$

$$U_W = 0.020\ U_C^2 - 0.920\ U_C - 11.287 \tag{15}$$

Equations [13] through [15] are from Karmeli et al. (1978), Hart and Heermann (1976) and Seniwongse et al. (1972) respectively.

Hart and Heermann (1976) expressed difficulties in evaluating real distributions due to scarcity of data points for analysis. One constraint is the cost of collecting these data sets. This may explain why most uniformity studies tend to be local rather than global.

## 2. Irrigation efficiency

The term efficiency presupposes or assumes a management scheme and is generally understood as a measure of an obtainable output from an input. Efficiency of an irrigation system practically relates to the consumption of the available resources. Low efficiencies indicate excess water not used by plants. The lost can be reflected in the pumping cost of water. Irrigation efficiency is constrained by natural resources, applied technology, human behaviour and socio-economic conditions (Thompson, 1988). Thus, efficiency can vary from place to place and from one farm to another in the same region.

Different concepts and definitions of efficiency (Table 1) have been used to evaluate the efficient use of water. Robinson (1978) lists six components included in the evaluation of irrigation efficiency: the water applied, soil and water quality, energy consumed, labour, investment/return on investment and net production. The "On Farm Irrigation Committee" (Kruse, 1978) defines irrigation efficiency as the ratio of the average depth of irrigation water beneficially used to the average depth of irrigation water applied. This definition is rather ambiguous as *beneficial use* can cover a wide range of activities ranging from salt leaching, crop needs, pesticide or fertilizer application, etc. Some authors have limited

**Definitions of efficiency**

| Title | | Definition: Ratio of ... | Source |
|---|---|---|---|
| 1. Application efficiency | a) | water in root zone to water delivered to field. | 1 |
| | b) | volume of irrigation water consumed by crops in an irrigated area to volume applied in area plus volume for intentional leaching. | 1 1 |
| | c) | b) + correction for effective rainfall. | 1 |
| | d) | net inches required to replace soil moisture in root zone to inches applied. | 2 |
| | e) | useful water volume to total volume delivered. | 3 |
| | f) | Product of uniformity coefficient and system efficiency. | 4 |
| 2. Application (pattern) efficiency of low quarter | | average low quarter depth of water infiltrated and stored in the root zone to the average depth of water applied. | 5 |
| 3. Consumptive use | | normal consumptive use of water to net amount depleted in root zone. | 6 |
| 4. Infiltration | | amount of water infiltrated to applied. | 7 |
| 5. Irrigation application efficiency | | percent of irrigated water stored in soil root zone. | 1 |
| 6. Irrigation efficiency | a) | volume of irrigation water consumed by crops in an irrigated area to volume applied in area. | 1 |
| | b) | ET of applied water to amount of applied water. | 8 |
| 7. Optimum irrigation efficiency | | maximum yield value to seasonal water applied. | 1 |
| 8. Storage efficiency | a) | quantity in root zone during irrigation to amount needed in root zone prior to irrigation. | 9, 10 |
| | b) | water stored in the root zone as percent of total applied. | 11 |
| 9. Water distribution efficiency | a) | absolute average deviation to mean depth | 10 |
| | b) | average low quarter depth of water infiltrated to average depth of water infiltrated the quarter of the area receiving the least amount of water. | |
| 10. Water use efficiency | a) | dry weight of crop to ET depth. | 11 |
| | b) | water beneficially used to amount delivered. | |

1 = Aljibury, 1978; 2,3 = Robinson, 1978; 4 = Kimbell et al., 1990; 5 = Kruse, 1978; 7 = Tsakiris, 1985; 9 = Anyoji and Wu, 1994; 6,8,10 = RauschKolb and Hornsby, 1994; 11 = Israelson and Hansen, 1967.

beneficial use to crop needs. The argument as to what constitutes beneficial use in addition to a lack of specifics in definitions makes the comparison of irrigation efficiency in different regions or cultures rather illusive.

In order to make an unbiased comparison of system performance, it is imperative that the definition of irrigation efficiency be agreed upon. Such a definition should be comprehensive enough to warrant use in all available situations and "include some objective characterization of the benefits of using the established relationships between the input variables of the irrigation system considered" (Yitayew, 1987).

*a. Application efficiency: definition and significance*

Figure 4 shows the distribution (curved line) of applied or infiltrated water in a soil profile and four regions (A, $A_D$, B and C) that describe an irrigated profile. The average depth of applied water is represented by the broken line at which half of the field receives more than the average and the other half less than the average. The root or required depth or minimum application ratio, $R_A$ (Chaudhry, 1978) is shown by the horizontal solid line.

"A" is that fraction of the field or root volume that would received at least the required depth at the, end of an irrigation period, while "$A_D$" (1 - A) is the deficiently irrigated portion. The average depth infiltrated in $A_D$ is $D_A$. "B" is the fraction of the soil profile that has not received any of the irrigated water; it is interesting to note that a portion of this profile belongs to the root zone. "C" represents the soil profile receiving the excess water. Efficiency definitions (e.g. storage, leaching and application) relate to one or more of the described areas of Figure 4.

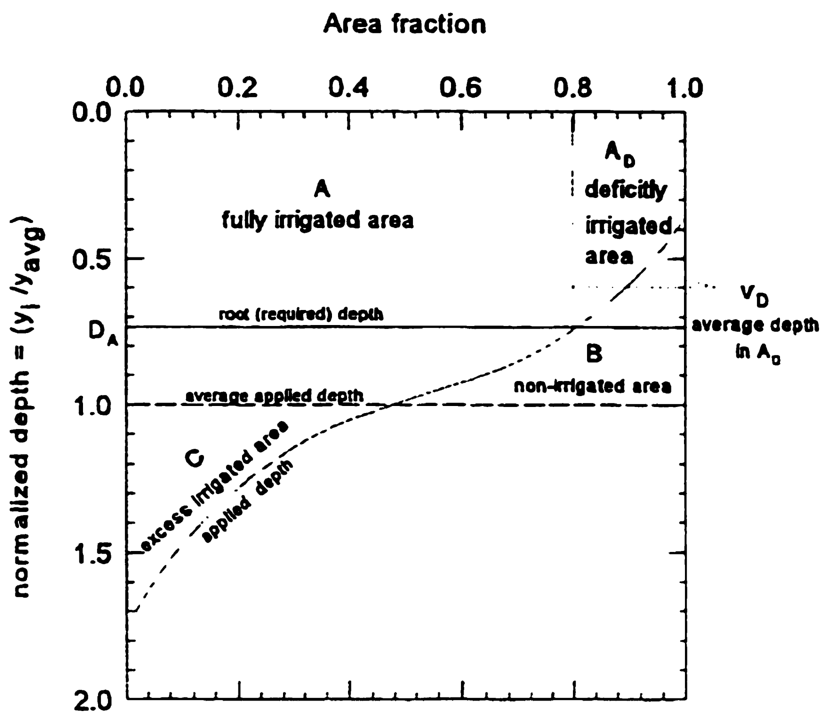



Figure 4. Application efficiency definition sketch.

ASAE (1993) defines application efficiency (AE) as the ratio of the averaged depth of irrigation water infiltrated and stored in the root zone to the average depth of water applied. expressed as a percent. The definition can be expressed in terms of areas in the figure as

$$AE = \frac{A + A_D}{A + A_D + C} \qquad [16]$$

Application efficiency is one of the most predominant indices for comparing management practices (Lamack and Niemiera, 1993), irrigation, cropping and tillage systems (Yonts et al., 1991). As an important index in evaluating an irrigation system. application efficiency indicates the excess water applied to the field (Walker. 1979). This would include the amount lost to deep seepage and run off (Clemmens, 1991; Tsakiris, 1985).

Application efficiency can be used to make an economic judgement on proposed installations of various systems (Chaudhry, 1978). Furthermore, it describes the effects of both management decisions and operational characteristics of an irrigation system (Shearer, 1978). Poorly managed irrigation systems result in excess water loss as deep percolation from the root zone. Lost water is costly to irrigators and posses an environmental hazard.

Application efficiency is a function of a system's operational time (Yadav et al., 1986) or the gross depth required (Chaudhry, 1978), as well as indicates the potential available water in the root zone to plants, (von Bernuth, 1993; equation [17]). Estimates of application efficiency in addition to seasonal ET can be used to determine seasonal water budgets and as a guide for irrigation management. High AEs will require low water amounts regardless of the ET (Rauschkolb and Hornsby, 1994). Kimbell et al. (1990) have derived water requirements for sprinkler irrigated alfalfa from application efficiency.

Nitrogen fertilizer is an important plant nutrient. Because its fate in the soil is unavoidably linked to that of water (Rauschkolb and Hornsby, 1994) there is a need to pay closer attention to the question of application efficiency in irrigation management. The concentration of nitrogen near the soil surface (when ammonium is applied) and the amount of nitrate leached are proportional to the quantity of water applied at that location or leached out of the root zone.

Application efficiency gives no indication of the adequacy or uniformity of the system (Walker, 1979). For example one can achieve a 100% efficiency with severe under-irrigation (Anyoji and Wu, 1994) even with poor uniformity (Shearer, 1978) or in cases where deep seepage is considered beneficial.

*b. Influence on application efficiency*

Several factors significantly influence application efficiency: the rate of root development and the active root depth; the irrigation method; the required amount of water to recharge the depleted soil profile, and soil type. Assuming the same system duration and application rate, sandy soils will have a lower AE than clay soils, since larger amounts of water will leave the sandy root zone during irrigation than in the clay soil.

Low AE values under shallow rooted crops, or continuous irrigation early in the growing season when the crop canopy does not cover the entire soil surface and the root system is limited to around the crop. This is because irrigating the entire surface results to massive evaporative loses (Yadav et al., 1986). In addition, any infiltrated water in non-rooted areas eventually finds its way below the tilled layer as deep percolation.

Application rates greater than the soil's intake rate distort the surface distribution pattern. Low spots where water accumulates or passes are over-irrigated and will have low AE. High spots from which water runs off will receive less water and consequently low AE (Taylor and Aschroft, 1972). In addition, Till and Bos (1985) mention uniformity and the amount of water leaching (deep seepage) including wind (Seginer et al., 1991) as some of the factors that influence application efficiency.

c. ***Application efficiency relations***

There exists a relationship between AE and crop available water (von Bernuth; 1993):

$$AW = \frac{d_n}{m} AE \qquad [17]$$

where AW = available water, $d_n$ = net depth of applied water and m = mean application depth. Hart and Reynolds (1965) developed tabulated relationships between application efficiency, application ratio and coefficient of variation (cv) based on a Gaussian distribution of infiltrated depths. (They defined application ratio as the average depth of water at the point of lowest application to the average depth required.)

Chaudhry (1978) presented AE, analytically and graphically, as a function of the coefficients of variation and skewness for various application ratios for both Gaussian and gamma distributions. The relationship allowed for quantitative evaluation of skewness effects. The author further showed a direct proportion between the average loss (1 - AE), deep percolation and cv when the depth of water required for adequate irrigation equals the average depth supplied.

Howell (1964) using various asymmetries for the same cv showed a dependence of AE on skewness. The results showed an increase in AE for positive asymmetry with a minimum application ratio less than or equal to one and a decrease for negative skews with a minimum application ratio greater than one. Chaudhry (1977) later confirmed these results for fixed application rates.

Warrick et al. (1989) showed that as the amount of water applied increases the area, A, fully irrigated increases and application efficiency decreases. They also noted that as the coefficient of variation for a given water level increases, both AE and A tend to decrease. Their work contains tabulated values for five cases of the specialized power, log-normal and normal functions.

AE is a function of the application depth which may not necessarily equal the crop need (Chaudhry, 1978). Hillel (1987) noted that AE is a function of sprinkler uniformity rather than soil properties so long as the application rate does not exceed the soil's intake rate. The dependence of application efficiency on uniformity von Bernuth (1993) is the basis for calculating application efficiency.

*d. Application efficiency determination*

Application efficiency determination is based on the amount of water replenished in the root zone at a given irrigation, runoff, deep percolation and the system's distribution uniformity. For a normal distribution of applied water depths, application efficiency can be calculated by integrating the probability density function (Warrick et al., 1989; Anyoji and Wu; 1994). One result from such a calculation is

$$AE = 1 - (2\pi)^{-0.5}\, cv\, e^{-0.5^2} + Acv \qquad [18]$$

where cv is the coefficient of variation for applied depths and A is the area receiving at least the required depth. Another equation developed by Chaudhry, (1978) is

$$AE = 1 - R_A - D_A(1 - A) \qquad [19]$$

where $R_A$ is minimum application ratio; $D_A$ is the average deficit and "1 - A" is the deficiently irrigated area. The equations involve the normal distribution function which does not have an explicit solution.

In recognition of this, Walker (1979) developed equation [20] (from a polynomial that estimates the Gaussian function) as a function of the area deficitly irrigated and cv.

$$AE = 1 - ( 3.634 - 1.123 A_D^{3} + 0.003 A_D^{1.233} )\, cv \qquad [20]$$

where $A_D$ is the area of the field that is deficiently irrigated. The author discourages the use of the equation when $A_D$ is below 10%; prediction errors rapidly increase to 10%. Clemmens (1991) gives a similar equation that makes use of the area deficiently irrigated.

$$AE = \frac{A\, R_D + (1 - A) U_D}{M_D + L} \qquad [21]$$

where A is the fraction of the field that is adequately irrigated: $R_D$ is the target or required depth; $U_D$ is average depth in the area less than $R_D$; $M_D$ is the average depth infiltrated and L represents surface losses as runoff. No associated errors are reported. The author has also given tables that relate AE to the fraction of the area with adequate and deficit irrigation, and storage efficiency.

Howell (1964) calculated AE as

$$AE = \frac{x_a}{\mu} - \frac{\Sigma (x_a - x_i)^{+}}{\Sigma x_i} \qquad [22]$$

where $x_a$ is the minimum application depth on an area, a; $\mu$ is the average depth applied; $x_i$ is the various measured depths and "+" indicates the sum of positive deviations only. For $x_a = \mu$ AE was related to Christiansen's uniformity, $U_C$, as

$$AE = 0.5(1 + U_C) \qquad [23]$$

When the mean application depth equals the root zone depth, the maximum possible AE when there is no over-irrigation is expressed as (von Bernuth, 1993)

$$AE = [1 - 0.5(1 - U_C /100)]. \qquad [24]$$

Rauschkolb and Hornsby (1994) have summarized water application efficiencies for a variety of crops, different locations and irrigation systems. Although water application efficiencies may vary from 30 to 90%, they noted small differences in application efficiencies for well managed systems (70-85% in sprinkler systems, 70-95% for surface level systems and 80-90% in drip systems).

The Soil Conservation Service (English and Nuss, 1980) recommended a 65% application efficiency. Some water districts require higher values. In 1993 efficiency requirements in the Southwest Florida Water Management District[6] were 75% and 80% for existing and new permits respectively. Efficiency goals (irrespective of the type of permit) have been set for 80% by 1997 and 85% by January 1, 2001 respectively for row crops, strawberries and citrus.

---

[6] *Water Use Permit Information Manual: Florida Administrative Code. Basis of review for water use permit applications, and design aids.*

Thompson (1988) evaluated 16 irrigation projects of the Bureau of Reclamation using data from 1963 to 1984. Nine had AE less than 40%, four between 40 and 65%, and 3 above 65%. The author concluded that efficiency time patterns showed no evidence of progressive improvement in efficiency. Two projects had statistically significant trends and both were towards lower efficiency levels.

*e. Improving application efficiency*

Izadi et al. (1991) presented two procedures for maximizing application efficiency in surface irrigation and suggest the use of a target depth. Decreasing the mean depth of application increases AE but the area adequately irrigated is reduced (von Bernuth, 1993). To increase the depth of water in an area with the least amount of water by x% would imply increasing the total application by x%. This causes significant increases in deep percolation when the percent area receiving adequate irrigation is increased (Kruse, 1978). Higher system efficiency increases AE as the amount of deep percolation decreases while the area adequately irrigated is increased. This is constrained by the cost of installing and maintaining a high uniformity system. von Bernuth notes that while it is technically feasible to achieve 100% system uniformity, it is economically unfeasible.

*f. Global and local efficiency*

In dealing with irrigation water efficiency, one distinguishes between global and local efficiency, to borrow from Solomon (1983). In global efficiency, it's the overall efficiency of the watershed that is important while in local efficiency or on-farm irrigation efficiency

(Robinson, 1978) relates to the net amount of water applied per unit area from crop consumption. According to global efficiency advocates, users up stream need not worry about efficiency; only the last user down stream should. This is because the excess water re-enters the underground water and is pumped and used over and over again. Although little water is lost in the process, maintaining water quality becomes a problem (Robinson, 1978). Except in communal systems, global efficiency is not economically efficient or beneficial to the users up stream. Striving for global efficiency without caution may result to an ecological disaster.

**D. Summary and discussion**

Inefficient and non-uniform systems tend to waste water, nutrients and energy. Management and system improvement allow for a high rate of application efficiency in any given system. Soil and water quality are the most delicate to manage in an irrigation set up. While we desire a high quality soil through proper leaching (removal) of salts from the soil over the years, we do not want leaching to occur to the point where underground or surrounding water contamination is likely to occur.

Resource exploitation, soil degradation, water resource depletion and pollution are insidious trends of the past prevalent in today's society. Lessons from history show that great losses, costs and consequences await us, unless there is an effort on our part to improve irrigation management. Irrigation agriculture should not be self destructive; it has supported most areas through millennia and has been the economic basis of societies through recorded history.

The design and management of irrigation systems contain more than the engineering and agronomic inputs. Human, economic and environmental factors must be taken into account. Many factors involved in crop production should and must be evaluated in an integrated management system. This calls for a systems approach in irrigation - a missing link in today's irrigation design and management practices.

In general, efficiency assumes a management scheme relating the output of a system to its inputs. When used as a performance measure, the term provides a basis on which to make decisions regarding system operations, which system components and to what extend need adjustment. It serves as a tool for comparing different systems. In irrigation management, environmental efficiency will signify the level of potential pollutants entering the environment.

Application efficiency is an important irrigation performance measure. Apart from its indirect estimation using the equations in the section *Application efficiency determination*, direct field measurement under sprinkler irrigation have not been documented. Furthermore, there is a need to investigate the impacts of management practices on application efficiency as well as the probability of such efficiencies under various management strategies.

Although there is wide recognition of the environmental concerns in irrigation management, attempts to address those concerns still emphasize the single discipline approach. There is a need to incorporate the systems approach in irrigation management and provide the farmer with a tool to make environmentally sound decisions.

# III. Research Procedure, Results and Discussion

*.. when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind.*[5]
*- Lord Kelvin -*

This section is divided into two papers, written in the format of the *Transactions of the ASAE* scientific journal. Each paper has an abstract, an introduction, specific objectives, procedures, results and conclusions. Both papers are related, but can be read in any order without loosing much content. The works cited in each of the papers can be found in Section VI - References.

Paper A deals with application efficiency determination under various statistical uniformities and application ratios. The results presented include the statistical distribution of application efficiency, and graphical and mathematical relationships between application ratio and system uniformity.

Paper B discusses, from systems theory, a method of characterizing environmental efficiency of irrigation management. A new performance measure in irrigation management termed irrigation environmental efficiency is proposed and graphically related to other commonly used irrigation measures. The measure is applied to some existing irrigation systems and management.

---

[5] Experience and meaning. *The Philosophical Review*, vol. xliii p. 134, 1934

## A. Estimating irrigation application efficiency and its statistical distribution

### 1. Abstract

A common performance measure in irrigation management is application efficiency (AE). The popularity of this index prompts the following research questions: How does AE vary with the applied depth of water under an imposed areal distribution? What is the AE uniformity in a given setting? This purpose of this study was to determine the statistical distribution of application efficiency for a range of minimum application ratios (required depth divided by the mean applied depth) - 0.4 to 1.2. Irrigation from center pivot systems were simulated assuming a normal distribution function. A new term for characterizing application efficiency, application uniformity (AU), is introduced based on a statistically derived uniformity coefficient. Regression equations relating AE to AU, minimum application ratio and statistical uniformity are presented.

### 2. Introduction

One of the most commonly used performance measures in irrigation is application efficiency (AE). AE is defined as the ratio of the average depth of irrigation water infiltrated and stored in the root zone to the average depth of water applied, expressed as a percent (ASAE, 1993). Although some researchers have noted that this measure gives no indication of the adequacy or uniformity of irrigation (Anyoji and Wu, 1994; Walker, 1979; Shearer, 1978), it does show how much water is lost from the field as runoff and/or deep percolation (Clemmens, 1991; Tsakiris, 1985; Walker, 1979). Lost water is costly to farmers and posses an environmental hazard since the fate of most nutrients is linked to that of water. Assuming a uniform mixture, the amount of nitrate leached in a given spot in the field is proportional to the quantity of water leached out of the root zone at that location (Rauschkolb and Hornsby, 1994).

Besides environmental concerns, AE can be used for comparing management practices (Lamack and Niemiera, 1993), irrigation, cropping and tillage systems (Yonts et al., 1991). As an evaluation index, it can be used to make an economic judgment on the installation of various proposed systems (Chaudhry, 1978). The measure has also been used in determining a system's operation time (Yadav et al., 1986; Wu and Gitlin, 1983), the potential available water in the root zone to plants, (von Bernuth, 1993) and the gross depth required (Chaudhry, 1978). Furthermore, it describes the effects of both management decisions and operational characteristics of an irrigation system (Shearer, 1978). Clemmens (1991) and Warrick et al. (1989) related application efficiency to the area receiving full irrigation. Warrick et al. tabulated values for five cases of the specialized power, normal and log-normal functions.

Estimates of application efficiency in addition to seasonal evapotranspiration (ET) can be used to determine seasonal water budgets. Kimbell et al. (1990) derived water requirements for sprinkler irrigated alfalfa from application efficiency. Low application efficiencies and high ETs indicate large quantities of water to meet plant needs (Rauschkolb and Hornsby, 1994).

The calculation of application efficiency depends on the assumed required depth - a function of the allowable soil water depletion. The allowable depletion is commonly based on rules of thumb such as 0.5, 0.25, etc. of the field capacity. However, other factors such as economics, labor availability, sources and methods of water supply, social and cultural habits can affect irrigation timing and the application depth. The application or required depth, as such, may not necessarily equal the root zone depth, thus affecting AE.

Three questions arise: Can AE be estimated from a given application ratio and statistical uniformity? How does application efficiency vary with the application ratio under a given imposed areal distribution? What is the nature of its statistical distribution for a given setting? The quest for these answers is the focus of this paper.

**3. Theoretical development**

The following discussion assumes that excess water applied for leaching requirements is considered a loss since it cannot be recovered by plants, once out of the root zone. If the fraction of an irrigated field, $X$, receives an applied or required depth, $w$, then the ratio of $w$ to the mean applied depth is termed minimum application ratio (MAR), (Chaudhry, 1978).

The areal distribution of water under sprinkler irrigation is the result of overlapping precipitation patterns from several individual sprinklers (Chaudhry, 1978). The irrigation depth over the field varies due to spatial variability in soil properties (Brakensiek et al., 1981). However, for a soil with constant soil properties across the field and assuming no translocation, soil water variability is strictly due to non-uniformity of the irrigation system. In either case, some areas will be over-irrigated and others under-irrigated (Figure 5). For a constant root depth (represented by the horizontal solid line) which may or may not define the required depth, non-uniformity (not necessarily the only factor) will lead to variability in application efficiency.

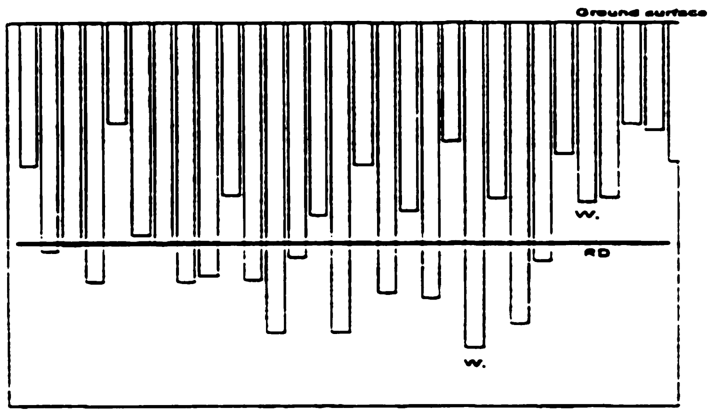



Figure 5. Infiltrated soil water variability.

Infiltrated water depths. $w_i$ . can be measured at discrete points where each point represents a small area. Application efficiency. for each $A_i$ can be calculated for a given required or root zone depth as follows:

$$AE_i = \begin{cases} 100 & : \quad w_i \le R_D \\ \frac{RD}{w_i}\, 100 & : \quad w_i > R_D \end{cases} \qquad [25]$$

where AE is the application efficiency of a given small area i. RD is the required or root depth and $w_i$ is the infiltrated water depth in the $i^{th}$ location in the field. Since the depths. $w_i$. over the entire area define an infiltrated distribution. $AE_i$ in a similar manner. will have a distribution that is dependent on RD. The application efficiency for the profile can be obtained as an average of $AE_i$. i.e..

$$\bar{AE} = \frac{\sum_{i=1}^{N} AE_i}{N} \qquad [26]$$

whose standard deviation is:

$$SD_{\bar{AE}} = \left( \frac{\sum_{i=1}^{N} (AE_i - \bar{AE})^2}{N - 1} \right)^{\frac{1}{2}} \qquad [27]$$

where N is the total number of observations. Equation [27] is a measure of the variation of application efficiency within the profile. $SD_{AE}$ can be standardized by dividing equation [27] by [26] to obtain the coefficient of variation, $CV_{AE}$.

A uniformity coefficient for AE, can be derived and termed application uniformity as

$$AU = (1 - CV_{\bar{AE}})100 \qquad [28]$$

Equation [28] compares with the statistical uniformity coefficient (Bralts et al., 1981).

$$U_S = (1 - CV)100 \qquad [29]$$

and provides a statistical description of application efficiency as well as the uniformity of the irrigated depths within the root zone.

### 4. Procedure

Eight data sets from Heermann et al. (1992) were reproduced using MINITAB's normal distribution algorithm (Minitab, 1993). The data were originally collected by the Soil

Conservation Service under various center pivot systems with different uniformity distributions. These sets were selected to represent a wide range of distribution uniformities. Selected sets with their respective means and standard deviations are shown in Table 2.

**Table 2. Selected data from Heermann et al. (1992).**

| System ID | Mean, mm | Std. Dev., mm | $U_S$ |
|---|---|---|---|
| SCS44 | 21.6 | 12.8 | 43.1 |
| SCS06 | 5.3 | 2.65 | 50.0 |
| SCS03 | 30.7 | 11.96 | 61.0 |
| SCS10 | 15.7 | 5.37 | 65.8 |
| SCS31 | 13.0 | 3.85 | 70.4 |
| SCS04 | 14.8 | 2.86 | 80.7 |
| SCS15 | 33.1 | 4.39 | 86.7 |
| SCS25 | 24.2 | 2.18 | 91.0 |

Three hundred data points were simulated for each set using a QuickBasic computer program (Appendix 1). To ensure the accuracy of the simulated data, the average and standard deviations were compared with the reported values. Each simulated value represented an infiltrated depth, w, for a given location. Eleven required depths were selected at regular intervals. Application efficiency for each set was calculated according to equation [26].

Table 3 shows part of an output from one sample set. For an infiltrated depth of 36.0 mm, the application efficiency at location 2, for example, ($w_2$) is 52.5% for an 18.9 mm required depth or 0.6 minimum application ratio (MAR). At the same location for a 37.7mm required depth (MAR = 1.2), the application efficiency is 100% ($w_2 < R_D$).

**Table 3. An example of a generated matrix from equation [26]**

**Mean infiltrated depth = 31.4 mm; $U_S$ = 61.8%**

| N | Infiltrated depth mm | Application efficiency for required depths | | | | |
|---|---|---|---|---|---|---|
| | | 12.6 (0.4)* | 18.9 (0.6) | 25.2 (0.8) | 31.4 (1.0) | 37.7 (1.2) |
| 1 | 22.5 | 55.9 | 83.8 | 100.0 | 100.0 | 100.0 |
| 2 | 36.0 | 35.0 | 52.5 | 69.9 | 87.4 | 100.0 |
| 3 | 35.0 | 35.9 | 53.9 | 71.8 | 89.8 | 100.0 |
| 4 | 40.7 | 30.9 | 46.4 | 61.8 | 77.3 | 92.7 |
| . | . | . | . | . | . | . |
| . | . | . | | | | . |
| 296 | 16.0 | 78.7 | 100.0 | 100.0 | 100.0 | 100.0 |
| 297 | 31.7 | 39.7 | 59.5 | 79.3 | 99.1 | 100.0 |
| 298 | 31.3 | 40.2 | 60.3 | 80.4 | 100.0 | 100.0 |
| 299 | 41.2 | 30.5 | 45.8 | 61.0 | 76.3 | 91.6 |
| 300 | 23.1 | 54.3 | 81.5 | 100.0 | 100.0 | 100.0 |
| | Average AE | 46.3 | 65.1 | 79.5 | 89.2 | 95.2 |
| | Std. Dev. | 20.17 | 21.40 | 18.62 | 13.96 | 9.21 |
| | C.V. | 43.6 | 32.9 | 23.4 | 15.7 | 9.7 |
| | A.U. | 56.4 | 67.1 | 76.6 | 84.3 | 90.3 |

* Minimum application ratio

The average application efficiency, its standard deviation and the corresponding uniformity were calculated in accordance with equations [26] through [28]. Two commonly used equations in estimating application efficiency were used to validate the approach in [26]. These represent equations [30] (Clemmens, 1991) and [31] (Walker, 1979) which are presented below using the authors' notations.

$$Ea = \frac{A\ R_D + (1 - A)U_D}{M_D + L} \qquad [30]$$

where A is the area fully irrigated, $R_D$ is the required depth, $U_D$ is the average depth infiltrated in the deficiently irrigated area, $M_D$ is the mean infiltrated depth and L represents losses due to surface runoff and evaporation (neglected in this study).

$$Ea = 1 - (3.634 - 1.123A_D^{0.3} + 0.003A_D^{1.233})cv \qquad [31]$$

where $A_D$ is a fraction of the area that is deficiently irrigated and *cv* is the coefficient of variation of the applied depth.

An application efficiency distribution pattern for each required depth was determined at 5% intervals. Regression equations relating application efficiency to minimum application ratio were fitted to the polynomial:

$$y = a_1 + a_2x^1 + \ldots + a_nx^{n-1} \qquad [32]$$

where $a_1$ through $a_n$ are functional coefficients of system uniformity, f($U_S$ - statistical uniformity); y is the application efficiency, x is the minimum application ratio (of $n^{th}$ order polynomial). All equation parameters were determined using SigmaPlot's curve fit procedure (Jendel Scientific, 1994).

### 5. Results and discussion

A detailed output of the results is presented in Appendix 2. A comparison of the results from the above procedure with other methods is shown in Table 4. There is a good agreement with results from Clemmens' equation. But for the MAR of 0.4 at cv = 30 and MAR of 0.4 to 0.8 at cv = 39, the discrepancy between the results is less than 10%. Generally, the error tends to reduce with a decrease in *cv* or an increase in the application ratio. A similar trend was observed in comparison with the Walker equation but with a significantly higher error (>13%) for the 0.4 and 0.6 application ratios in all but cv = 19. Walker cautioned the use of the equation when the deficiently irrigated area was less than 10%. The fractional area receiving minimum irrigation in these cases was below the 10% margin and this, may explain the large observed differences.

**Table 4. Validity of AE results from the procedure of Equation [25].**

| | | Application Efficiency | | |
|---|---|---|---|---|
| cv | MAR | Regression Equation | Equation 30 (Clemmens 1991) | Equation 31 (Walker, 1979) |
| | 0.4 | 40.3 | 40.0 | 69.8 |
| | 0.6 | 60.4 | 60.0 | 69.8 |
| 9 | 0.8 | 80.5 | 80.0 | 78.0 |
| | 1.0 | 97.1 | 96.5 | 96.7 |
| | 1.2 | 100.0 | 98.6 | 100.0 |
| | 0.4 | 41.8 | 40.0 | 40.8 |
| | 0.6 | 62.4 | 59.9 | 56.3 |
| 19 | 0.8 | 80.9 | 78.3 | 76.7 |
| | 1.0 | 93.5 | 92.4 | 93.0 |
| | 1.2 | 98.9 | 99.5 | 99.1 |
| | 0.4 | 44.0 | 39.8 | 34.2 |
| | 0.6 | 63.9 | 58.8 | 55.5 |
| 30 | 0.8 | 80.3 | 75.5 | 75.7 |
| | 1.0 | 91.5 | 88.3 | 89.3 |
| | 1.2 | 97.1 | 96.8 | 96.5 |
| | 0.4 | 46.3 | 39.0 | 33.0 |
| | 0.6 | 65.1 | 56.9 | 54.7 |
| 39 | 0.8 | 79.5 | 72.3 | 73.2 |
| | 1.0 | 89.2 | 84.7 | 85.9 |
| | 1.2 | 95.2 | 93.7 | 93.7 |

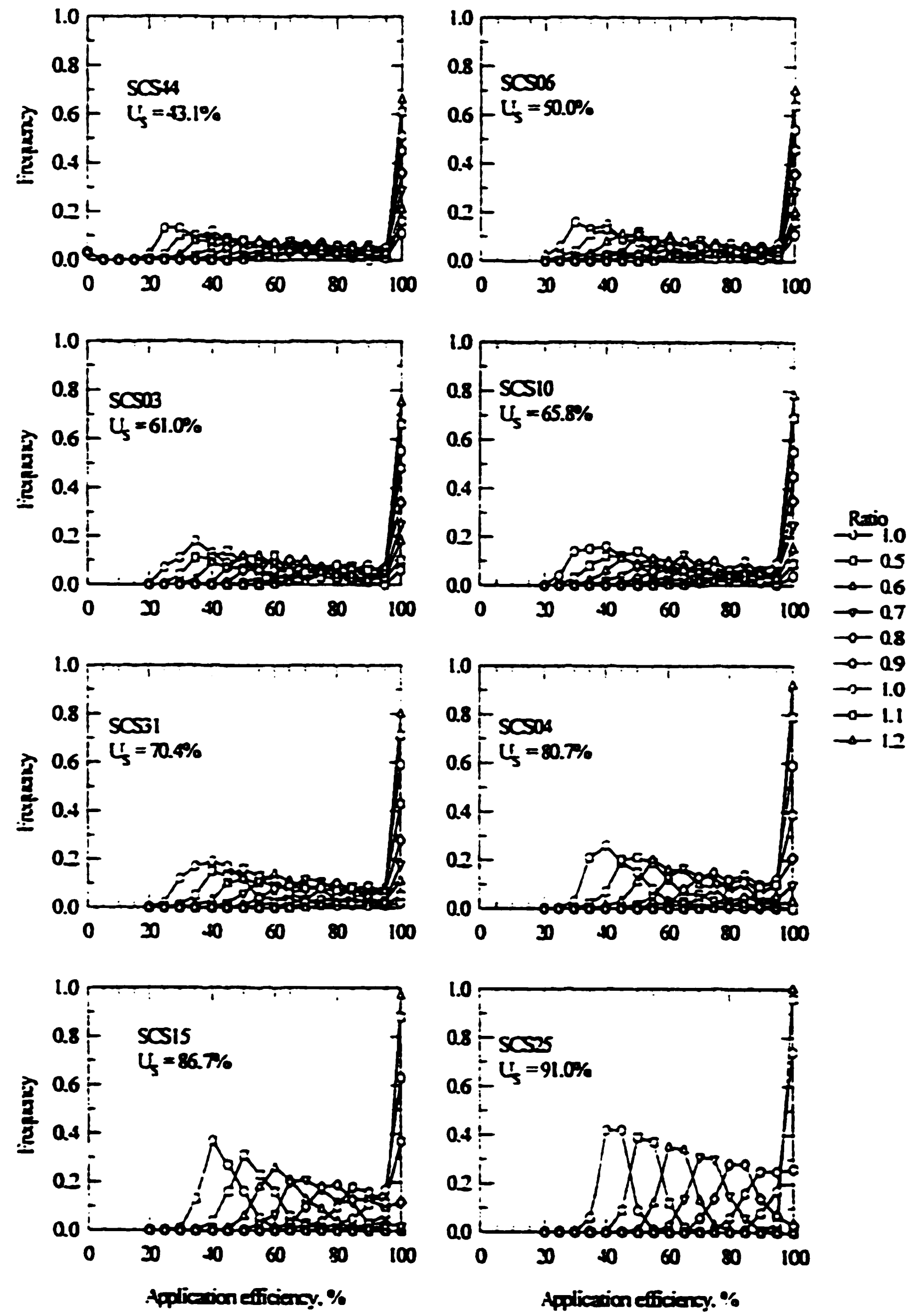



Figure 6. AE frequency distributions for selected systems.

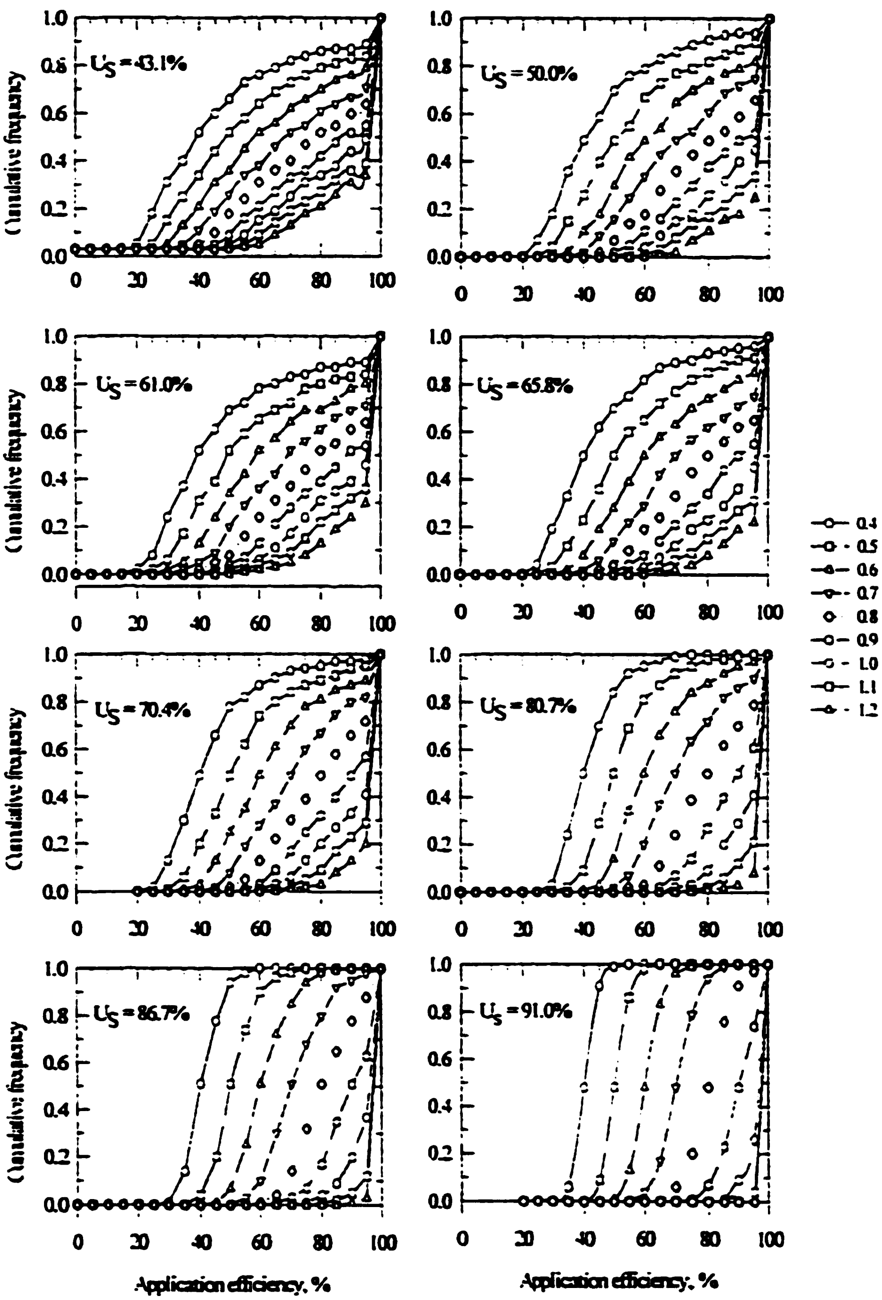



Figure 7 Cumulative frequency distributions from Figure 6.

Figure 6 shows a frequency distribution of application efficiency over application ratio ranges of 0.4 to 1.2. For a given system, the distribution tends to shift toward 100% AE with an increase in the minimum application ratio. Two peaks can be observed - a fixed peak at 100% AE for all cases and one to its left that varies with AE. These peaks seem to suggest a dependency on each other. For example, as the application ratio increases the peak at 100% AE increases while the other peak decreases. The increase in the peak at 100% AE stems from the fact that more of the applied water is within the required depth.

The cumulative frequency distribution is shown in Figure 7. The curves portray a consistent and repeated trend in all systems. However, the higher the system uniformity the steeper the slopes and the wider the spread between the curves.

ET demands generally increase with the growing season partly because of an increase in the active root volume and plant canopy. This implies that the required depth, and consequently the application ratio, will increase with the root zone depth. Therefore, the shape of the cumulative application efficiency function over the season will depend on the actual infiltrated water depth. The actual AE statistical distribution can be described by non-dimensional curves as shown in Figure 7. For any given system the seasonal application efficiency can be characterized by a family of curves similar to those in Figure 7, where the curves to the left represent early season and those to the right, late season. These curves suggest application efficiency is not a constant, but a variable value for any given management practice throughout the season.

Application efficiency generally increases with minimum application ratio for all uniformities (Figure 8). These results support an earlier finding where von Bernuth (1983), using a profit function demonstrated that the optimal coefficient of uniformity increases with the mean irrigation water applied. However, with reference to slopes of the system curves in Figure 8. AE in lower uniformity systems increases at a slower rate than higher uniformity systems. The difference in the slopes account for the system curves crossing over at about the 0.7 MAR. A detailed look at where the curves converge revealed that all but the 40. 50 and 98 $U_S$ curves (extreme cases) cross over at 0.72 MAR (73% AE).

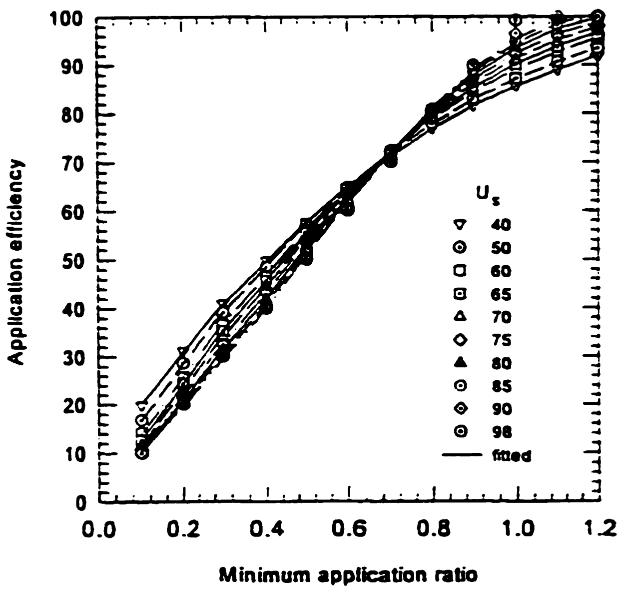



Figure 8. Application efficiency as a function of MAR and $U_S$.

Figure 8 shows that below 0.7 MAR a 50% uniformity system has a better efficiency than a 90% uniformity system. For example, consider two systems: I and II with a statistical uniformity of 50 and 90% respectively. At 0.4 MAR system I has an AE of 48% and system II has a 40% AE. AT 0.9 MAR system I has 83% AE and system II has 90% AE. But they both have about 72% at 0.7 MAR.

A "t statistic" testing the significance of $U_S$ on AE in the range of 0.6 to 0.8 (near the cross-over) showed no significant difference ($\alpha = 0.05$). At 0.7 MAR, the AE range is 1.9%, 4.9% at 0.6 MAR and 4.4% at 0.8 MAR. The 0.6 to 0.8 MAR interval may be significant for three reasons. First, AE decreases with uniformity below 0.6 MAR. This implies that large volumes of water and nutrients are leached out of the root zone. Lost water is costly to producers. Leached nutrients pose an environmental hazard and reduce yields. Second, AE increases with uniformity above 0.8 MAR but this is not necessarily a desired goal in a case where all of the soil's available water has been depleted. This is because the fractional area that is adequately irrigated decreases with increasing AE (Clemmens, 1991). Third, the relative AE insensitivity to system uniformity at around 0.7 MAR seems to suggest that value as an ideal application ratio, especially if an irrigator has no knowledge of the system uniformity in use.

The relationship between application efficiency and the minimum application ratio (Figure 8) can be expressed by the following polynomial:

$$AE = a_0 - a_1 MAR - a_2 MAR^2 - a_3 MAR^3 \qquad [33]$$

where MAR is the minimum application ratio and $a_0$, $a_1$, $a_2$, and $a_3$ are functional coefficients of system uniformity. The mathematical representations of these coefficients are expressed in [34].

$$a_0 = 48.3 - 1.48U_S + 0.0132U_S^2 - 2.56 \times 10^{-5}U_S^3$$
$$a_1 = -153 + 12.8U_S - 0.176U_S^2 + 6.69 \times 10^{-4}U_S^3 \qquad [34]$$
$$a_2 = 375 - 21.3U_S + 0.319U_S^2 - 1.31 \times 10^{-3}U_S^3$$
$$a_3 = 179 + 9.47U_S - 0.146U_S^2 + 6.09 \times 10^{-4}U_S^3$$

The equations in [34] were developed using regression analysis. A plot of equations [33] and [34] is shown as fitted lines in Figure 8. The equations show a good fit to the data (adjusted $R^2$ of 0.99, Appendix 3) with the following exceptions. For the $U_S$ = 98, the equations tend to under predict at 0.9 and 1.0 MAR, and over predict at 0.6, 0.7, 1.1 and 1.2 MAR. The largest absolute prediction error was 4% at 1.0 MAR. The error in all other cases was less than 2%.

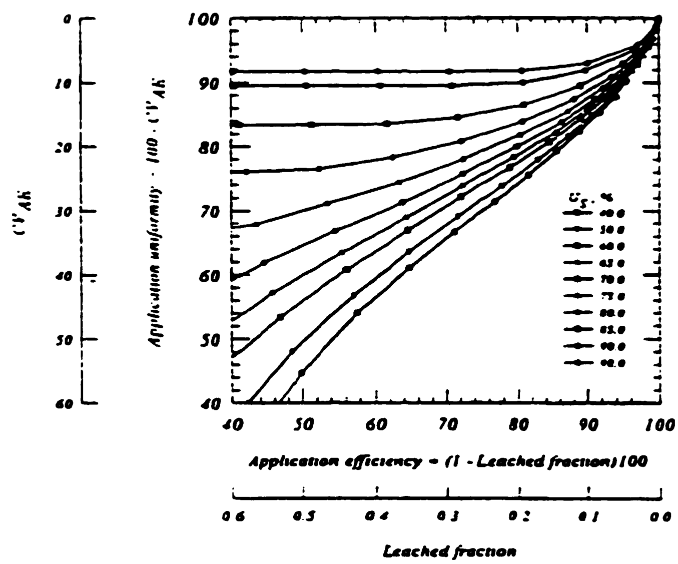



Figure 9. Relating application uniformity to application efficiency and leached fraction.

Figure 9 shows a plot of application efficiency and application uniformity (AU) relationships. The fitted lines were obtained from a fifth order polynomial fit whose parameters are shown in Appendix 3. AU describes the uniformity of application efficiency in the soil profile. The 80 to 98 $U_S$ systems show a nearly constant AU below 80% application efficiency. The figure further illustrates that, at 80% AE a system whose distribution uniformity is 40% will have an AU of 72%, whereas a 90% uniformity system will have an AU of about 90%. Figure 10 offers an alternative to calculating AU from equation [28] which assumes the availability of AE data collected in a manner described by equation [26]. Such data are rarely available and collecting them can be time consuming and costly. Indirect methods such as those presented by Walker (1979) and Clemmens (1991) are often used but they do not give a corresponding standard deviation for estimating the $CV_{AE}$ of equation [26].

There exists an inverse relationship between AE and the area that is adequately irrigated regardless of system uniformity (Figure 10). By increasing the AE from 60 to 80% under a 70% system uniformity the fully recharged area decreases by 17%. The observed trends are consistent with previous findings of Wu and Gitlin (1983) and Clemmens (1991). This figure can be used to make management decisions with respect

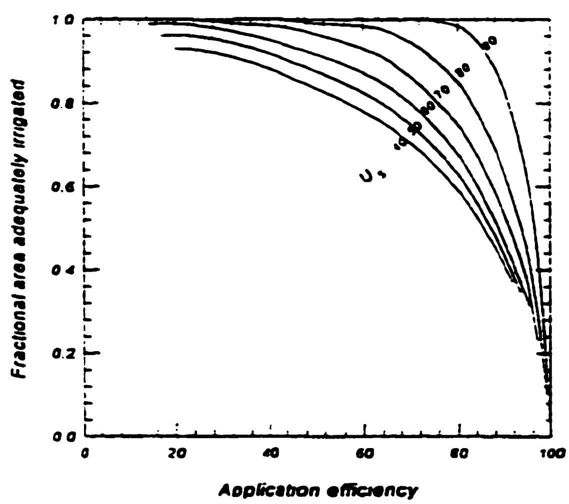


Figure 10. Relationship between AE, $U_S$ and fully irrigated area.

to the amount of area under deficit irrigation for a known system and desired AE. Figures 8 and 10 show there are trade-offs among AE, system uniformity and MAR from which producers can conveniently select design and/or management options.

***Example problem***

A center-pivot system has an 80% statistical uniformity coefficient. The average depth of water to be applied from the system on a field is 23 cm. If the root depth of 18 cm is to be completely recharged, determine: 1) application efficiency, 2) application uniformity, and 3) the fractional area fully recharged.

***Example solution***

The minimum application ratio is (required depth/mean depth) = 18/23 = 0.78.

1. From equation [34], $a_0$ = 1.27, $a_1$ = 87.13, $a_2$ = 41.88 and $a_3$ = 43.99. Substitute values in equation [33]: AE = 74%.
2. From Figure 11 enter the X-axis at the 74$^{th}$ AE mark. Read up to the 80% uniformity curve (fourth curve from the top) and across to the Y-axis: Application uniformity = 81%.
3. Locate the 80% uniformity curve in Figure 12. A 74% AE corresponds to a 0.92 fractional area fully recharged.

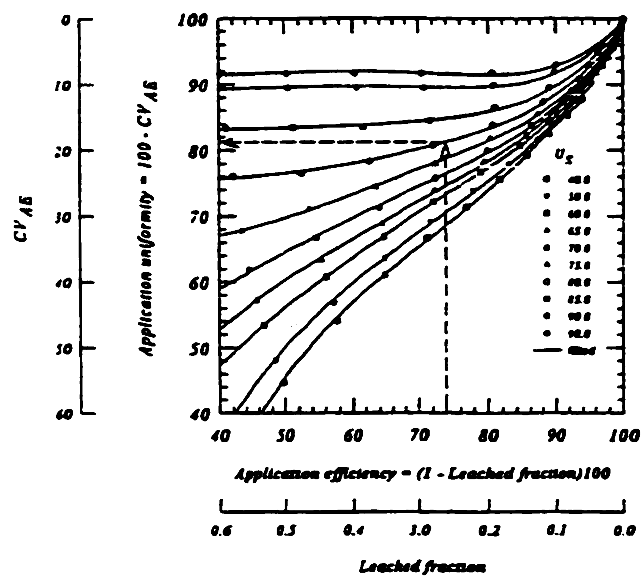



Figure 11. Estimating application uniformity from AE and $U_S$ for an example problem.

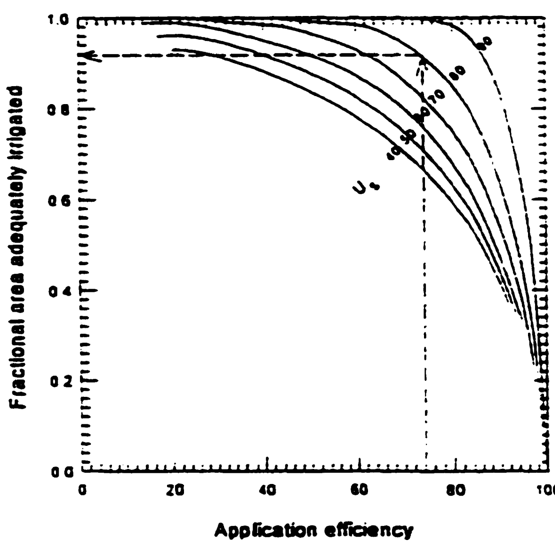



Figure 12. Estimating the fractional area adequately irrigated from AE and $U_S$ for an example problem.

## 6. Conclusions

A procedure was developed for estimating application efficiency as a function of minimum application ratio and system uniformity. Simulated application efficiency results agree with those from existing methods. Application efficiency increases with minimum application ratio (MAR) and can be estimated as a function of statistical uniformity and MAR. One limitation of application efficiency has been its inability to indicate irrigation uniformity. Such a limitation may no longer exist; as shown in this study, a term can be defined which evaluates the uniformity of application efficiency.

Frequencies of, and variations in application efficiency with required application depths and system uniformities have been presented. These relations serve two purposes. First, they characterize the nature of application efficiency at a particular irrigation schedule (minimum application ratio). Second, they describe the expected variation in seasonal application efficiency (with increasing ET demand) for a given system.

Statistical uniformity appears to have an insignificant influence on application efficiency at 0.7 MAR. The fractional area under adequate irrigation decreases with an increase in application efficiency regardless of system uniformity. Relationships among application efficiency, statistical uniformity, MAR and irrigated area provide trade-offs from which managers can make informed decisions.

## B. An environmental efficiency performance measure for irrigation management

### 1. Abstract

Managing irrigation systems in an environmentally sound manner throughout the growing season is a major challenge to managers. The purpose of this study was to develop a new performance measure - irrigation environmental efficiency ($E_{IE}$) - for irrigation management by combining two commonly used performance measures: application efficiency (AE) and statistical uniformity ($U_S$). Charts are presented that relate irrigation environmental efficiency to AE, $U_S$, and the fractional area fully irrigated. $E_{IE}$ was used to show and compare the statistical distribution of various center pivot systems, from two United States geographical regions, and to evaluate five Michigan farms using actual irrigation scheduling data.

### 2. Introduction

Operating an irrigation system in a manner that minimizes the potential for environmental degradation throughout the growing season is an issue of urgency today. This stems in part from the fact that some portions of the field, during irrigation, receive more than the required soil water to meet crop needs. This over-irrigation leads to deep percolation and/or runoff. Deep percolation occurs when a portion of the irrigated water moves beyond the root zone and can no longer be recovered by plants.

One of the most important considerations in irrigation management is the system performance throughout the growing season. In an attempt to improve on irrigation system design, Bagley and Criddle (1956) proposed using the product of distribution efficiency and application efficiency. Cuenca (1989) used that concept (which is further explored in this paper) in determining the overall efficiency of surface systems, and Keller and Bliesner

(1990) also used this concept in estimating the required gross application depth.

Performance measures such as statistical uniformity (Bralts et al., 1981) have been used in the design and evaluation of irrigation systems without regard to the environment. This neglect is perhaps because society has generally, by default, assigned a zero value to any system output to the environment in its cost-benefit analysis. There appears to be no functional link between the engineering and agronomic aspects of irrigation management and the environment.

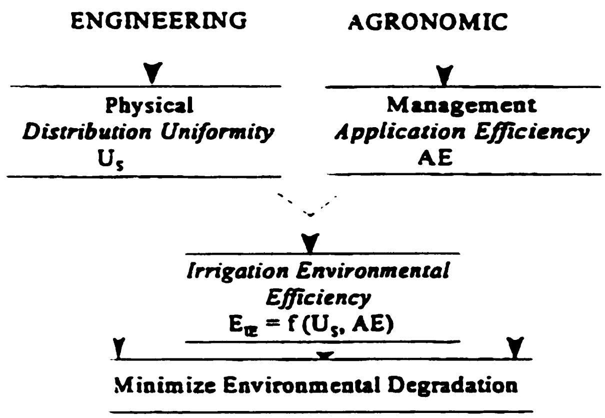



**Figure 13.** Bridging the gap between the physical and management aspects of irrigation.

Two performance indices commonly used in irrigation management are application efficiency and distribution (statistical) uniformity. Application efficiency is indicative of how well the system is managed. Distribution uniformity characterizes system performance. Both have an impact on the immediate surrounding, but there is no index to quantify this potential impact. The design and evaluation of irrigation systems should have an environmental efficiency term (Figure 13) that includes losses, for example, from deep percolation and system leakages.

This paper proposes a definition for environmental efficiency in irrigation management and develops a variance equation for its determination from application efficiency and distribution uniformity. The combination of variance approach, derived from the theory of propagation of errors (Beers, 1957; Parratt, 1961), allows for the determination of the variance of a parameter of interest, from variances of individual parameters (Clemmens, 1991). In its development, the equation parameters are either expressed as quotients, sums or products (Mood et al., 1974; Meyer, 1975; Clemmens, 1991).

Bralts et al. (1981) first used the variance combination technique in trickle irrigation, combining manufacturer's and emitter flow variations. Clemmens (1988) later used the same technique to account for factors affecting surface irrigation and to develop irrigation uniformity relationships (Clemmens, 1991). Jaynes and Clemmens (1986) determined statistical equations for the variance of infiltration depths using variances of different infiltration components. Their results were used to calculate distribution uniformity of the lower quartile.

Bralts et al. (1981) and Clemmens (1991) offer three justifications for the combination of variance technique. First, the magnitude and variability of a parameter is more easily estimated or measured than the actual distribution. Second, the impact of the variation of each parameter on the distribution of applied water can be analyzed. Third, because the approach uses statistical relations to integrate several factors, its use can be extended to systems other than those for which it was developed, or different systems can be evaluated using the same procedures.

The objectives of this research were to develop an irrigation environmental efficiency performance measure in irrigation management, relate it to other irrigation measures and evaluate selected irrigation systems and farms using this performance measure.

### 3. Theoretical development

A typical irrigation-farm-management system comprises four components: the irrigation system, irrigator, soil, and the environment. Environment is defined in this study as that portion of the irrigated field or soil profile that is excluded from the root zone. Consequently, *irrigation environmental efficiency*, $E_{IE}$, is defined in this study as a function of application efficiency, $AE$, distribution or statistical uniformity, $U_S$ and soil type, ST.

$$E_{IE} = f\,(AE,\ U_S,\ ST) \qquad [35]$$

$E_{IE}$ is a value computed from measured values of $U_S$, AE and ST. $f$ is a mathematical function. ST is treated in equation [35] as a constant. The validity of a constant assumption is based on the fact that seasonal changes in spatial variation of ST within the same field are considered insignificant compared to variations among fields. $U_S$ contains design parameters and can be considered a constant in those systems where the irrigator has no control. Since some design parameters are also management parameters and can, to some extent, be controlled by the irrigator, $U_S$ is treated as a variable. AE is a management variable directly controlled by the irrigator and is expected to have the most influence on $E_{IE}$.

Equation [35] shows that $E_{IE}$ can be estimated from measured quantities of AE and $U_S$ and an observed ST. The resulting term will have an error due to the individual errors in AE and $U_S$. These errors may be correlated.

A case can be made for the dependent error assumption. For correlated errors. AE and $U_S$ of unit area (i.e. $AE_i$ and $U_{Si}$) can be *paired* "in accordance with some known or suspected correlation" (Beers. 1957). The dependence of application efficiency on uniformity (von Bernuth. 1993; Walker. 1979) suggests such a correlation between the two parameters. Furthermore, systems with poor uniformity tend to use more water to attain the required depths. For example, a system that is only 50% uniform will take twice as much water as required if the water distribution is linear (Karmeli. 1978) to meet the required amounts if every part or a significant portion of the field is to receive at least the required depth. One can, therefore, associate low AE locations in the field with those areas receiving high amounts of water. However, spatial variability in infiltration rates and subsurface distribution effects are likely to weaken this correlation thus, tilting the balance towards an independent variable assumption.

Independent errors can be assumed considering that:

1. Irrigation frequency, applied depth and soil properties which dictate AE have no effect on $U_S$.
2. Economic, social and cultural habits in most cases influence management decisions such as allowable soil water deficit, irrigation duration and depth regardless $U_S$.
3. Variations in emitter flow, operating pressure heads, distortions from wind patterns, which constitute $U_S$ can be measured independent of AE.
4. Infiltration rates depend more on soil physical properties than the irrigation system.

Argument 3 implies that in any given observation there would be $N$ measurements of AE and

$U_S$ to compute $E_{IE}$. A set of AE and $U_S$ values can be imagined such that $E_{IE}$ is computed from randomly sampled $AE_i$ and $U_{Si}$ (Parratt, 1961). This imaginary set would represent the actual measured values of $AE_i$ and $U_{Si}$.

Assuming an independent error assumption, AE and $U_S$ measurements can be averaged to obtain $\mu_{AE}$ and $\mu_{Us}$. According to Meyer (1975), the best estimate of a function can be obtained from a Taylor series expansion. Similarly, the best estimate of $E_{IE}$ (equation [35]) can be obtained using a Taylor series expansion but ignoring higher order terms as

$$E_{IE} = f\left( [\mu_{AE} - \delta AE_i], [\mu_{U_s} - \delta U_{S_i}] \right) = f(\mu_{AE}, \mu_{U_s}) - \frac{\partial E_{IE}}{\partial AE} \delta AE_i - \frac{\partial E_{IE}}{\partial U_S} \delta U_{S_i} \quad [36]$$

where $\delta AE_i = AE_i - \mu_{AE}$ and $\delta U_S = U_{Si} - \mu_{Us}$ are relatively small deviations (Parratt, 1961). An individual deviation $\delta E_{IE}$ can be obtained by propagating individual errors in AE and $U_S$ as follows:

$$\delta E_{IE_i} = \frac{\partial E_{IE}}{\partial AE} \delta AE_i - \frac{\partial E_{IE}}{\partial U_S} \delta Us_i \quad [37]$$

From statistics, the sample variance, $S^2$, of a measured quantity is defined as the square of its standard deviation. Its mathematical expression, in terms of $E_{IE}$ is

$$S^2_{E_{IE_i}} = \frac{\sum_{i=1}^{N} (\delta E_{IE_i})^2}{N - 1} \quad [38]$$

Squaring equation [37] and substituting in [38] gives

$$S^2_{E_{IE}} = \frac{\left(\frac{\partial E_{IE}}{\partial AE}\right)^2 \Sigma(\delta AE_i)^2 + \left(\frac{\partial E_{IE}}{\partial U_s}\right)^2 \Sigma(\delta U_{s_i})^2 + 2\,\frac{\partial E_{IE}}{\partial AE}\,\frac{\partial E_{IE}}{\partial U_s}\,\Sigma(\delta AE_i)\,\Sigma(\delta U_{s_i})}{N-1} \qquad [39]$$

From the definition of the variance we obtain

$$S^2_{AE} = \frac{\Sigma(\delta AE_i)^2}{N-1}; \qquad S^2_{U_s} = \frac{\Sigma(\delta U_{s_i})^2}{N-1} \qquad [40]$$

The results from [40] when substituted in [39] give a variance for $E_{IE}$ as

$$S^2_{E_{IE}} = \left(\frac{\partial E_{IE}}{\partial AE}\right)^2 S^2_{AE} + \left(\frac{\partial E_{IE}}{\partial U_s}\right)^2 S^2_{U_s} + 2\,\frac{\partial E_{IE}}{\partial AE}\frac{\partial E_{IE}}{\partial U_s}\,S_{AE}\,S_{U_s} \qquad [41]$$

From systems theory (Beers, 1957; Parratt, 1961; Doebelin, 1966), the overall inaccuracy or error of a system can be calculated, as in equation [41] if the individual component errors are known. These errors may be considered absolute limits, statistical bounds (i.e., within a specified number of standard deviations) or uncertainties on which some odds can be accepted (Doebelin, 1966). Since most irrigation and soil properties are treated as random variables with statistical bounds, we use the latter concept to derive a variance equation for irrigation environmental efficiency.

$$E_{IE} = AE \cdot U_s \qquad [42]$$

Taking the partial derivatives of [42] and evaluating at their mean values $\mu$, yields

$$\frac{\partial E_{env}}{\partial U_S} = \mu_{AE} \qquad \frac{\partial E_{env}}{\partial AE} = \mu_{U_S} \qquad [43]$$

The values of [43], best estimaters of AE and $U_S$, can be substituted in [41] to obtain

$$S^2_{E_{IE}} = \mu^2_{U_S} S^2_{AE} + \mu^2_{AE} S^2_{U_S} + \mu_{U_S} \mu_{AE} 2 S_{AE} S_{U_S} \qquad [44]$$

A common statistical parameter, the coefficient of variation, can be obtained by dividing [44] by their respective means.

$$\frac{S^2_{E_{IE}}}{\mu^2_{E_{IE}}} = \frac{S^2_{AE} \mu^2_{U_S}}{\mu^2_{AE} \mu^2_{U_S}} + \frac{S^2_{U_S} \mu^2_{AE}}{\mu^2_{AE} \mu^2_{U_S}} + 2 \frac{S_{AE} S_{U_S} \mu_{U_S} \mu_{AE}}{\mu^2_{AE} \mu^2_{U_S}} \qquad [45]$$

A variance equation for irrigation environmental efficiency is thus derived as

$$CV^2_{E_{env}} = CV^2_{AE} + CV^2_{U_S} + 2 \frac{S_{AE} S_{U_S}}{\mu_{AE} \mu_{U_S}} \qquad [46]$$

Because of the independent error assumption (Beers, 1957) in AE and $U_S$ the covariance (last) term in [46] goes to zero and the equation reduces to

$$CV^2_{E_{IE}} = CV^2_{AE} + CV^2_{U_S} \qquad [47]$$

The resulting irrigation environmental efficiency term is obtained by subtracting the sqaure root of [47] from one and multiplying by 100 in the manner of Bralts et al. (1981). i.e..

$$E_{IE} = (1 - CV_{E_{IE}})100 \qquad [48]$$

$E_{IE}$ can be interpreted as a probabilistic measure of the potential to posing an environmental hazard in irrigation management. An $E_{IE}$ of 40% would imply that the current practice is six of ten times environmentally friendly or that one poses a potential environmental concern four of every ten times.

**4. Procedures**

A computer simulation program (Appendix 1) was written to calculate irrigation environmental efficiency in accordance with equations [47] and [48] for various minimum application ratios. application efficiency and uniformity values. For any given system. the mean depth and its standard deviation describe its uniformity. Uniformity values were calculated assuming a normal distribution function. The values ranged from 40 to 90 and reflect ranges in data from St. Joseph Irrigation District. MI and those reported in the literature (Heermann et al.. 1992). $CV_{AE}$ values were obtained using the procedure and equations developed in section III-A.

Statistical uniformity. application efficiency and the fractional area receiving adequate irrigation were related to irrigation environmental efficiency through the $E_{IE}$ concept with charts that combine non-dimensional water depths. system uniformity and application efficiency. Irrigation environmental efficiency classification ranges were established based on recommended statistical uniformity ranges (Bralts et al.. 1981).

Data from 65 center pivot systems in St. Joseph Irrigation District, MI were analyzed and classified according to the $E_{IE}$ ranges. The data were collected by the Soil Conservation Service irrigation team for the district in 1987, 1989-1992 (Appendix 5). The results were compared to similar data analysis from Fort Collins, Colorado (Heermann et al., 1992). The aim was to answer the following questions: Suppose these systems were operated at the SCS's recommended 65% application efficiency (English and Nuss, 1980), how would they fare environmentally? What difference will it make in changing a management practice, e.g., by increasing the application efficiency?

Five farms from St. Joseph County Irrigation District, MI (whose irrigation schedules could be matched with their respective center pivot systems) were evaluated using farmers' actual irrigation schedules and SCS-Scheduler (Shayya and Bralts, 1994). SCS-Scheduler, is an irrigation scheduling package that uses field characteristics, local weather data and the root zone water balance method for water budget updates and irrigation scheduling. The required inputs which include amounts of water applied, rainfall events, soil characteristics and weather information were obtained from farm records in the irrigation district office.

SCS-Scheduler has the capability of reporting excess water from either irrigation or rainfall. Excess water is the amount of water above the soil's available water capacity for a given depth. For each irrigation event (the day the farm was irrigated, expressed as a fraction of the growing season), application efficiency was calculated as one minus the ratio of excess irrigation water to the total water applied. From the application efficiency and system uniformity, $E_{IE}$ values for each scheduled irrigation farm were determined and related to the percent of the growing season.

## 5. Results and discussion

### *a. Irrigation environmental efficiency and related performance measures*

Irrigation environmental efficiency ($E_{IE}$) results for different system uniformities ($U_S$) and application efficiencies (AE) are presented graphically in Figures 14 and 15. A detailed output of the simulation results is shown in Appendix 2.

Figure 14 shows $E_{IE}$ as a function of application efficiency, statistical uniformity and minimum application ratio (MAR). The figure suggests that a manager has two possible options to improve an unsatisfactory current $E_{IE}$ value. The first, which assumes a desired constant application efficiency, is to improve system uniformity. For example, with reference to Figure 14, $E_{IE}$ can be increased from 56% to 72% while maintaining a 70% AE, if the system uniformity of 65% is improved to 80%. The coefficient of variation, by definition, suggests system uniformity can be increased by reducing the standard deviation of the mean applied depth. Improving system uniformity requires repairing and/replacing system components and in some instances a complete overhaul of the entire system. Bralts and Edwards (1987) discussed various options. One alternative is to increase the deficiently irrigated area (Clemmens, 1991). Improving system uniformity up to 100% is theoretically possible, but economically infeasible (von Bernuth, 1993).

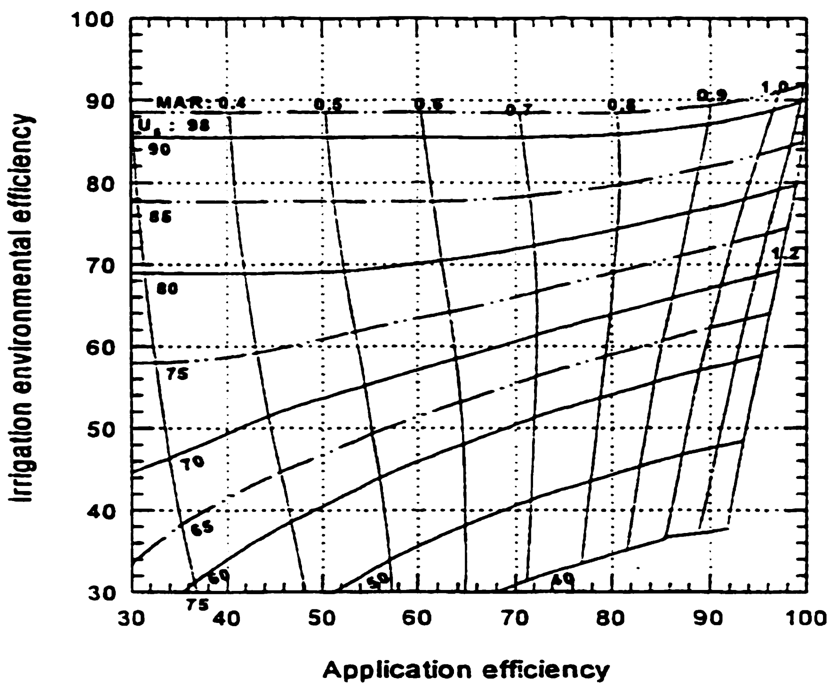



Figure 14. Irrigation environmental efficiency related to MAR, $U_S$ and AE.

The second option is to increase application efficiency. A system whose statistical uniformity is 65% and operates at 56% application efficiency has a 50% $E_{IE}$. This system can have a 60% $E_{IE}$ if it is operated at 83% application efficiency (Figure 14). However, the fractional area receiving at least the required application depth decreases by 0.24 (from 0.92 to 0.68, Figure 15). Using these figures the irrigator can decide on what fractional area needs to be fully recharged to significantly influence yield. Management decisions can be made based on derived trade offs in $E_{IE}$, area and AE.

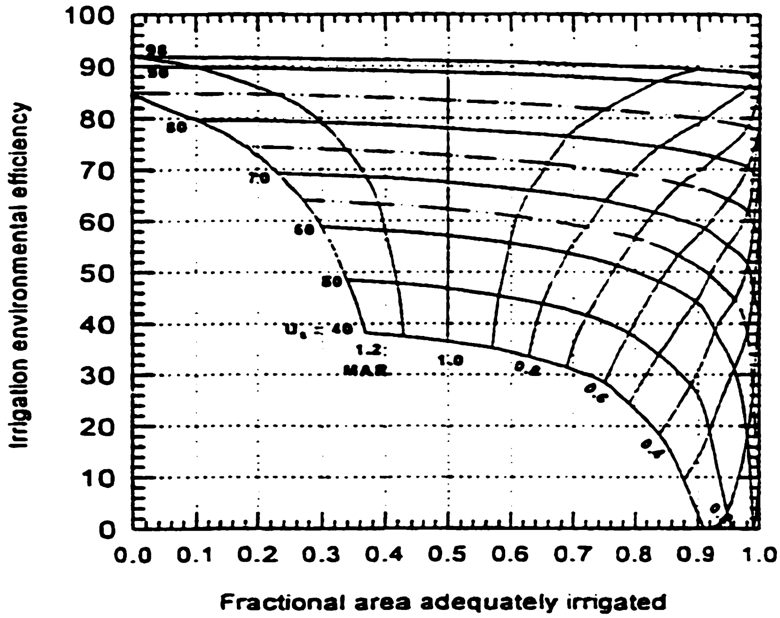



Figure 15. Irrigation environmental efficiency related to MAR, $U_S$, and irrigated area.

Figures 14 and 15 were developed to: 1) indicate the effects of possible changes in the required depths in irrigation management assuming a constant coefficient of variation: and 2) estimate or predict irrigation environmental efficiency in the design and management of irrigation systems. If the minimum application ratio and system uniformity are known, then AE and $E_{IE}$ can be determined. Also, if the fractional area to be fully irrigated is known for a recommended $E_{IE}$ level, MAR and $U_S$ can be selected to satisfy those conditions. The $E_{IE}$ charts presented bridge the gap between the agronomic and engineering aspects of irrigation management (Figure 13, page 63). They can serve as an advisory tool for both mangers and designers in making tactful and strategic decisions as well as suggest some practical ideas for management options. One must, however, recognize that other variables such as labor availability, soil and climatic conditions, social and cultural habits and system capacity still significantly influence daily or seasonal practical management decisions.

*b. Example problem 1*

A center pivot irrigation system has a statistical uniformity of 85%. If 90% of the irrigated area is to be fully recharged, determine MAR, $E_{IE}$ and AE.

***Solution***

Ninety percent of the irrigated area corresponds to 0.90 of the fractional area adequately irrigated. From Figure 17, locate 0.90 (circled 1) and $U_S$ = 85% (3rd horizontal solid line, in the body of Figure 17, from the top). Where the two lines intersect, read across the dotted line: $E_{IE}$ = 80% and down the curved line: MAR = 0.8.

Go to Figure 16. Enter the chart at the $E_{IE}$ = 80 tick (circled 1). Follow the $E_{IE}$ = 80 line to where the $U_S$ = 85 and MAR = 0.8 lines meet. Read vertically on the x-axis. AE = 81%.

*c. Example problem 2*

Determine the environmental efficiency of a drip irrigation system whose uniformity is 70% if the mean application depth is 12 mm and the required depth is 7 mm. What fraction of the field will be under-irrigated. Can the irrigator raise $E_{IE}$ to 70%?

***Solution***

The minimum application ratio is, required depth divided by mean depth: 7/12 = 0.58. From Figure 17, locate $U_S$ = 70% and MAR = 0.58 lines (boxed 2). Read across to the y-axis: $E_{IE}$ = 58% and down to the x-axis: AE = 62%. From Figure 17, enter the Y-axis at $E_{IE}$ = 58 (boxed 2).

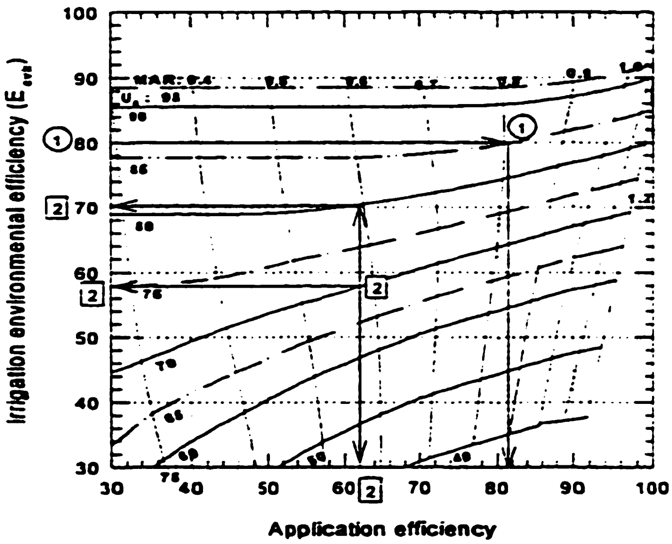



Figure 16. Estimating $E_{IE}$ from AE. $U_S$ and MAR for two example problems.

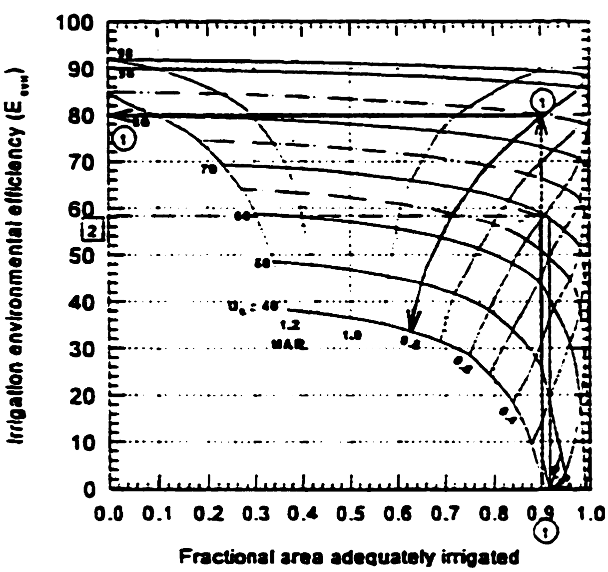



Figure 17. Estimating $E_{IE}$ from fractional area adequately irrigated. MAR and $U_S$ for two example problems.

Move across to MAR = 0.58 to $U_S$ = 70. Move vertically to the X- axis and find the fractional area fully irrigated is about 0.91. Therefore the under irrigated area is: 1 - fully irrigated area = 0.09 or 9%. For the same application efficiency. $E_{IE}$ can be raised to 70% by increasing system uniformity to 80% (Figure 17). A 70% $E_{IE}$ value cannot be achieved by increasing AE with this system.

d. ***Recommended and suggested performance measures***

Ideally. acceptable $E_{IE}$ values should be based on acceptable statistical uniformity levels and the effective root zone. Table 5 shows suggested acceptable $E_{IE}$ values based on recommended statistical uniformity values (Bralts et al.: 1981). The lowest average AE value corresponding to $E_{IE}$ and $U_S$ was 62%. The Soil Conservation Service (English and Nuss. 1980) generally recommends 65% regardless of system uniformity. In light of $E_{IE}$ . this value may be somewhat misleading for unspecified system and management conditions. Consider a system whose statistical uniformity is 60% and operates at 65% AE: both are acceptable and recommended values. Figure 16 shows such a system has 48% $E_{IE}$ - an unacceptable. Even at 90% AE this system will still be classified as environmentally poor.

**Table 5. Irrigation measures and suggested $E_{IE}$ classification values**

| Comment | $U_S$* | CU** | $E_{IE}$ |
|---|---|---|---|
| Excellent | > 90 | > 90 | > 85 |
| Very good | 80 - 90 | 75 - 90 | 75 - 85 |
| Fair | 70 - 80 | 70 - 78 | 60 - 75 |
| Poor | 60 - 70 | 65 - 78 | 50 - 60 |
| Unacceptable | <60 | <65 | < 50 |

*$U_S$ obtained from Bralts et al. (1981).

**CU = Christiansen uniformity coefficient (Christiansen, 1942).

The following conclusions can be made from Table 5 and Figure 16.

1. Systems with 50% statistical uniformity and below are environmentally unacceptable regardless of the application efficiency and minimum application ratios.

2. $E_{IE}$ should be the guiding index in recommending acceptable values for combined statistical uniformity and application efficiency.

*e. Center pivot-$E_{IE}$ statistical distribution*

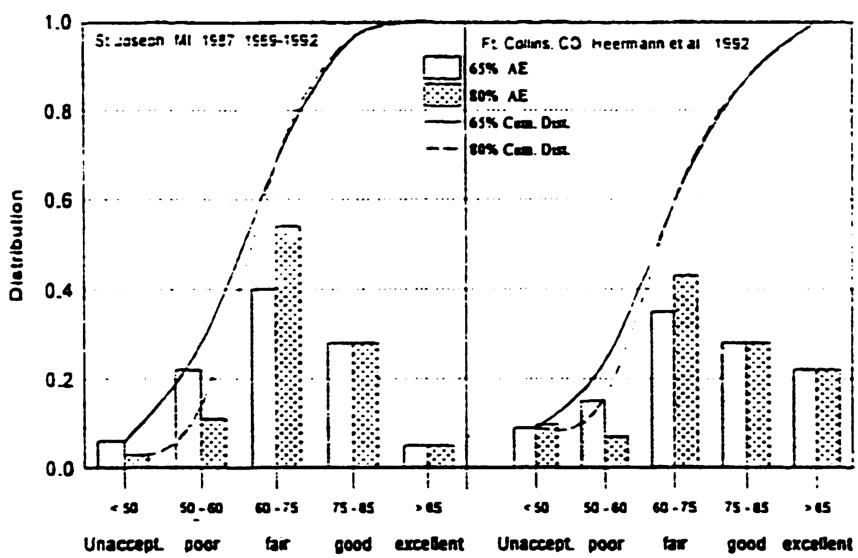



Figure 18. $E_{IE}$ distribution of center pivot systems from Michigan and Colorado.

Figure 18 shows the statistical distribution of evaluated center pivot systems in five $E_{IE}$ categories. The right diagonal bars assume a 65% AE management while the cross hatched bars assume an 80% AE management. The cumulative distributions of the data are shown as the S-curves.

In accordance with Table 5, 70% of the systems from Michigan and 75% from Colorado fall in the fair to excellent group. There is, however, a 10% significant difference between the two locations in the excellent category. This difference seems to suggest that managers in drier regions are more likely to strive for well calibrated systems than those in humid areas where irrigation frequencies are fairly low. Both locations have a majority of the systems in the *fair* category, about the same proportion in the *good* category and the least proportion in the *unacceptable* category.

Increasing the application efficiency from 65 to 80% in the systems from Michigan significantly reduced the number of *poor* systems by 8% and increased the number of *fair* systems by 14%. The *fair* and *poor* categories from Colorado were, respectively, increased and reduced by 8%. This change was not significant. There was no observed change in the good and excellent categories in both locations.

These results do show that increased application efficiency for poor uniform systems is a necessity if environmental constraints are to be met. For high uniform systems environmental efficiency is not very sensitive to application efficiency. This means that an investment in a high uniform system pays off both environmentally and in an increased irrigated area. In arid areas increased irrigated area means increased yields. Increasing AE from 65 to 80 in an 80% uniform system has little impact on $E_{IE}$, but significantly reduces the fully irrigated area. It is likely that the manager on the 65% AE schedule is more likely to endure increased water costs.

*f. Irrigation Scheduling and $E_{IE}$*

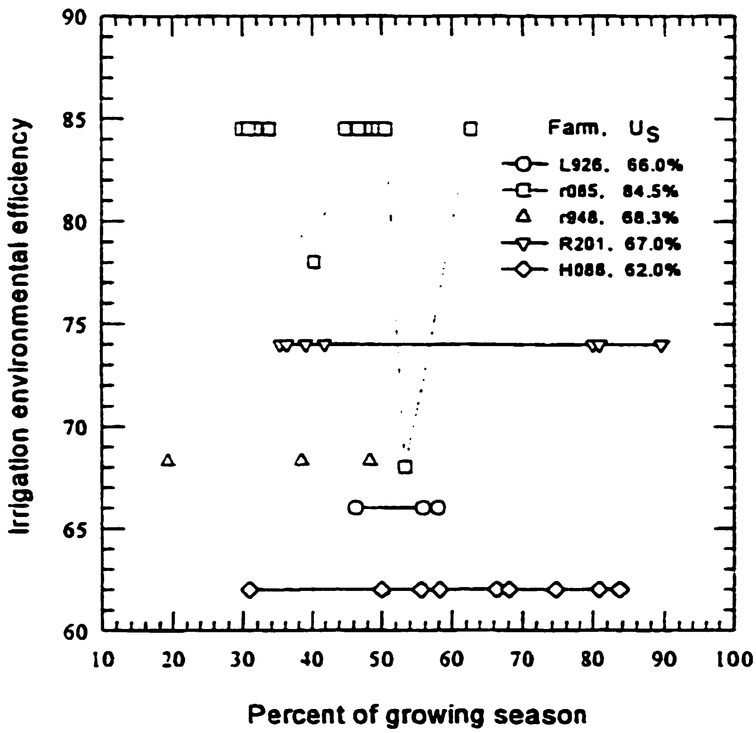



Figure 19. Seasonal variation of $E_{IE}$ for selected Michigan farms.

SCS-Scheduler output for the five evaluated farms are shown in Appendix 4. Evaluation results are shown in Figure 19. Four of the five farms, on the average operated in the *fair* $E_{IE}$ category and one in the *very good* category. The results show that three of five farms were not over-irrigating for that season. It is interesting to note that the two farms that over-irrigated in some schedules belonged to one farmer and were operated in different years (1990 - r948 and 1991 - r085). One other farm irrigated in 1991 was H088. The farmer maintained 100% AE in all schedules but had a poor $E_{IE}$ compared to R085.

These results show two things: 1) if a farm is irrigated at 100% AE then $E_{IE}$ for the farm is the system uniformity. That means no matter how hard management tries, they will never do as well as they would like to. In other words, it is impossible to achieve a high $E_{IE}$ value under the best management practice with a poor system. The only alternative is to improve the system. 2) A highly uniform system (such as r085 in Figure 19) can be operated in an environmentally unsound manner. This is where management becomes the most sensitive variable in the $E_{IE}$ equation. These two scenario represent the extremes and are easy to handle. The most complicated case is that in which both management variables and the irrigation system are unstable. Management has to simultaneously stabilize its variables and adjust system variables to compensate for the instability in the system. The danger here is paying more attention to one set of variables, and that is something likely to happen.

The usefulness of this approach draws its strengths from the ability to operate and manage the system within accepted limits. This raises some interesting questions. Why would r085 bother to afford a higher uniformity system or maintain a high AE when at worst, the manager is still environmentally better than H088? What societal incentives are there to move H088 to a higher level and keep r085 at the present level? Are the social, economic and environmental benefits justified by the added costs? Answers to these questions are definitely controversial and require input from multi-disciplinary groups. Unfortunately, such group discussions often tend to be guided by emotional and political knowledge rather than scientific facts.

## 6. Conclusions

The design and management of irrigation systems require an environmental dependent variable for various design and management alternatives. $E_{IE}$, with the accompanying charts, quantifies the environmental efficiency of irrigation management and system uniformity. $E_{IE}$ should, therefore, be estimated in the design and operation of irrigation systems.

$E_{IE}$ charts presented bridge the gap between agronomic (management) and engineering (physical) aspects of irrigation and link their operational consequences to the environment. They serve as a tool for comparing management options whose results are environmental protection and effective water use.

A well calibrated system can be managed in an environmentally unsound manner. Under the best management practice irrigation environmental efficiency cannot be better than system uniformity.

A large proportion of the center pivot systems used in this study fall in the fair to excellent category of the irrigation environmental efficiency classification.

# IV. General Conclusion

*What is observed depends on who is looking*[9]
*- W. H. George -*

Resource exploitation, soil degradation, water resource depletion and pollution are insidious trends of the past still prevalent in today's society. Lessons from history show that great losses, costs and consequences await us, unless there is an effort on our part to improve irrigation management. Improved management practices and the willingness to sacrifice are a necessity to balance environmental, economic and social values.

In general, efficiency assumes a management scheme relating the output of a system to its inputs. When used as a performance measure, the term provides a basis on which decisions can be made regarding system operations. Also, it can be used to determine which system components need adjustment, and to what extend. It's also a useful tool for comparing different systems. In irrigation management, irrigation environmental efficiency will be an indicator of the potential to environmental pollution.

Statistical distributions of application efficiency for various statistical (system) uniformities have been presented which can be used to characterize the nature of application efficiency at a particular irrigation schedule (minimum application ratio) and/or describe the expected variation in seasonal application efficiency (with increasing ET demand). One limitation of application efficiency has been its inability to indicate irrigation uniformity. Such a limitation may no

[9] *The Scientist: a scientific study of his methods.* Williams & Norgate, Ltd., London. 1936.

longer exist, as a term can be defined which evaluates the uniformity of infiltrated water from irrigation.

Regression equations were developed to estimate application efficiency as a function of the minimum application ratio (MAR) and statistical (system) uniformity. However, system uniformity has no significant influence on application efficiency at about 0.7 MAR. Relationships among application efficiency, statistical uniformity, MAR and irrigated area provide trade-offs from which managers can make informed decisions.

A new performance measure, irrigation environmental efficiency ($E_{IE}$), was presented that can be applied to the design and management of irrigation systems. $E_{IE}$ should therefore be estimated in the design and operation of irrigation systems.

$E_{IE}$ charts presented, bridge the gap between agronomic (management) and engineering (physical) aspects of irrigation and link their operational consequences to the environment. They serve as a tool for comparing management options whose results are environmental protection and effective water use.

Systems with 50% statistical uniformity and below are environmentally unacceptable regardless of the application efficiency and minimum application ratios. $E_{IE}$ should be the guiding index in recommending acceptable values for both system uniformity and application efficiency.

About 70% of the center pivot systems used in the study fall in the fair to excellent category of the irrigation environmental efficiency classification. A well calibrated system can be operated in a manner that is environmentally unsound. Under the best management practice, $E_{IE}$ can never be better than the system's uniformity.

# V. Recommendations

*New combinations in our thoughts arise from rational associations ... or perhaps chance circumstances*[10]
*- W. I. B. Beveridge -*

The design and management of irrigation systems contain more than the engineering and agronomic inputs. Human. economic and environmental factors must be taken into account. Many factors involved in crop production should and must be evaluated in an integrated management system. This calls for an interdisciplinary approach in irrigation design and management.

Although there is wide recognition of the environmental concerns in irrigation management. attempts to address those concerns still emphasize the single discipline approach. There is a need to incorporate the systems approach in irrigation management in order to provide managers and farmers with options from which they can make economically and environmentally sound decisions.

Application efficiency is an important irrigation performance measure. Apart from its indirect estimation using the equations in the section *Application efficiency determination.* (page 36). direct field measurements of. or any proposed procedures in sprinkler irrigation have not been documented. Furthermore. there is a need to investigate the impacts of

---

[10] Imagination: *The art of scientific investigation.* 3rd Ed. p. 89. 1957.

management practices on application efficiency as well as the probability of such efficiencies under various management strategies.

Irrigation environmental efficiency ($E_{IE}$) should be the guiding index in recommending acceptable values for both system uniformity and application efficiency. As a management tool. $E_{IE}$ may be useful in determining the gross amount of water to supply to any given irrigation field. For example. the gross depth of water application per irrigation is computed by dividing the net depth required by the overall system efficiency. It is proposed that the system efficiency in that equation be replaced by irrigation environmental efficiency: i.e $d_{gross} = d_{net}/E_{IE}$ and validated under various field conditions.

The approach used in this study. and the developed performance measure ($E_{IE}$) should find application in any type of irrigation system and management. The usefulness of this approach depends on whether the irrigation system(s) and management option(s) can be maintained within reasonable and/or acceptable standards. It also depend on whether society can determine if the economic and social rewards for adjusting management practices or design are likely sufficient to justify added costs.

# VI. References


Adams. M. C. 1974. Historic patterns of Mesopotamian irrigation agriculture. In: *Irrigation-Impact on Society*. Anthropological papers of the University of Arizona #25. p. 1-6. University of Arizona Press Tuscan. Arizona.

Aljibury. F. K. 1978. Introduction to irrigation efficiency and scheduling. In: *Efficiency in Irrigation*. The Irrigation Association: Technical Conference Proceedings. 160-161.

Anyoji. H and I. P. Wu. 1994. Normal distribution water application for drip irrigation schedules. *Transactions of the ASAE*. 37(1):159-164.

ASAE. 1993. Soil and water engineering terminology. *American Society of Agricultural Engineering Standards: ASAE S526.*

Bagley. J.M. and Criddle. W.D. 1956. Evaluating sprinkler irrigation systems. *Utah Experiment Station Bulletin*. #387. Utah State University.

Beck. V. J. and J. A. Kenneth. 1977. *Parameter Estimation in Engineering and Science*. John Wiley & Sons. New York. 501 pp.

Beers. Y. 1957. *Introduction to the Theory of Error.* Addison-Wesley Publishing.

Benami. A. and F. R. Hore. 1964. A new irrigation-sprinkler distribution coefficient. *Transactions of the ASAE*. 7:157-158.

Brakensiek. D. L., R. L. Engleman and W. J. Rawls. 1981. Variation within texture classes of soil water parameters. *Transactions of the ASAE*. 24(2):355-339.

Bralts. V. F., I. Wu and H. M. Gitlin. 1981. Manufacturing variation in drip irrigation uniformity. *Transactions of the ASAE*. 24(5):113-119.

Bralts. V. F. and D. M. Edwards. 1987. Drip irrigation and evaluation based on the statistical uniformity concept. In: D. Hillel. ed.. *Advances in Irrigation*. Vol. 4:67-117.

Cantor. L. M. 1970. *A World Geography of Irrigation*. Praeger. New York.

Carruthers. I and C. Clark. 1981. Planning irrigation development. Chapter 8. In: *The Economics of Irrigation.* LiverPool University Press. England.

Carter. D. L. 1980. The impact of irrigation of ground water quality. In : J. Eggleston. ed. *Irrigation and Drainage: Today's Challenges.*

Chaudhry. F. H. 1977. Sprinkler uniformity measures and skewness. *Journal of the Irrigation and Drainage Engineering,* 102 (IR4): 425-433.

——— 1978. Non-uniform sprinkler irrigation application efficiency. *Journal of Irrigation and Drainage Division.* 104(IR2): 165-178.

Chestnut. H. 1966. *Systems Engineering Tools.* John Wiley and Sons. New York. 646p.

Christiansen. J. E. 1942. Irrigation by sprinkling. *California Agricultural Experiment Station Bulletin 670.* University of California. Berkeley.

Clemmens. A. J. 1991. Irrigation uniformity relationships for irrigation system management. *Journal of the Irrigation and Drainage Engineering,* 117(5): 682-699.

——— 1988. Method for analyzing field scale surface irrigation efficiency. *Journal of the Irrigation and Drainage Engineering,* 114 (1): 74-88.

Cohen. O. P. and E. Bresler. 1967. The effect of non-uniform water application on soil moisture content. moisture depletion and irrigation efficiency. *Soil Science Society of America Proceedings.* 31:117-121.

Cuenca. R. H. 1989. *Irrigation System Design: An Engineering Approach.* Prentice Hall. Englewood Cliffs. New Jersey.

Dabbous. B. J. 1962. A study of sprinkler uniformity evaluation methods. Master of Science Thesis. Utah State University. Logan. Utah.

Dent. J. B. 1975. The application of systems theory in agriculture. In: G. E. Dalton. ed.. *Study of Agricultural Systems.* Applied Science Publishers. London.

Doebelin. E.O. 1966. *Measurement Systems: Application and Design.* McGraw-Hill. New York.

Doyle. C. J. 1990. Application of systems theory to farm planning and control: modelling resource allocation. In: J. G. W. Jones and P. R. Street. eds.. *Systems Theory Applied to Agriculture and the Food Chain.* 89-112. *Elsevier Applied Science.* London and

New York.

Elliot. R.L.. J. D. Nelson. J. C. Loftis and W. E. Hart. 1980. Comparison of sprinkler uniformity models. *Journal of the Irrigation and Drainage Engineering,* 106(IR4): 321-330.

English. M. J. and G. S. Nuss. 1980. Designing for deficit irrigation. In : J. Eggleston. ed.. *Irrigation and Drainage: Today's Challenges.*

Falcon. W. P. and C. H. Gotsch. 1971. Relative price response. economic efficiency and technological change: A case study of the Punjab agriculture. In: W.P. Falcon and G. E. Dalton. eds.. *Development Policy II - The Pakistan Experience.* Cambridge: Harvard University Press.

Gulhati. N. D. and W. C. Smith. 1967. Irrigated Agriculture and historical review. In: R. M. Hagen. H. R. Haise and T. W. Edminister. eds.. *Irrigation of Agricultural Lands.* Agronomy Monograph # 11. American Society of Agronomy. Madison. Wisconsin.

Harding. G. 1968. The tragedy of the commons. *Science.* 143-148.

Harris. F. S. 1920. *Soil Alkali, its Origin Nature and Treatment.* John Wiley and Sons. New York.

Hart. W. E. 1972. Subsurface distribution of nonuniformity applied surface water. *Transactions of the ASAE.* 15(4):656-661. 666.

Hart. W. E. and D. F. Heermann. 1976. Evaluating water distributions of sprinkler irrigation systems. Colorado State University Experiment Station. Technical Bulletin No. 128.

Hart. W. E. and W. N. Reynolds. 1965. Analytical design of sprinkler systems. *Transactions of the ASAE.* 8(1):83-85. 89.

Heermann. D.F.. H. R. Duke and A. M. Serafim. 1992. Distribution functions to represent center-pivot water distribution. *Transaction of the ASAE.* 35(5):1465-1472.

Hill. R. W. and J. Keller. 1980. Irrigation system selection for maximum crop profit. *Transaction of the ASAE.* 23(2):366-372.

Hillel. D. 1987. *The Efficient Use of Water in Irrigation.* World Bank technical paper No. 64.

Holy. M. 1981. Irrigation systems and their role in the food crises. International Commission on Irrigation and Drainage Conference.

Howell, D. T. 1964. Non-uniformity and sprinkler application efficiency. *Journal of Irrigation and Drainage Division*, ASCE(IR3): 41-53.

ICID. 1980. *The Application of System Analysis to Problems of Irrigation, Drainage and Flood Control: A Manual for Water and Agricultural Engineers*. A. W. Biswas, ed. International Committee on Irrigation and Drainage. Pergamon Press. New York.

Israelson, O. W. and V. E. Hansen. 1967. *Irrigation Principles and Practices*. 3rd Edition. John Wiley. New York.

Izadi, B., P. Studer and I. McCann. 1991. Maximizing set-wide furrow irrigation application efficiency under full irrigation strategy. *Transactions of the ASAE*. 34(5):2006-2014.

James, P. W., R. J. Hanks and J. J. Jurinak. 1982. *Modern Irrigated Soils*. John Wiley and Sons. New York.

Jaynes, D. B. and A. J. Clemmens. 1986. Accounting for spatial variable infiltration in border irrigation. *Water Resources Research*. 22(8):1257-1262.

Jendel Scientific. 1994. Transforms and curve fitting. SigmaPlot Scientific Graphing Software for Windows. Ver. 2.0.

Jensen, M. D., (ed.). 1980. *Design and Operation of Farm Irrigation Systems*. ASAE Monograph No. 3. St Joseph, MI 49085.

Kappel, W. 1974. Irrigation development and population pressure. In: *Irrigation-Impact on Society*. Anthropological papers of the University of Arizona #25. p. 159-167. University of Arizona Press Tuscan, Arizona.

Karmeli, D. 1977. Water distribution patterns for sprinkler and surface irrigation systems. Proc. National Conference on Irrigation Return Flow Quality Management, Colorado State University. Fort Collins, Colorado.

——— 1978. Estimating sprinkler distribution patterns using linear regression. *Transactions of the ASAE*. 21(4):682-686.

Karmeli, D., L. J. Salazar and W. R. Walker. 1978. Assessing the spatial variability of irrigation water applications. Document No. EPA-600/2-78-041. U.S. Environmental Protection Agency. ADA, OK.

Keller, J. and R. D. Bliesner. 1990. *Sprinkle and trickle irrigation*. Van Nostran Reihnhold. New York.

Keller. J. and D. Karmeli. 1974a. *Trickle Irrigation Design*. Rain Bird Sprinkler Manufacturing Corporation. Glendora. CA.

——— 1974b. Trickle irrigation design parameters. *Transactions of the ASAE*. 17(4):678-784.

Kelley. W. P. 1964. Maintenance of a permanent irrigation agriculture. *Soil Science*. 98:(113-117).

Kimbell. M. K.. W. M. Miller. C. N. Mohannah and E. H. Jensen. 1990. Applied water required for sprinkler irrigated alfalfa in Western Nevada. *Applied Agricultural Resources*. 5(4):268-275.

Kruse. E. G. 1978. Describing irrigation efficiency and uniformity. *Journal of Irrigation and Drainage. Division of ASCE*. 104(IR1):35-41.

Lamack. W. F. and Z. X. Niemiera. 1993. Application method affects water application efficiency of spray stake-irrigated containers. *Horticultural Science*. 28(6):625-627.

Ley. T. W. and W. Chyma. 1981. Furrow irrigation practices in Northern Colorado. *Transactions of the ASAE*. 24(3):610-616.

McCuen. R. H. 1973. The role of sensitivity analysis in hydrologic modeling. *Journal of Hydrology*. 18:37-53.

Manetsch. T. J. and G. L. Park. 1993. The systems approach as a problem solving methodology. In: *Systems Analysis and Simulation with Applications to Economic and Social Systems*. Dept. of Electrical Engineering. Michigan State University.

Martin. E.C. 1992. *Management Strategies to Minimize Nitrate Leaching in Seed Corn Production*. Ph.D. Dissertation. Michigan State University.

Meyer. S.L. 1975. *Data Analysis for Scientists and Engineers*. John Wiley & Sons. New York.

Minitab. 1993. *Minitab Reference Manual*. Release 9 for Windows. Minitab Inc.. Lebanon. PA

Mintzberg. H. 1976. Planning on the left side and managing on the right. *Harvard Business Review*. July-August.

Mood. A.M.. Graybill. F.A. and Boes. D.C. 1974. *Introduction to Theory of Statistics*. McGraw Hill. New York.

Naylor. T. H. and J. W. Finger. 1967. Verification of computer simulation models. *Management Science.* 14:2.

Neter. J., W. Wasserman and M. H. Kutner. 1990. *Applied Linear Statistical Models.* 3rd Edition. IRWIN. Boston. MA.

Ogata. K. 1978. *Systems Dynamics.* Prentice-Hall. Englewood Cliffs. New Jersey.

Parratt. L. G. 1961. *Probability and Experimental Errors in Science.* John Wiley & Sons. New York.

Rauschkolb. R. S. and A. G. Hornsby. 1994. *Nitrogen Management in Irrigated Agriculture.* Oxford University Press. Oxford.

Robinson. S. C. 1978. Measuring efficiency of surface irrigation systems. In: *Efficiency in Irrigation.* The Irrigation Association: Technical Conference Proceedings. 209-212.

Rountree. J. H. 1977. Systems thinking - some fundamental aspects. *Agricultural Systems.* 2:247-254.

Seginer. I., D. Kantz and D. Nir. 1991. The distribution by wind of the distribution patterns of single sprinklers. *Agricultural Water Management.* 12:344-359.

Seniwongse. C., I. Wu and W. N. Reynolds. 1972. The effects of skewness and kurtosis on the uniformity coefficient and their application to sprinkler irrigation design. *Transactions of the ASAE.* 15(2):266-271.

Shayya. W. H. and V. F. Bralts. 1994. SCS-Scheduler Microcomputer Irrigation Scheduling Package. Version 3. Department of Agricultural Engineering. Michigan State University. East Lansing. MI.

Shearer. M. N. 1978. Comparative efficiency of irrigation systems. In: *Efficiency in Irrigation.* The Irrigation Association: Technical Conference Proceedings. 183-188.

Sinai. G. and D. Zaslavsky. 1977. Factors affecting water distribution after uniformity irrigation. ASAE paper. St Joseph. MI 49805.

Solomon. K. H. 1985. Global uniformity of trickle irrigation systems. *Transactions of the ASAE.* 28(4):1151-1158.

——— 1983. Irrigation uniformity and yield theory. Ph.D. Dissertation. Utah State University. Logan. Utah.

Street. P. R. 1990. A systems view of commercial supply and marketing links. In: J. G. W. Jones and P. R. Street. eds.. *Systems Theory Applied to Agriculture and the Food Chain.* 159-204. Elsevier Applied Science. London and New York.

Su. M. 1979. Comparative evaluation of irrigation uniformity indices. Master of Science Thesis. Utah State University. Logan. Utah.

Taylor. S. A. and G. L. Ashcroft. 1972. *Physical Edaphology: The Physics of irrigated and non-irrigated soils.* chapter 16. W. H. Freeman and Company. San Francisco.

Thompson. S. A. 1988. Patterns and trends in irrigation efficiency. *Water Resources Bulletin.* 24(1):57-63.

Till. M. R. and M. G. Boss. 1985. The influence of uniformity and leaching on the field application efficiency. *Bulletin of International Committee on Irrigation and Drainage. New Delhi.* 34(1):32-35. 60.

Tsakiris. G. P. 1985. Infiltration efficiency in sprinkler irrigation. *Advances in Water Resources.* 8:44-47.

van Schilfgaarde. J. 1994. Irrigation - a blessing or a curse. *Agricultural Water Management.* 25:203-209.

Vang. H. and K. Barney. 1994. *Computer Simulation Analysis of Biological and Agricultural Systems.* CRC Press. Ann Arbor. MI.

von Bernuth. R. D. 1983. Uniformity design criteria under limited water. *Transactions of the ASAE.* 26(5):1418-1421.

——— 1993. Surface and Sprinkle irrigation: comparison of uniformities and efficiencies. In: *AGRITECH 93. proceedings of the 6th International Conference on Irrigation.* Tel-Avi. Israel. 3-4 May

Walker. W. R. 1979. Explicit sprinkler irrigation uniformity: efficiency model. *Journal of the Irrigation and Drainage Engineering.* 105 (IR2): 129-136.

Warrick. A. W.. W. E. Hart and M. Yitayew. 1989. Calculation of distribution and application efficiency for nonuniform irrigation. *Journal of Irrigation and Drainage Engineering.* 115(4):674-687.

Warrick. A.W. 1983. Interrelationships of irrigation uniformity terms. *Journal of the Irrigation and Drainage Engineering.* 109 (3): 317-332.

White House. 1964. Report on Land and Water Development in the Indus Plain. The White House-Department of Interior Panel on Waterlogging and Salinity in West Pakistan. Washington, D.C.

Wilcox, J. C. and G. E. Swailes. 1947. Uniformity of water distribution by some under-tree orchard sprinklers. *Scientific Agriculture*, 27(11):565-583.

Wright, A. 1975. Farming systems, models and simulations. Chapter 2. In: *Techniques and Methods in Simulation*. 17-33.

Wu and Gitlin. 1983. Drip irrigation application efficiency and schedules. *Transactions of the ASAE*. 26(1):92-99.

Wyseure, G. 1986. Hydrologic system modelling of the total rainfall-direct runoff conversion. Ph.D. Thesis No. 147. Katholieke University, Leuven, Belgium.

Yadav, R.C., V. Kumar and V. B. Ogunela. 1986. Partitioning of rain water and its implication on application efficiency of overhead irrigation. *Transaction of the Indian Society of Desert Technology*, 11(2):91-97.

Yitayew, M. 1987. Interrelationships of performance parameters for irrigation borders. *Agricultural Water Management*, 12:221-230.

Yonts, C. D., J. A. Smith and J. E. Bailie. 1991. Furrow irrigation performance in reduced-tillage systems. *Transactions of the ASAE*. 34(1):91-96.

# APPENDICES

## Appendix 1. QuickBasic Program Listing

```
DECLARE FUNCTION RndNorm! (Mean!, StanDev!)
DECLARE SUB Stats (NumArray!(), Count%, Mean!, StanDev!, CoVar!, Min!, Max!)
DECLARE SUB tabext (vte!(), smxe!, dxe!, kte!, xte!, yte!)
DECLARE SUB tabbex (van!(), arg!(), inx!, dxe!, yte!)
  CLS
OPEN "c:\fn.csv" FOR OUTPUT AS #1
PRINT #1,
PRINT #1, "SCS" f31: Us
REM  USER INPUTS
     Run1% = 300
     Mean! = 24.2
     StanDev! = 7.26: cvUS! = StanDev! / Mean!
     MStep = .1: MRD = MStep * Mean!
     alpha = .5
     ARD = 23
     awc = .43: IWC = (1 - alpha) * awc
    ReqDep = alpha * awc * ARD

     DIM Area(91), InfArray(Run1%), AEArray!(Run1%), LFArray!(Run1%)
     kte = 90: smxe = 0!: dxe = .04
     FOR i = 1 TO kte + 1
       READ Area(i)
     NEXT i

     FOR M% = 1 TO Run1%
       InfArray!(M%) = RndNorm!(Mean!, StanDev!)
     NEXT M%

     FOR ReqDep = MRD TO (Mean! + 3 * MRD) STEP MRD
       FOR N% = 1 TO Run1%
         IF InfArray!(N%) <= ReqDep THEN
           AppEff = 1
         ELSE
           AppEff = ReqDep / InfArray!(N%)
         END IF
         AEArray!(N%) = AppEff
       NEXT N%

       CALL Stats(AEArray!(), Run1%, AvgAE!, StdAE!, cvAE!, Min!, Max!)
       IF cvAE! > 1 THEN cvAE! = 1!
       Zinf = (Mean! - ReqDep) / StanDev!
       Rinf = .788 - .3075 * Zinf + .0486 * Zinf ^ 2
       Tinf = .788 - .693 * Zinf + .0485 * Zinf ^ 2

       CALL tabext(Area(), smxe, dxe, kte, Zinf, FulArea)
       IF FulArea < 0 THEN FulArea = 0
       DefArea = 1 - FulArea

       MAR = ReqDep / Mean!
       AvgDefDep = ReqDep - StanDev! * Rinf:          'Avg. depth received in deficit area
```

```
      IF AvgDefDep < 0 THEN AvgDefDep = 0
      DefRatio = AvgDefDep / ReqDep
      StoEff = FulArea + (DefArea * DefRatio)
     CAW = AvgAE! * MAR
     cvEE! = SQR(cvAE! ^ 2 + cvUS! ^ 2)
     IF cvEE! > 1 THEN cvEE! = 1
     EnvEff! = 1 - cvEE!

REM    UNIFORMITY EFFICIENCY PER CENTAGES
    Us! = (1 - (StanDev! / Mean!)) * 100
    AE! = AvgAE! * 100
    SE! = StoEff * 100
    EE! = EnvEff! * 100
    SAE! = (1 - cvAE!) * 100

    PRINT USING "###.# ###.# ###.# ###.# ###.# ###.### ###.### ##.### #.### #.###"; Us!; AE!; SAE!; SE!;
EE!; CAW;         DefRatio; FulArea; MAR
    PRINT #1, USING "###.# ###.# ###.# ###.# ###.# ###.## ###.### ###.##"; Us!; AE!; SAE!; SE!; EE!; CAW;
DefRatio;         FulArea; MAR
NEXT

 PRINT SPC(2); "US"; SPC(5); "AE"; SPC(5); "SAE"; SPC(3); "SE"; SPC(4); "EE"; SPC(4); "CAW"; SPC(3);
"DefRatio"; SPC(2);        "Area"; SPC(3); "MAR"
 CLOSE #1
 END
   DATA .5000,.5160,.5319,.5478,.5636,.5793,.5948,.6103,.6255,.6406
   DATA .6554,.6700,.6844,.6985,.7123,.7257,.7389,.7517,.7642,.7764
   DATA .7881,.7995,.8106,.8212,.8315,.8413,.8508,.8599,.8686,.8770
   DATA .8849,.8925,.8997,.9066,.9131,.9192,.9251,.9306,.9357,.9406
   DATA .9452,.9495,.9535,.9573,.9608,.9641,.9671,.9699,.9726,.9750
   DATA .9772,.9793,.9812,.9830,.9846,.9861,.9875,.9887,.9898,.9909
   DATA .9918,.9927,.9934,.9941,.9948,.9953,.9959,.9963,.9967,.9967
   DATA .9971,.9974,.9977,.9980,.9982,.9985,.9987,.9989,.9990,.9992
   DATA .9993,.9994,.9994,.9995,.9996,.9996,.9997,.9997,.9998,.9999
   DATA .9999

FUNCTION RndNorm! (Mean!, StanDev!)
  DO
    RandomA! = 2! * RND - 1!
    RandomB! = 2! * RND - 1!
    Radius2! = RandomA! ^ 2 + RandomB! ^ 2
  LOOP UNTIL (Radius2! < 1!): REM AND (Radius2! > 0!)            'Mod. #2
  Deviate! = RandomA! * SQR((-2! * LOG(Radius2!)) / Radius2!)
  RndNorm! = Mean! + Deviate! * StanDev!
END FUNCTION

SUB Stats (NumArray!(), Count%, Mean!, StanDev!, CoVar!, Min!, Max!)
  IF Count% < 1 THEN EXIT SUB
  FOR j% = 2 TO Count%
    Temp! = NumArray!(j%)
    K% = j% - 1
    DO WHILE ((Temp! < NumArray!(K%)) AND (K% > 0))
      NumArray!(K% + 1) = NumArray!(K%)
      K% = K% - 1
    LOOP
    NumArray!(K% + 1) = Temp!
  NEXT j%
```

```
 FOR j% = 1 TO Count%
   ValueSum! = ValueSum! + NumArray!(j%)
   SquareSum! = SquareSum! + NumArray!(j%) ^ 2
 NEXT j%
 Min! = NumArray!(1)
 Max! = NumArray!(Count%)
 IF ((Count% + 1) \ 2) = Count% \ 2 THEN
   Mid% = Count% \ 2
   Median! = (NumArray!(Mid%) + NumArray!(Mid% + 1)) / 2!
 ELSE
   Median! = NumArray!((Count% + 1) \ 2)
 END IF
 Mean! = ValueSum! / Count%
 IF Count% = 1 THEN
   StanDev! = 0!
 ELSE
   StanDev! = SQR((SquareSum! - Count% * Mean! * Mean!) / (Count% - 1))
 END IF
 CoVar! = StanDev! / Mean!
END SUB

  SUB tabext (vte(), smxe, dxe, kte, inx, yte)
    dume = inx - smxe
    ite = .5 + dume / dxe
    IF ite < 1 THEN ite = 1 ELSE IF ite > kte THEN ite = kte
    yte = vte(ite) + (vte(ite - 1) - vte(ite)) * (dume - (ite - 1) * dxe) / dxe
  END SUB

SUB YldNetRet
REM Environmental Yield Function
  ETf = 1 - pfrac: BDC = 1 - beta * DefCoef
  YLD = YLDm * ETf * BDC
  NetRet = (YLD * Cst) - WatCst - EEvio * CstEE
END SUB
```

## Appendix 2. Detailed Program Output

| application efficiency | application uniformity | storage efficiency | irrigation environ. efficiency | crop available water | deficit ratio | fully irrigated area | minimum application ratio |
|---|---|---|---|---|---|---|---|
| | | | $U_s = 40$ | | | | |
| 19.9 | 0 | 93.3 | 0 | 0.02 | 0 | 0.93 | 0.1 |
| 31.2 | 11.7 | 91 | 0 | 0.06 | 0 | 0.91 | 0.2 |
| 41 | 32 | 88.2 | 9.3 | 0.12 | 0.01 | 0.88 | 0.3 |
| 49.8 | 44.7 | 87.4 | 18.4 | 0.2 | 0.21 | 0.84 | 0.4 |
| 57.6 | 54.1 | 86 | 24.4 | 0.29 | 0.32 | 0.79 | 0.5 |
| 64.8 | 61.1 | 84.6 | 28.5 | 0.39 | 0.4 | 0.75 | 0.6 |
| 71.2 | 66.7 | 82.9 | 31.4 | 0.5 | 0.45 | 0.69 | 0.7 |
| 76.9 | 71.4 | 81 | 33.5 | 0.61 | 0.48 | 0.63 | 0.8 |
| 81.6 | 75.6 | 78.9 | 35.2 | 0.73 | 0.51 | 0.57 | 0.9 |
| 85.6 | 79.3 | 76.4 | 36.5 | 0.86 | 0.53 | 0.5 | 1 |
| 89 | 82.5 | 74 | 37.5 | 0.98 | 0.54 | 0.43 | 1.1 |
| 91.8 | 85.3 | 71.6 | 38.2 | 1.1 | 0.55 | 0.37 | 1.2 |
| 94 | 87.8 | 69.2 | 38.8 | 1.22 | 0.56 | 0.3 | 1.3 |
| | | | $U_s = 50$ | | | | |
| 16.8 | 0 | 96.4 | 0 | 0.02 | 0 | 0.96 | 0.1 |
| 28.6 | 17.3 | 94.5 | 3.3 | 0.06 | 0 | 0.95 | 0.2 |
| 39.1 | 36.2 | 93.9 | 19 | 0.12 | 0.25 | 0.92 | 0.3 |
| 48.5 | 48.1 | 93.2 | 28 | 0.19 | 0.39 | 0.89 | 0.4 |
| 57.1 | 56.8 | 91.6 | 33.9 | 0.29 | 0.47 | 0.84 | 0.5 |
| 64.8 | 63.7 | 89.9 | 38.2 | 0.39 | 0.52 | 0.79 | 0.6 |
| 71.7 | 69.2 | 88.1 | 41.3 | 0.5 | 0.56 | 0.73 | 0.7 |
| 77.9 | 73.9 | 85.5 | 43.6 | 0.62 | 0.58 | 0.66 | 0.8 |
| 83 | 78 | 83 | 45.4 | 0.75 | 0.6 | 0.58 | 0.9 |
| 87.3 | 81.7 | 80.3 | 46.8 | 0.87 | 0.61 | 0.5 | 1 |
| 90.8 | 84.9 | 77.6 | 47.8 | 1 | 0.61 | 0.42 | 1.1 |
| 93.5 | 87.7 | 74.7 | 48.5 | 1.12 | 0.62 | 0.34 | 1.2 |
| 95.5 | 90.2 | 71.8 | 49 | 1.24 | 0.62 | 0.26 | 1.3 |
| | | | $U_s = 60$ | | | | |
| 14.2 | 0 | 98.8 | 0 | 0.01 | 0 | 0.99 | 0.1 |
| 25.7 | 28.3 | 98.3 | 17.9 | 0.05 | 0.27 | 0.98 | 0.2 |
| 36.6 | 44 | 97.8 | 31.2 | 0.11 | 0.47 | 0.96 | 0.3 |
| 46.8 | 53.4 | 97.1 | 38.6 | 0.19 | 0.56 | 0.93 | 0.4 |
| 56.1 | 60.8 | 96 | 44 | 0.28 | 0.62 | 0.9 | 0.5 |
| 64.6 | 66.9 | 94.4 | 48.1 | 0.39 | 0.65 | 0.84 | 0.6 |
| 72.1 | 72.2 | 92.3 | 51.3 | 0.51 | 0.67 | 0.77 | 0.7 |
| 78.9 | 76.7 | 90 | 53.7 | 0.63 | 0.68 | 0.69 | 0.8 |
| 84.5 | 80.7 | 87.4 | 55.6 | 0.76 | 0.68 | 0.6 | 0.9 |
| 89.1 | 84.4 | 84.2 | 57.1 | 0.89 | 0.68 | 0.5 | 1 |
| 92.7 | 87.6 | 81.1 | 58.1 | 1.02 | 0.68 | 0.4 | 1.1 |

| application efficiency | application uniformity | storage efficiency | irrigation environ. efficiency | crop available water | deficit ratio | fully irrigated area | minimum application ratio |
|---|---|---|---|---|---|---|---|
| 95.3 | 90.4 | 77.7 | 58.9 | 1.14 | 0.68 | 0.3 | 1.2 |
| 97 | 92.8 | 74.3 | 59.4 | 1.26 | 0.68 | 0.2 | 1.3 |
| | | | $U_s = 65$ | | | | |
| 12.6 | 16.5 | 99.5 | 9.5 | 0.01 | 0 | 1 | 0.1 |
| 24.4 | 35.7 | 99.4 | 26.8 | 0.05 | 0.41 | 0.99 | 0.2 |
| 35.3 | 49.2 | 99 | 38.3 | 0.11 | 0.57 | 0.98 | 0.3 |
| 45.7 | 57.2 | 98.4 | 44.7 | 0.18 | 0.65 | 0.96 | 0.4 |
| 55.4 | 63.4 | 97.6 | 49.4 | 0.28 | 0.69 | 0.92 | 0.5 |
| 64.3 | 68.9 | 96.3 | 53.2 | 0.39 | 0.71 | 0.87 | 0.6 |
| 72.3 | 73.9 | 94.5 | 56.3 | 0.51 | 0.72 | 0.81 | 0.7 |
| 79.4 | 78.3 | 92.3 | 58.8 | 0.64 | 0.73 | 0.72 | 0.8 |
| 85.4 | 82.2 | 89.5 | 60.7 | 0.77 | 0.73 | 0.62 | 0.9 |
| 90.1 | 85.9 | 86.2 | 62.3 | 0.9 | 0.72 | 0.5 | 1 |
| 93.7 | 89.1 | 82.8 | 63.3 | 1.03 | 0.72 | 0.39 | 1.1 |
| 96.2 | 91.8 | 79.2 | 64.1 | 1.15 | 0.71 | 0.27 | 1.2 |
| 97.8 | 94.2 | 75.3 | 64.5 | 1.27 | 0.71 | 0.16 | 1.3 |
| | | | $U_s = 70$ | | | | |
| 11.5 | 49.3 | 99.9 | 41.1 | 0.01 | 0.09 | 1 | 0.1 |
| 22.9 | 50.7 | 99.8 | 42.3 | 0.05 | 0.53 | 1 | 0.2 |
| 34 | 55.6 | 99.7 | 46.4 | 0.1 | 0.66 | 0.99 | 0.3 |
| 44.5 | 61.9 | 99.4 | 51.5 | 0.18 | 0.72 | 0.98 | 0.4 |
| 54.6 | 66.8 | 98.8 | 55.2 | 0.27 | 0.75 | 0.95 | 0.5 |
| 63.9 | 71.3 | 97.9 | 58.5 | 0.38 | 0.77 | 0.91 | 0.6 |
| 72.4 | 75.8 | 96.4 | 61.4 | 0.51 | 0.77 | 0.84 | 0.7 |
| 79.9 | 80 | 94.2 | 63.9 | 0.64 | 0.77 | 0.75 | 0.8 |
| 86.3 | 83.8 | 91.5 | 65.9 | 0.78 | 0.77 | 0.63 | 0.9 |
| 91.2 | 87.4 | 88.2 | 67.5 | 0.91 | 0.76 | 0.5 | 1 |
| 94.8 | 90.7 | 84.5 | 68.6 | 1.04 | 0.76 | 0.37 | 1.1 |
| 97.1 | 93.4 | 80.6 | 69.3 | 1.17 | 0.75 | 0.23 | 1.2 |
| 98.6 | 95.6 | 76.2 | 69.7 | 1.28 | 0.74 | 0.1 | 1.3 |
| | | | $U_s = 75$ | | | | |
| 10.9 | 66.2 | 100 | 58 | 0.01 | 0.22 | 1 | 0.1 |
| 21.7 | 66.2 | 100 | 58 | 0.04 | 0.62 | 1 | 0.2 |
| 32.6 | 66.2 | 99.9 | 58 | 0.1 | 0.74 | 1 | 0.3 |
| 43.3 | 67.8 | 99.8 | 59.2 | 0.17 | 0.79 | 0.99 | 0.4 |
| 53.5 | 71.1 | 99.6 | 61.8 | 0.27 | 0.82 | 0.98 | 0.5 |
| 63.3 | 74.4 | 99 | 64.2 | 0.38 | 0.82 | 0.95 | 0.6 |
| 72.4 | 78 | 98.1 | 66.7 | 0.51 | 0.83 | 0.89 | 0.7 |
| 80.3 | 81.8 | 96.2 | 69.1 | 0.64 | 0.82 | 0.79 | 0.8 |
| 87.2 | 85.5 | 93.6 | 71.1 | 0.78 | 0.81 | 0.66 | 0.9 |
| 92.3 | 89.1 | 90.2 | 72.7 | 0.92 | 0.8 | 0.5 | 1 |
| 95.9 | 92.3 | 86.2 | 73.8 | 1.06 | 0.79 | 0.34 | 1.1 |
| 98 | 95 | 81.8 | 74.5 | 1.18 | 0.78 | 0.18 | 1.2 |

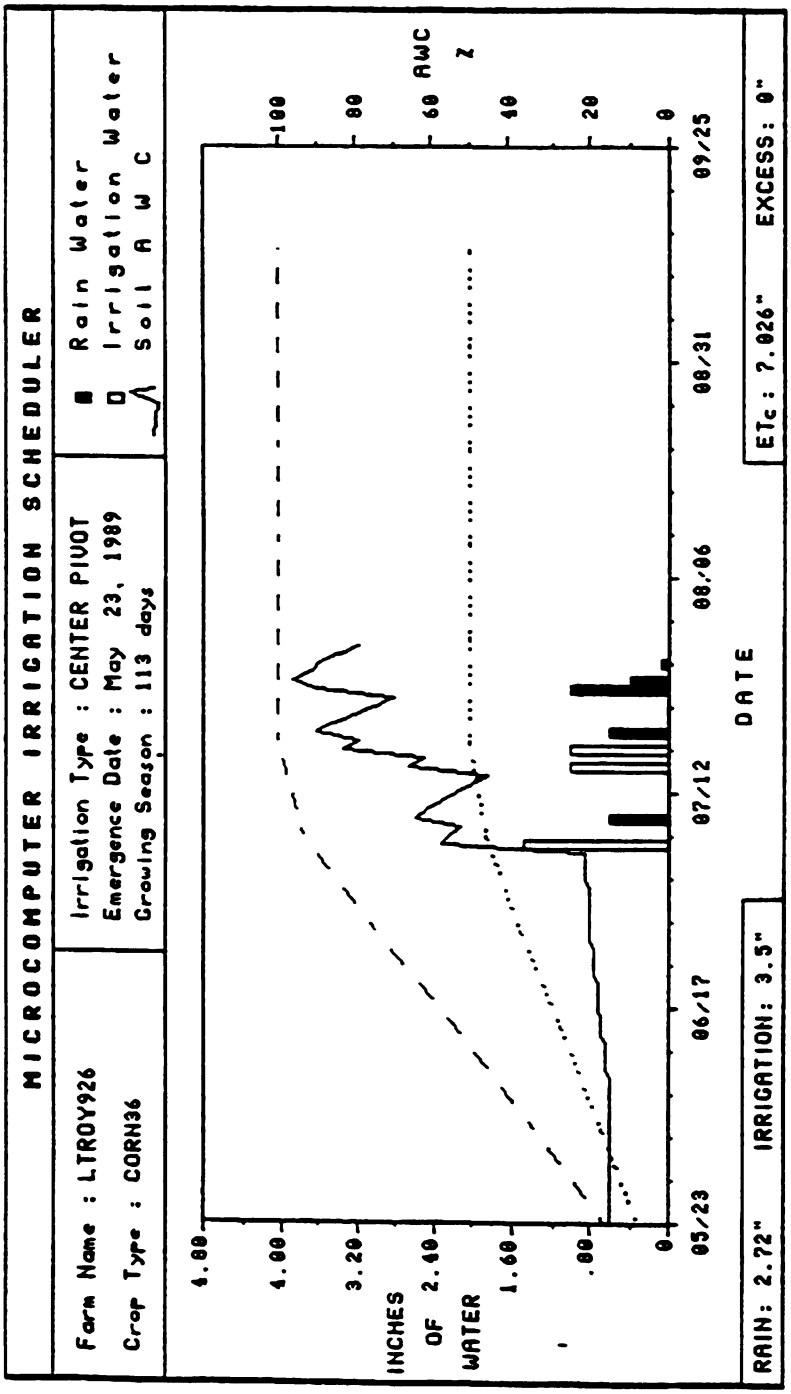
| application efficiency | application uniformity | storage efficiency | irrigation environ. efficiency | crop available water | deficit ratio | fully irrigated area | minimum application ratio |
|---|---|---|---|---|---|---|---|
| 99.2 | 97 | 76.9 | 74.8 | 1.29 | 0.76 | 0.02 | 1.3 |
| | | | $U_s = 80$ | | | | |
| 10.5 | 76.1 | 100 | 68.9 | 0.01 | 0.22 | 1 | 0.1 |
| 21 | 76.1 | 100 | 68.9 | 0.04 | 0.66 | 1 | 0.2 |
| 31.5 | 76.1 | 100 | 68.9 | 0.09 | 0.8 | 1 | 0.3 |
| 42 | 76.1 | 100 | 68.9 | 0.17 | 0.85 | 1 | 0.4 |
| 52.4 | 76.5 | 99.9 | 69.2 | 0.26 | 0.87 | 0.99 | 0.5 |
| 62.5 | 78.3 | 99.7 | 70.5 | 0.38 | 0.88 | 0.98 | 0.6 |
| 72.1 | 80.8 | 99.2 | 72.3 | 0.5 | 0.88 | 0.93 | 0.7 |
| 80.7 | 83.9 | 97.9 | 74.4 | 0.65 | 0.87 | 0.84 | 0.8 |
| 88.1 | 87.4 | 95.6 | 76.4 | 0.79 | 0.86 | 0.69 | 0.9 |
| 93.6 | 90.9 | 92.1 | 78 | 0.94 | 0.84 | 0.5 | 1 |
| 97.1 | 94.1 | 87.9 | 79.2 | 1.07 | 0.83 | 0.3 | 1.1 |
| 98.9 | 96.6 | 82.8 | 79.7 | 1.19 | 0.81 | 0.1 | 1.2 |
| 99.7 | 98.4 | 79.1 | 79.9 | 1.3 | 0.79 | 0 | 1.3 |
| | | | $U_s = 85$ | | | | |
| 10.3 | 83.4 | 100 | 77.7 | 0.01 | 0 | 1 | 0.1 |
| 20.5 | 83.4 | 100 | 77.7 | 0.04 | 0.6 | 1 | 0.2 |
| 30.8 | 83.4 | 100 | 77.7 | 0.09 | 0.79 | 1 | 0.3 |
| 41 | 83.4 | 100 | 77.7 | 0.16 | 0.87 | 1 | 0.4 |
| 51.3 | 83.4 | 100 | 77.7 | 0.26 | 0.91 | 1 | 0.5 |
| 61.6 | 83.5 | 100 | 77.7 | 0.37 | 0.92 | 1 | 0.6 |
| 71.6 | 84.5 | 99.8 | 78.4 | 0.5 | 0.92 | 0.98 | 0.7 |
| 80.9 | 86.5 | 99.2 | 79.8 | 0.65 | 0.91 | 0.91 | 0.8 |
| 89 | 89.5 | 97.4 | 81.7 | 0.8 | 0.9 | 0.75 | 0.9 |
| 95 | 92.9 | 94.1 | 83.4 | 0.95 | 0.88 | 0.5 | 1 |
| 98.3 | 96 | 89.4 | 84.5 | 1.08 | 0.86 | 0.23 | 1.1 |
| 99.6 | 98.3 | 83.9 | 84.9 | 1.2 | 0.84 | 0 | 1.2 |
| 99.9 | 99.6 | 81.6 | 85 | 1.3 | 0.82 | 0 | 1.3 |
| | | | $U_s = 90$ | | | | |
| 10.1 | 89.5 | 100 | 85.5 | 0.01 | 0 | 1 | 0.1 |
| 20.2 | 89.5 | 100 | 85.5 | 0.04 | 0.28 | 1 | 0.2 |
| 30.3 | 89.5 | 100 | 85.5 | 0.09 | 0.66 | 1 | 0.3 |
| 40.5 | 89.5 | 100 | 85.5 | 0.16 | 0.83 | 1 | 0.4 |
| 50.6 | 89.5 | 100 | 85.5 | 0.25 | 0.91 | 1 | 0.5 |
| 60.7 | 89.5 | 100 | 85.5 | 0.36 | 0.94 | 1 | 0.6 |
| 70.8 | 89.5 | 100 | 85.5 | 0.5 | 0.96 | 1 | 0.7 |
| 80.8 | 90 | 99.9 | 85.9 | 0.65 | 0.95 | 0.98 | 0.8 |
| 89.8 | 91.9 | 99.1 | 87.1 | 0.81 | 0.94 | 0.84 | 0.9 |
| 96.5 | 95 | 96.1 | 88.8 | 0.96 | 0.92 | 0.5 | 1 |
| 99.4 | 98.1 | 90.6 | 89.8 | 1.09 | 0.9 | 0.1 | 1.1 |
| 100 | 99.7 | 86.7 | 90 | 1.2 | 0.87 | 0 | 1.2 |
| 100 | 100 | 83.5 | 90 | 1.3 | 0.83 | 0 | 1.3 |

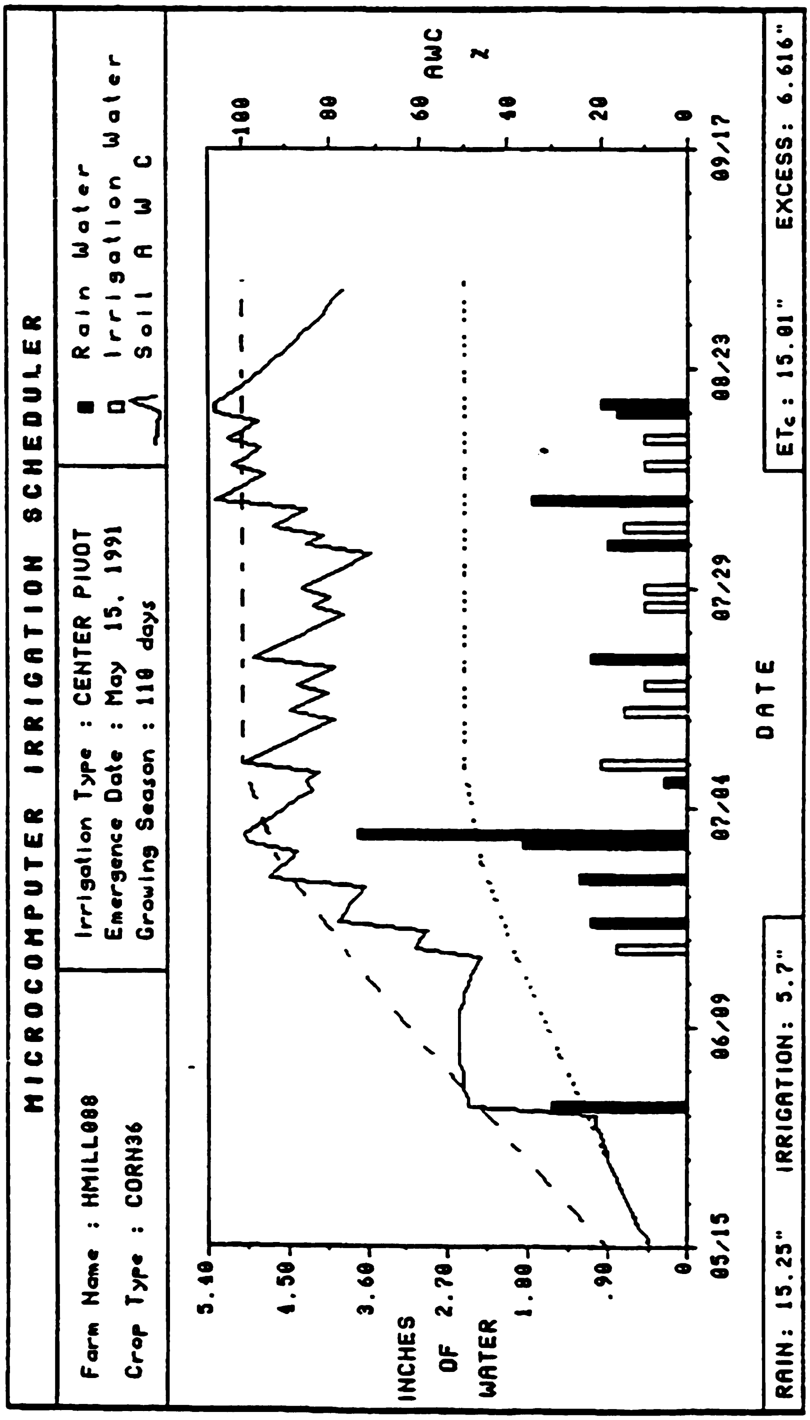
| application efficiency | application uniformity | storage efficiency | irrigation environ. efficiency | crop available water | deficit ratio | fully irrigated area | minimum application ratio |
|---|---|---|---|---|---|---|---|
| | | | $U_s = 98$ | | | | |
| 10 | 98 | 100 | 97.2 | 0.01 | 0 | 1 | 0.1 |
| 20 | 98 | 100 | 97.2 | 0.04 | 0 | 1 | 0.2 |
| 30 | 98 | 100 | 97.2 | 0.09 | 0 | 1 | 0.3 |
| 40 | 98 | 100 | 97.2 | 0.16 | 0 | 1 | 0.4 |
| 50 | 98 | 100 | 97.2 | 0.25 | 0.061 | 1 | 0.5 |
| 60 | 98 | 100 | 97.2 | 0.36 | 0.531 | 1 | 0.6 |
| 70 | 98 | 100 | 97.2 | 0.49 | 0.797 | 1 | 0.7 |
| 80 | 98 | 100 | 97.2 | 0.64 | 0.936 | 1 | 0.8 |
| 90.1 | 98 | 100 | 97.2 | 0.81 | 0.99 | 1 | 0.9 |
| 99.2 | 98.9 | 99.2 | 97.7 | 0.99 | 0.984 | 0.5 | 1 |
| 100 | 100 | 93.6 | 98 | 1.1 | 0.936 | 0 | 1.1 |
| 100 | 100 | 85.5 | 98 | 1.2 | 0.855 | 0 | 1.2 |
| 100 | 100 | 74.9 | 98 | 1.3 | 0.749 | 0 | 1.3 |

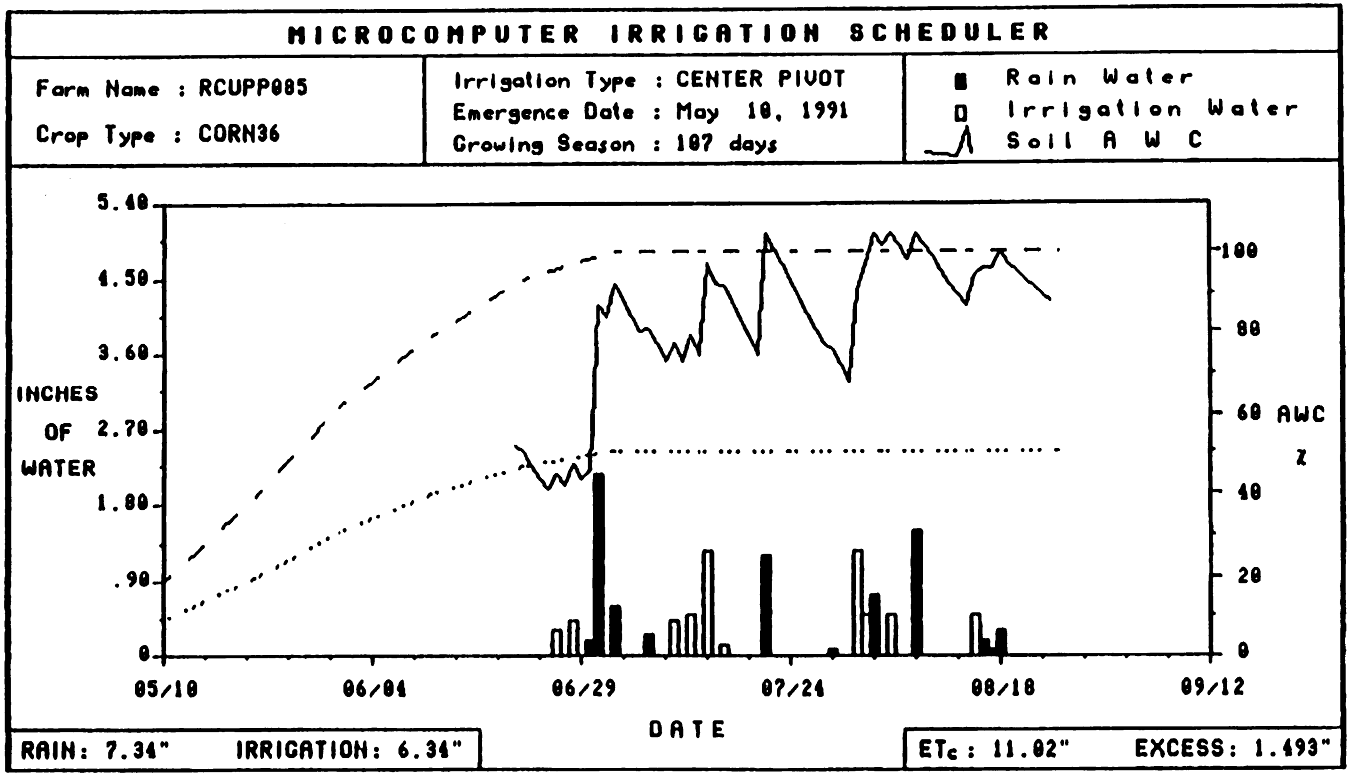
## Appendix 3. Regression Coefficients

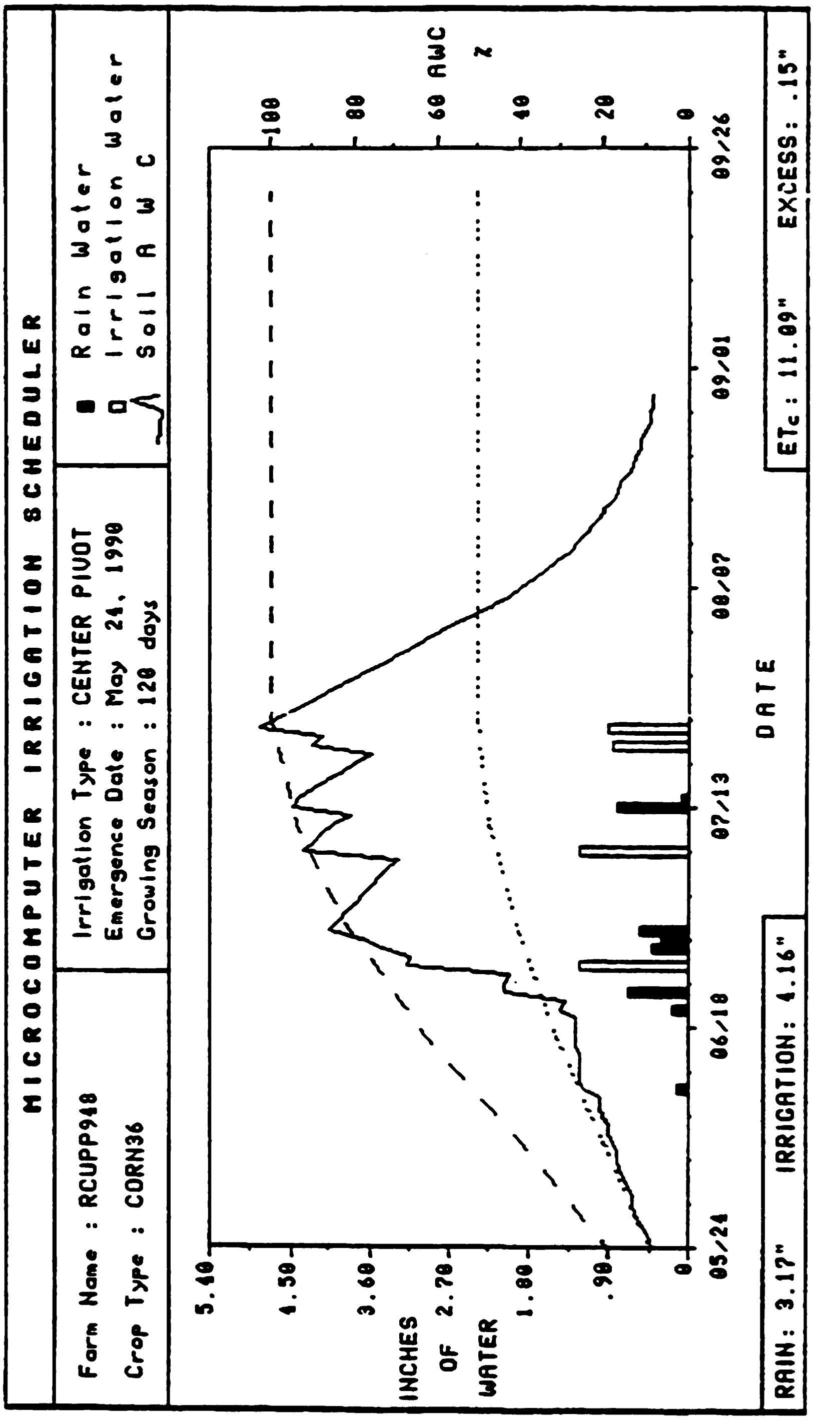
| $U_S$ | $a_0$ | $a_1$ | $a_2$ | $a_3$ | $a_4$ | $a_5$ | Adj. $R^2$ |
|---|---|---|---|---|---|---|---|
| | $AE = a_0 + a_1\,mar + a_2\,mar^2 + a_3\,mar^3$ [Equation 33], page 56. | | | | | | |
| 40 | 8.1500 | 124.64 | -54.28 | 7.08 | | | 0.9999 |
| 50 | 4.4800 | 129.67 | -50.20 | 3.32 | | | 0.9998 |
| 60 | 1.7510 | 127.08 | -33.81 | -5.89 | | | 0.9999 |
| 65 | 0.3420 | 125.00 | -23.91 | -11.31 | | | 0.9999 |
| 70 | -0.3790 | 118.87 | -7.98 | -19.29 | | | 0.9999 |
| 75 | -0.0965 | 107.38 | 15.45 | -30.42 | | | 0.9999 |
| 80 | 0.9049 | 92.76 | 42.87 | -43.09 | | | 0.9999 |
| 85 | 2.3130 | 77.11 | 71.13 | -56.09 | | | 0.9998 |
| 90 | 3.5600 | 64.21 | 94.07 | -66.58 | | | 0.9994 |
| 98 | 4.0700 | 59.52 | 102.19 | -70.28 | | | 0.9920 |
| | $AU = a_0 + a_1\,AE + a_2\,AE^2 + a_3\,AE^3 + a_4\,AE^4 + a_5\,AE^5$ [Figure 11], page 60. | | | | | | |
| 40 | 106.7727 | -13.6889 | 0.5985 | -0.0107 | 8.88e-05 | -2.78e-07 | 0.9997 |
| 50 | 8.6829 | -2.9786 | 0.2042 | -0.0040 | 3.38e-05 | -1.05e-07 | 0.9998 |
| 60 | -73.0429 | 7.4100 | -0.1985 | 0.0031 | -2.42e-05 | 7.78e-08 | 1.0000 |
| 65 | -16.5055 | 3.2734 | -0.0611 | 0.0008 | -5.41e-06 | 1.87e-08 | 0.9998 |
| 70 | 55.0446 | -0.9449 | 0.0447 | -0.0006 | 2.46e-06 | 9.08e-10 | 0.9998 |
| 75 | 61.6693 | 0.8448 | -0.0526 | 0.0014 | -1.45e-05 | 5.65e-08 | 0.9998 |
| 80 | 71.2514 | 0.8209 | -0.0447 | 0.0010 | -1.03e-05 | 4.02e-08 | 0.9984 |
| 85 | 80.5361 | 0.4934 | -0.0278 | 0.0007 | -7.62e-06 | 3.30e-08 | 0.9956 |
| 90 | 86.0354 | 0.6223 | -0.0367 | 0.0009 | -1.08e-05 | 4.61e-08 | 0.9922 |
| 98 | 87.7003 | 0.7162 | -0.0420 | 0.0011 | -1.21e-05 | 5.04e-08 | 0.9883 |

**Appendix 4. SCS-Scheduler Output - Soil Water Content**

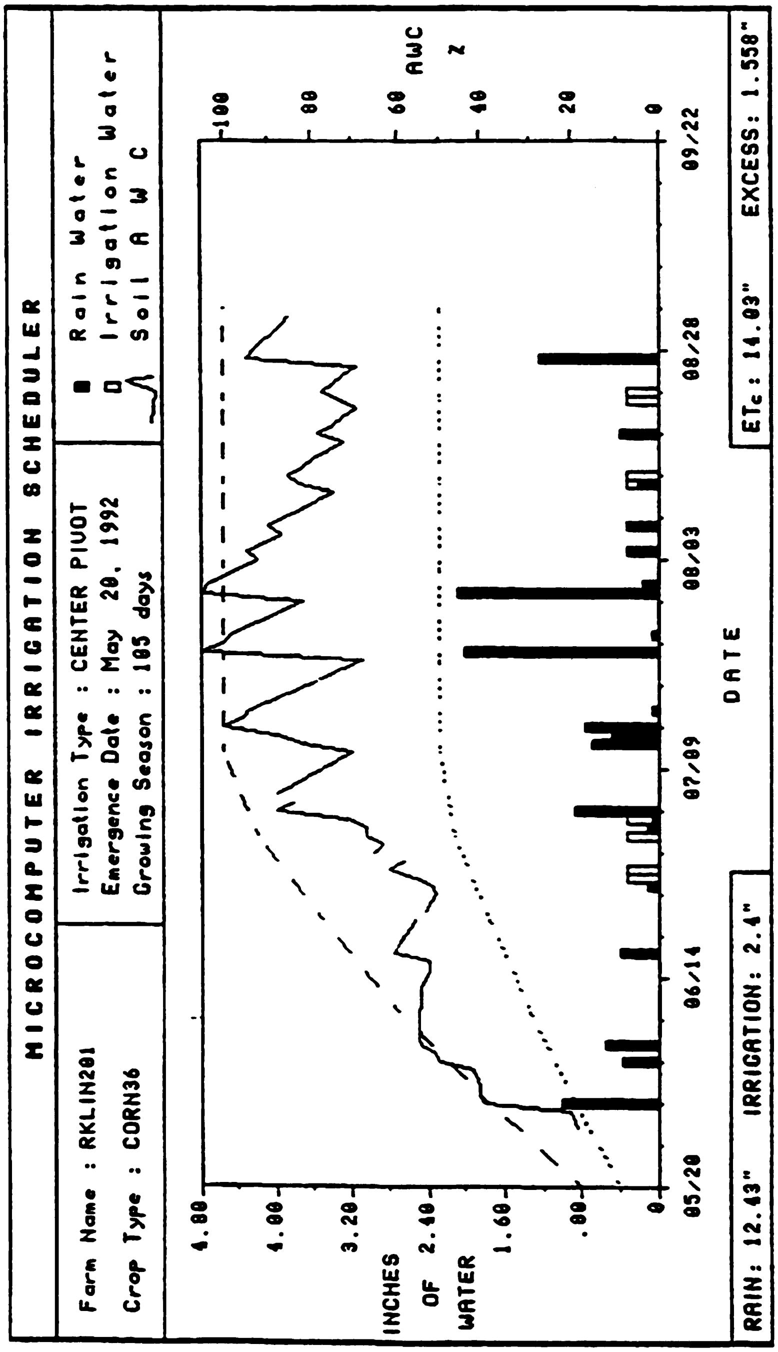



MICROCOMPUTER IRRIGATION SCHEDULER
Farm Name : HMILL088
Crop Type : CORN36
Irrigation Type : CENTER PIVOT
Emergence Date : May 15, 1991
Growing Season : 110 days
Rain Water
Irrigation Water
Soil A W C
5.40
4.50
3.60
2.70
1.80
.90
0
INCHES
OF
WATER
100
80
60
40
20
0
AWC
%
05/15
06/09
07/04
07/29
08/23
09/17
DATE
RAIN: 15.25"
IRRIGATION: 5.7"
ETc : 15.01"
EXCESS: 6.616"


MICROCOMPUTER IRRIGATION SCHEDULER
Farm Name : RCUPP005
Crop Type : CORN36
Irrigation Type : CENTER PIVOT
Emergence Date : May 10, 1991
Growing Season : 107 days
Rain Water
Irrigation Water
Soil A W C
INCHES OF WATER
5.40
4.50
3.60
2.70
1.80
.90
0
100
80
60 AWC
%
40
20
0
05/10
06/04
06/29
07/24
08/18
09/12
DATE
RAIN: 7.34"
IRRIGATION: 6.34"
ETc : 11.02"
EXCESS: 1.493"



MICROCOMPUTER IRRIGATION SCHEDULER
Farm Name : RCUPP948
Crop Type : CORN36
Irrigation Type : CENTER PIVOT
Emergence Date : May 24, 1990
Growing Season : 120 days
Rain Water
Irrigation Water
Soil A W C
5.40
4.50
3.60
2.70
1.80
.90
0
INCHES
OF
WATER
100
80
60 AWC
%
40
20
0
05/24
06/18
07/13
08/07
09/01
09/26
DATE
RAIN: 3.17"
IRRIGATION: 4.16"
ETc: 11.09"
EXCESS: .15"


MICROCOMPUTER IRRIGATION SCHEDULER
Farm Name : RKLIN201
Crop Type : CORN36
Irrigation Type : CENTER PIVOT
Emergence Date : May 20, 1992
Growing Season : 105 days
Rain Water
Irrigation Water
Soil AWC
INCHES OF WATER
4.80
4.00
3.20
2.40
1.60
.80
0
AWC %
100
80
60
40
20
0
05/20
06/14
07/09
08/03
08/28
09/22
DATE
RAIN: 12.43"
IRRIGATION: 2.4"
ETc: 14.03"
EXCESS: 1.558"

**Appendix 5. Center Pivot Evaluation Data for St. Joseph, MI.**

| Year | System | Average appl. depth inches. | Chrisiansen unifomtiy | Statistical uniformity | Irrigated area acres | Wind speed mph | Relative humidity % |
|---|---|---|---|---|---|---|---|
| 1987 | rgent87 | 0.37 | 60 | 49.9 | 153.5 | 8.5 | 92 |
| 1988 | file88 | 0.32 | 66 | 57.4 | 210.9 | 3 | 60 |
| 1988 | myers88 | 0.31 | 79 | 73.7 | 124.1 | 10 | 75 |
| 1988 | manhowes | 0.86 | 80 | 74.9 | 89.0 | 2 | 77 |
| 1988 | iotka88 | 0.72 | 85 | 81.2 | 132.4 | 2 | 41 |
| 1988 | ivyod882 | 0.6 | 65 | 56.1 | 86.1 | 2 | 15 |
| 1988 | milli88 | 0.72 | 74 | 67.4 | 58.2 | 5 | 11 |
| 1988 | kauf88 | 0.46 | 79 | 73.7 | 137.3 | 3 | 18 |
| 1988 | freck88 | 0.32 | 69 | 61.2 | 182.3 | 3-4 | 56 |
| 1988 | finner88 | 0.27 | 84 | 80.0 | 160.7 | 8 | 78 |
| 1989 | rgent89 | 0.38 | 90 | 87.5 | 157.4 | 5 | 75 |
| 1989 | benqui89 | 0.24 | 80 | 74.9 | 162.5 | 5 | 66 |
| 1989 | rcupp89 | 0.69 | 79 | 73.7 | 95.4 | 5 | 65 |
| 1989 | dcrip89 | 0.29 | 70 | 62.4 | 103.9 | 6 | 70 |
| 1989 | rklein89 | 0.57 | 83 | 78.7 | 125.7 | 9 | 68 |
| 1989 | cgrab933 | 1.78 | 74 | 67.4 | 40.6 | 5 | 77 |
| 1989 | dchen940 | 1.01 | 85 | 81.2 | 79.5 | 7 | 81 |
| 1989 | kinma945 | 0.95 | 74 | 67.4 | 34.3 | 4 | 81 |
| 1989 | dstubnex | 0.32 | 86 | 82.5 | 50.9 | 2 | 92 |
| 1989 | stubnex | 0.85 | 85 | 81.2 | 103.2 | 2 | 92 |
| 1989 | stubnex | 0.74 | 85 | 81.2 | 225.9 | 4 | 76 |
| 1989 | rgent921 | 0.74 | 85 | 81.2 | 225.9 | 5 | 75 |
| 1989 | wwild970 | 0.63 | 89 | 86.2 | 309.0 | 3 | 61 |
| 1989 | ebarn89 | 0.24 | 80 | 74.9 | 146.3 | 10 | 78 |
| 1990 | rfarmo17 | 1.28 | 80 | 74.9 | 66.6 | 10-12 | 80 |
| 1990 | fgroveye | 0.43 | 74 | 67.4 | 175.5 | 3 | 64 |
| 1990 | fgrovene | 0.79 | 79 | 73.7 | 147.5 | 4 | 44 |
| 1990 | astutzne | 0.98 | 82 | 77.4 | 159.0 | 9 | 95 |
| 1990 | astutzye | 0.88 | 86 | 82.5 | 158.0 | 5 | 39 |
| 1990 | mmill034 | 0.56 | 70 | 62.4 | 108.2 | 4-5 | 81 |
| 1990 | bstraus | 0.53 | 80 | 74.9 | 171.0 | 4-5 | 100 |
| 1990 | dstur201 | 0.46 | 85 | 81.2 | 148.5 | 4-5 | 66 |
| 1990 | dsturbur | 0.58 | 88 | 85.0 | 84.9 | | |
| 1990 | mkauf190 | 0.59 | 84 | 80.0 | 42.2 | 8 | 89 |
| 1990 | hmill232 | 0.53 | 81 | 76.2 | 43.9 | 5 | 80 |
| 1990 | gmajo928 | 0.17 | 82 | 77.4 | 37.4 | 2 | 93 |
| 1990 | mkauf190 | 0.38 | 70 | 62.4 | 68.7 | 8 | 89 |

| Year | System | Average appl. depth inches. | Chrisiansen unifomtiy | Statistical uniformity | Irrigated area acres | Wind speed mph | Relative humidity % |
|---|---|---|---|---|---|---|---|
| 1990 | dborg90 | 0.54 | 81 | 76.2 | 111.8 | calm | 85 |
| 1990 | ltroy90 | 0.17 | 82 | 77.4 | 37.4 | 5-6 | 92 |
| 1990 | hmill290 | 0.33 | 71 | 63.7 | 162.9 | 6-7 | 85 |
| 1990 | cgrab90 | 0.58 | 73 | 66.2 | 46.2 | 5-6 | 90 |
| 1990 | mkauf390 | 0.43 | 88 | 85.0 | 124.7 | | |
| 1991 | hmillpvi | 0.31 | 78 | 72.4 | 74.3 | 4-7 | 74 |
| 1991 | hmillida | 0.53 | 75 | 68.7 | 208.4 | 8 | 60 |
| 1991 | gcoom101 | 0.23 | 85 | 81.2 | 168.8 | 0-3 | 80 |
| 1991 | rrobg101 | 0.19 | 83 | 78.7 | 91.3 | light 5-7 | 75 |
| 1991 | mbenne91 | 0.37 | 81 | 76.2 | 123.6 | 5-7 | 62 |
| 1991 | gentz91f | 0.36 | 88 | 85.0 | 105.6 | 5-10 | 78 |
| 1991 | ebarn918 | 0.29 | 77 | 71.2 | 203.6 | 0-5 | 75 |
| 1991 | rrob91so | 0.35 | 84 | 80.0 | 155.7 | 5-8 | 80 |
| 1991 | cgrabe91 | 0.41 | 85 | 81.2 | 175.5 | 0-7 | 76 |
| 1991 | ebarn912 | 0.45 | 91 | 88.7 | 30.0 | 0-3 | 90 |
| 1991 | ebar-ex1 | 0.39 | 88 | 85.0 | 78.9 | 0 | - |
| 1991 | ebr-ex2 | 0.38 | 85 | 81.2 | 116.3 | none | - |
| 1991 | stubyx91 | 0.38 | 86 | 82.5 | 3.8 | 5-9 | 65 |
| 1992 | rkline92 | 0.41 | 84 | 80.0 | 0.1 | 3 | 82 |
| 1992 | gentzhas | 0.24 | 87 | 83.7 | 116.3 | 4-5 | 70 |
| 1992 | gentzsax | 0.33 | 74 | 67.4 | 114.5 | none | 83 |
| 1992 | benne92 | 0.36 | 81 | 76.2 | 42.1 | 3-5 | 85 |
| 1993 | dstur93e | 0.27 | 78 | 72.4 | 43.9 | 5-6 | 80 |
| 1993 | dstur93w | 0.5 | 82 | 77.4 | 203.6 | 5-6 | 80 |