PN-AAQ-562

ISN 35711

TECHNICAL REPORT NO. 40

263001

A PROCEDURE FOR EVALUATING CROP GROWTH ENVIRONMENTS FOR OPTIMAL DRAIN DESIGN

By:

D. S. Durnford, E. V. Richardson, T. H. Podmore

June, 1984

EGYPT WATER USE AND MANAGEMENT PROJECT

22 El Galaa St., Bulak, Cairo, Egypt

TECHNICAL REPORT NO. 40

A PROCEDURE FOR EVALUATING CROP GROWTH ENVIRONMENTS FOR OPTIMAL DRAIN DESIGN

Prepared under support of

WATER DISTRIBUTION RESEARCH INSTITUTE, WATER RESEARCH CENTER

MINISTRY OF IRRIGATION, GOVERNMENT OF EGYPT

UNITED STATES AGENCY FOR INTERNATIONAL DEVELOPMENT
Contract No. AID/ME-C-1351

Contracting Agencies

Colorado State University
Engineering Research Center
Ft. Collins, Colorado 80523
USA

Consortium for International Development
5151 E. Broadway, Ste. 1500
Tucson, Arizona 85711, USA

All reported opinions, conclusions or recommendations are those of the writers and not those of the supporting or contracting agencies

ABSTRACT

This report documents a methodology and computer model which can be used to evaluate an existing crop growth environment, analyze on-farm water management decisions, compare costs of proposed open or closed relief subsurface drainage systems and determine an economically optimum drain layout. The procedures and assumptions used in the computer model are explained and examples of how the program can be used are given. The appendices contain a complete program listing, a variable list, the input requirements and an input-output example.

مستخلص

يتضمن هذا التقرير نموذج الكمبيوتر والطريقة المستعملة لتقدير مراحل نمو الموصول وملائمته للظروف المحيطة به ، وكذلك التحليل الخاص بتطوير الري الحقلي مع المقارنة بين التكاليف المقترحة لكل من نظام المصارف المغطاة أو المكشوفة ، كما يتضمن نموذج للتخطيط اللازم للمصرف الذي يعطي أقصى كفاءة إقتصادية ممكنة . وقد تم شرح الطرق والافتراضات التي استعملت في نموذج الكمبيوتر مع إعطاء أمثلة لكيفية إستعمال البرنامج . ويحتوي الفهرس على كشف كامل للبرنامج مع المتغيرات الداخلة المطلوبة ، كما يحتوي على مثال يتضمن المتغيرات الداخلة والخارجة اللازمة .

ACKNOWLEDGEMENTS

This report was prepared with the cooperation of the staff of the Egypt Water Use and Management Project (EWUP). The Project is funded jointly by the Arab Republic of Egypt, and by the United States Agency for International Development under the directorship of Dr. D. S. Brown with Mr. Niel Dimick as the USAID Project officer. The Consortium for International Development, based in Tucson, Arizona, is the USAID contractor for the Project.

The Egypt Water Use and Management Project (EWUP) works under the auspices of the Ministry of Irrigation's Water Management and Irrigation Technologies Research Institute. EWUP works in collaboration with both the Ministry of Irrigation and the Ministry of Agriculture through the Soil and Water Research Institute and the Agricultural Economics Institute.

TABLE OF CONTENTS

Chapter	Page
CHAPTER I: INTRODUCTION	1
1.1 Objectives	2
1.2 Scope	3
CHAPTER II: MODEL DEVELOPMENT	5
2.1 Quantification of system performance	10
2.2 Program outline	13
2.3 Root zone environment	19
2.3.1 The depth of the root zone	20
2.3.2 The root zone soil moisture status	22
2.3.3 Root zone salinity status	25
2.4 System costs	29
2.4.1 Costs of closed drains	30
2.4.2 Costs of open drains	43
2.5 Crop response to subsurface drainage	53
2.5.1 The uptake of water by plants	53
2.5.2 The effect of salts on water uptake and yields	56
2.6 System benefits	62
CHAPTER III: PROGRAM APPLICATIONS	70
3.1 Existing field situation-one crop	70
3.2 Existing field case-two crops	77
3.3 Existing field case-four crops	85
3.4 Closed drain selection-one crop	90
3.5 Open drain selection-one crop	100
3.6 Expanded program use-one crop	100
3.7 Summary and discussion	103
CHAPTER IV: SUMMARY	105
REFERENCES:	109

TABLE OF CONTENTS (continued)

Chapter	Page
APPENDIX A: PROGRAM DOCUMENTATION	113
A.1 Program listing	113
A.2 Input data requirements	160
A.3 Major variables	169
APPENDIX B: EXAMPLE PROGRAM INPUT AND OUTPUT	175
B.1 Example input	175
B.2 Example output	177

LIST OF TABLES

Table		Page
2.1	Subroutines	16
2.2	Gradient matrix entries for closed drains	40
2.3	Gradient matrix entries for open drains	50
3.1	Summary of program input data	79
3.2	Summary of computer results for Summer season, 1978	79
3.3	Costs assumed for closed drains	91
3.4	Summary of results for closed drain analysis - one crop	97
3.5	Seasonal summary of computer results for closed analysis - one crop	98
3.6	Summary of results for open drain analysis - one crop	101
A.1	Summary of input requirements	167

LIST OF FIGURES

Figure		Page
1	Example curve showing relationship between system level, benefits and costs	7
2	General procedure	9
3	Alternative drain layouts with the same minimum midspan depth to water	12
4	Flow chart of main program, DRAINS	14
5	Hierarchy of subroutines	15
6	Flow chart of subroutine RTZ	21
7	Elevation and plan view of closed drain system	31
8	Elevation of open ditch	44
9	Membrane system illustrating concepts of matric suction, solute suction and total suction of soil water	59
10	Illustration of effect of salt content on total soil moisture suction	68
11	Soil moisture status computed for the Summer season	73
12	Salinity levels computed for the Summer season	73
13	Effective and input root distribution and water table evaluations for the Summer season	76
14	Water and salt balances for two crop seasons and three soil moisture availability assumptions	81
15	Root depths and water table elevations for one year period	82
16	Root zone salinity levels for one year period	84
17	Water and salt balances for two year period and three soil moisture availability assumptions	86
18	Soil moisture status for two year period	87

LIST OF FIGURES (continued)

Figure		Page
19	Salinity levels for two year period	88
20	Root depths and water table elevations for two year period	89
21	Soil moisture ratio computed for the Summer season, with drains installed, HMIN = 100 cm	93
22	Salinity levels computed for the Summer season, with drains installed, HMIN = 100 cm	94
23	Root depths and water table elevations with drains installed for the Summer season	95

NOMENCLATURE

A	Area
b	Depth to impermeable sublayer from ground surface
b_1	Bottom width of an open drain
b*	Berm and spoil width
C	Cost coefficient
CS_{di}	Crop susceptibility factor
D	Effective flow depth
DPM	Distance per manhole
d	Depth to water level in drain from ground surface
d_d	Quantity of drainage water expressed as a depth
d_e	Effective flow depth
d_i	Quantity of irrigation water expressed as a depth
dsm	Quantity of soil moisture expressed as a depth
dw	Quantity of water expressed as a depth
EC	Electrical conductivity
ECS	Electrical conductivity of water saturated with indigenous soil salts
EC_e	Electrical conductivity of saturated extract
ET	Evapotranspiration
f	Functional constraint
g	Force of gravity
HMIN	Minimum allowable depth to water from ground surface
h	Water table height above drain level, also vertical space coordinate
h_c	Midspan water table height above drain level

NOMENCLATURE (continued)

heq	Equivalent midspan water table height above drain level
I	Depth of water added to the water table from an irrigation event
i	Rate
K	Hydraulic conductivity
K_1	Shape factor
K_2	Shape factor
L	Drain spacing, center to center
l	Drain length, field length
M_i	Mass pickup
p	Pressure
Q_{max}	Maximum drain flow capacity
q_{lim}	Limiting upflow from water table
q*	Inflow into drain from one side
R	Hydraulic radius
S	Bottom slope of drain, also field slope
SD_d	Drainage stress factor
SDI	Stress day index
SEW_x	Sum of excess water days above x
SM	Soil moisture
S_d	Salinity of drainage water
S_i	Salinity of irrigation water
S_{sm}	Salinity of soil moisture
Sya	Apparent specific yield
s	Side slope of ditch
T	Time period

t	Time coordinate
V	Average flow velocity
W	Width
x	Horizontal space coordinate
Y	Yield
Ya	Actual or computed yield
Ym	Maximum yield
Yo	No stress yield
Z	Objective function
z	Vertical space coordinate

Greek letters

α	Aquifer response coefficient
γ	Coefficient of leaching efficiency
θ	Volumetric soil moisture content
ρ	Density
τ	Time coordinate

AMERICAN EQUIVALENTS OF EGYPTIAN ARABIC TERMS AND MEASURES COMMONLY USED IN IRRIGATION WORK

LAND AREA	IN SQ METERS	IN ACRES	IN FEDDANS	IN HECTARES
1 acre	4,046.856	1.000	0.963	0.405
1 feddan	4,200.833	1.038	1.000	0.420
1 hectare (ha)	10,000.000	2.471	2.380	1.000
1 sq. kilometer	100×10^4	247.105	238.048	100.000
1 sq. mile	259×10^6	640.000	616.400	259.000

WATER MEASUREMENTS	FEDDAN-CM	ACRE-FEET	ACRE-INCHES
1 billion m^3	23,809,000.000	810,710.000	
1,000 m^3	23.809	0.811	9.728
1,000 m^3 /Feddan (= 238 mm rainfall)	23.809	0.781	9.372
420 m^3 /Feddan (= 100 mm rainfall)	10.00	0.328	3.936

OTHER CONVERSION		METRIC	U.S.
1 ardab	=	198 liters	5.62 bushels
1 ardab/feddan	=		5.41 bushels/acre
1 kg/feddan	=		2.12 lb/acre
1 donkey load	=	100 kg	
1 camel load	=	250 kg	
1 donkey load of manure	=	0.1 m^3	
1 camel load of manure	=	0.25 m^3	

EGYPTIAN UNITS OF FIELD CROPS

CROP	EG. UNIT	IN KG	IN LBS	IN BUSHELS
Lentils	ardeb	160.0	352.42	5.87
Clover	ardeb	157.0	345.81	5.76
Broadbeans	ardeb	155.0	341.41	6.10
Wheat	ardeb	150.0	330.40	5.51
Maize, Sorghum	ardeb	140.0	308.37	5.51
Barley	ardeb	120.0	264.32	5.51
Cottonseed	ardeb	120.0	264.32	8.26
Sesame	ardeb	120.0	264.32	
Groundnut	ardeb	75.0	165.20	7.51
Rice	dariba	945.0	2081.50	46.26
Chick-peas	ardeb	150.0	330.40	
Lupine	ardeb	150.0	330.40	
Linseed	ardeb	122.0	268.72	
Fenugreek	ardeb	155.0	341.41	
Cotton (unginned)	metric qintar	157.5	346.92	
Cotton (lint or ginned)	metric qintar	50.0	110.13	

EGYPTIAN FARMING AND IRRIGATION TERMS

fara = branch
marwa = small distributer, irrigation ditch
masraf = field drain
mesqa = small canal feeding from 10 to 40 farms
qirat = cf. English "karat", A land measure of 1/24 feddan, 175.03 m^2
qaria = village
sahm = 1/24th of a qirat, 7.29 m^2
saqia = animal powered water wheel
sarf = drain (vb.), or drainage. See also masraf, (n.)

CHAPTER I

INTRODUCTION

Enormous investments in drainage of irrigated lands have been made in recent years throughout the world. With the introduction of irrigation into an area, natural or artificial drainage is almost always a consideration. Without it, salinity problems and high water tables often eventually lower the productivity of the land. The total irrigated area in the world is estimated to be about 230 million hectares (Donnan, 1977). Thorne and Thorne (1979) report that 122 million hectares or over half the world's irrigated land have developed drainage and salinity problems.

In Egypt, a comprehensive soil survey started in 1957 and completed in the last decade classified cultivated areas by considering productivity, soil texture, soil salinity and alkalinity, water table level and need for drainage. Only 7% of the area cultivated in 1971 was classified as excellent and 43% as good. The remaining 50% (over 100,000 hectares) was classified as medium to poor (El-Tobgy, 1974). In many cases, artificial drainage represents the only way to maintain and improve the productivity of this land. In response to the growing awareness of the need for artificial drainage in Egypt, an ambitious program to install drainage systems has been undertaken. In 1975, a 10 year plan was adopted to spend over one billion U. S. dollars on drainage (Arar and Bishay, 1975). This is an enormous investment and the need for investing wisely is evident.

The theory and data pertinent to drain design is rapidly advancing the selection of drain sizes and layouts from an art to a science. However, despite the staggering investment being made in drainage, the associated economic aspects of drain design have not received the same attention, and workable procedures for the economic planning of systems are still lacking. The work reported in this paper is an attempt to provide a workable procedure which can be used by the designer as an aid in the economic planning of subsurface drain systems in arid regions.

1.1 OBJECTIVES:

The primary objective of the current study is to develop a methodology and model which can be used to determine economically optimum subsurface agricultural relief drainage systems in irrigated areas. The model is to be simple enough to be usable by the drain designer and have realistic data requirements. At the same time, it is to be complete enough for the results to have a high degree of reliability. The format is to be flexible to allow for easy revision, modification and updating of components.

In brief, the computer model is to include the following components:

(i) An analysis of existing field situations.

(ii) An analysis of the physical effects on the plant environment of installing open or closed field drainage systems.

(iii) A procedure which relates the physical effects of drain installation to the economic benefits derived.

(iv) A procedure which compares costs and benefits and allows identification of the optimum system.

In addition to determining the optimal drain system, the program should be able to be used with little or no modification for the following:

(i) Evaluate alternative irrigation schedules for existing field cases or in conjunction with proposed drain systems.

(ii) Indicate long term changes in the plant root environment.

(iii) Evaluate the economic desirability of additional field testing and data collection.

(iv) Serve as a guide for the types of field data which are needed for an economic evaluation of a proposed drain system.

(v) Determine in general when one type of drainage system (open or closed) is preferable to the other.

(vi) Determine an irrigation schedule (frequency and quantity) that will result in higher crop yields.

1.2 SCOPE:

The following general assumptions are made to limit the scope of the current study:

(i) Only irrigated agriculture is considered. The climate is assumed to be arid and rainfall is neglected.

(ii) The topography of the study area is assumed relatively flat. Highly irregular topography is probably best drained by random drains or interception drains. In this study, only relief drainage systems are considered.

(iii) It is assumed that high water tables and consequent waterlogging conditions and salinity problems are a general condition of the entire area and are induced by high applications of irrigation water with poor natural drainage. Inflow from adjacent areas is neglected.

(iv) The study is limited to consideration of closed drains and open field ditches only. Of course, these are not the only methods of groundwater control. A variety of distribution and on-farm management techniques could contribute significantly to the control of high water tables. In addition, other types of drainage systems may be economical and acceptable. Chemical soil treatments or applications may also alter existing conditions. It is assumed that these possibilities have been previously investigated and found to be physically or economically undesirable or that the systems studied are to be used in conjunction with one or several of these other options.

(v) The pattern of irrigations is assumed to repeat each year or period and the selection of drain sizes and layouts is based on dynamic equilibrium criteria.

(vi) Crop yield is assumed directly related to plant growth. Plant growth, in turn, is assumed limited only by the availability of soil water for plant uptake and use, and soil water availability is a function of soil moisture content, root zone salinity level and effective root depth. All other factors are assumed constant.

CHAPTER II

MODEL DEVELOPMENT

There are many possible economic criteria on which the decision of a "best" on-farm drainage system could be based. Two are minimization of costs and maximization of net benefits. The first alternative recognizes that there is often more than one drainage system which will meet some predetermined requirements of performance. The "best" system, then, is the one that satisfies the requirements for the least cost. This alternative, however, does not give any indication of which system requirements will result in an optimum level of performance. For example, assume that the performance requirement of a drain system is to keep the water table below 100 centimeters during a crop season. Various depth and spacing combinations would satisfy this requirement and if the selection criterion was minimization of costs, the least cost combination would be selected. However, this criterion gives no information on the appropriateness of the system requirements, e.g., instead of a minimum depth to water of 100 centimeters, should the water table be allowed to rise to within 75 centimeters of the surface or, alternatively, should the water table be constrained below a depth of 125 centimeters?

Maximization of net benefits is more comprehensive than minimization of costs in that it incorporates a decision as to the desired level of system performance. Unfortunately, it is often more difficult to quantify benefits than costs. In this study, benefits will be measured in terms of crop yield and net benefits defined as that income derived by the farmer from the additional crop yields attributable to installation of a drain system minus the costs of that

system. Maximization of net benefits further implies that differing levels of system performance are compared. Quantification of these system levels is discussed in Section 2.1. However, assuming that these levels of performance can be quantified satisfactorily, then for each level there is a minimum cost required to achieve that level and an associated benefit or crop yield. The relationships between benefits, costs and system level can be visualized as shown in Figure 1. In this figure, benefits and costs are plotted for several system levels. In general, it is expected that as the level of the system (or level of protection) increases, the benefits or yields also increase, at least to a point, but the costs must also increase to obtain the additional protection. In the example curve shown, it is assumed that some benefit is derived from the land with no artificial drainage. It may be that in a proposed reclamation project, the benefits without additional drainage are zero, or even negative if such things as aesthetics and health factors are considered. In addition, benefits are shown leveling off as the crop yields approach some maximum level. In most cases, crop yields are limited by environmental conditions and crop characteristics independent of water/plant growth relationships. Further, at some point, benefits may even decrease if more restrictive drain requirements are imposed. Therefore, the derived benefits level off as the crop yield approaches some maximum attainable level and may decline beyond this point.

Costs, on the other hand, may show some economies of scale, but eventually it would be expected that additional levels of protection would require higher marginal costs. Obviously, from an economic standpoint, the level of protection should not be increased if the

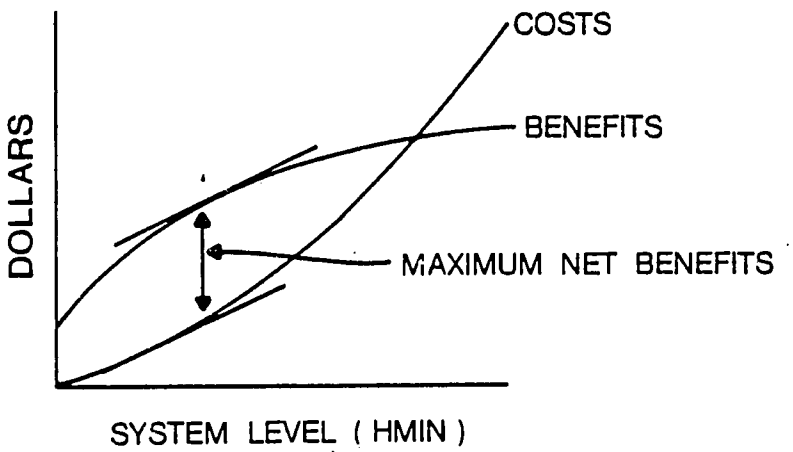


Figure 1 Example curve showing relationship between system level, benefits and costs.

marginal cost exceeds the marginal benefits. Therefore, theoretically, the point where the marginal costs and marginal benefits are equal represents an optimum point. However, other factors such as availability of funding, sociopolitical factors, external diseconomies and farmer preferences enter into a final decision. This, however, is why any methodology developed can serve only as an aid to the designer and not as a substitute. It should be noted, also, that Figure 1 is an idealized curve and variations of the curve are possible. For example, in some cases, any proposed drain system may always result in negative net benefits and the existing field case is more desirable.

A brief outline of the general procedure is shown in Figure 2. It combines

(i) an optimization routine which minimizes costs, and

(ii) an incremental search to determine the best system level for the given crop, field conditions, and management decisions.

If the relationships between variables are expressed in analytical form and changes in given factors are made systematically, the proposed methodology should facilitate mapping or following trends in the system designs and in identifying significant variables. The process also offers a high degree of flexibility. For instance, one component of the program involves the influence of waterlogging conditions on crop yields. This relationship is not well defined at this time. The segregation of components of the model allows easy replacement of a part of the existing model with a better one as the level of technical understanding in this area increases. One major advantage of the proposed methodology is that significantly fewer combinations of drain spacings and depths need be investigated. A least cost combination for

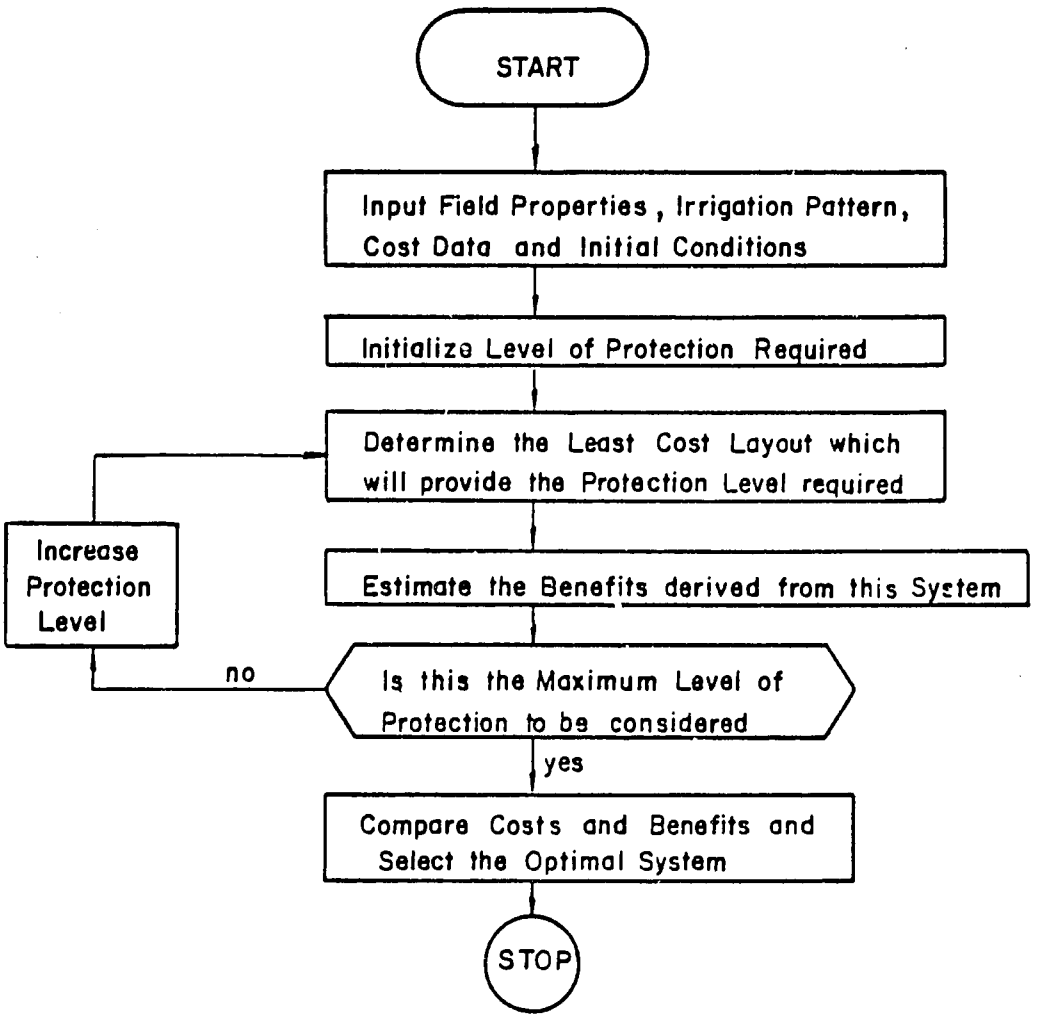


Figure 2 General procedure.

each prespecified level of system performance is determined first, thereby eliminating the need to check all combinations of drain layout.

2.1 QUANTIFICATION OF SYSTEM PERFORMANCE:

The aim of any agricultural drainage system is to provide a healthy environment for plant growth. This implies that a drainage system must be designed with the requirements of the plant in mind and since there are a wide variety of plant growth environments, there are a corresponding large number of reasons why drainage may be beneficial. There are two aspects which enter into an attempt to quantify the performance of a drain system: first, the conditions which limit plant growth must be identified, and secondly, design criteria which represent levels of performance must be determined.

In this study, it is assumed that the area experiences high water table conditions due to overirrigation needed for leaching and inadequate natural drainage. A fluctuating water table exists with a net rise occurring over the cropping season with accompanying nonaeration and salinity problems possibly resulting. The basic purpose of the drains then is to lower the water table and consequently limit the upflow to the root zone from the water table if the groundwater is saline, allow effective leaching to occur and minimize the frequency and spatial extent of nonaerated conditions in the root zone without creating excessive soil moisture deficit conditions. All other factors in the plant environment are considered nonlimiting to growth.

The second aspect of quantifying drain system performance is to devise design criteria which represent different levels of performance. The design requirement used in this paper is specified by the variable, HMIN. HMIN is the minimum depth to water occurring midway between the

drains allowed for the crop season or period. This will generally, but not necessarily, occur after the last irrigation of the season. It is assumed that, for an input irrigation pattern, soil conditions and preseason initial conditions, increasing values of HMIN represent correspondingly decreasing quantities of upflow of salts and water from the water table and also decreasing frequency and extent of nonaerated conditions. Therefore, HMIN is inversely related to the level of protection afforded by the drain system. It is not necessarily an indicator of crop yields since soil moisture deficits may increase as HMIN increases. However, HMIN is considered to be an adequate measure of the restrictiveness of the system.

It is further assumed that a number of combinations of drain depths and drain spacings will limit the water table rise and hence afford approximately equal degrees of protection for the root zone. Of course, this is not strictly true. Consider the two layouts shown in Figure 3. Both drain systems result in the same minimum depth to water at midspan. However, the actual area of the field subjected to high water table conditions is different in the first case than in the second. Also, in the second case, the plants above the drains may actually be stressed due to water deficits. However, within limits, there is a trade-off between depth and spacing with one combination being the least expensive way to limit the minimum depth to water to HMIN. In addition, the purpose of HMIN is to provide levels at which to compare net benefits. The same cost structure is generally applicable for each level. Therefore, a cost structure which has a severe penalty for decreasing the spacing but a small penalty for increases in depth will result in a series of least cost layouts with large spacings and large depths.

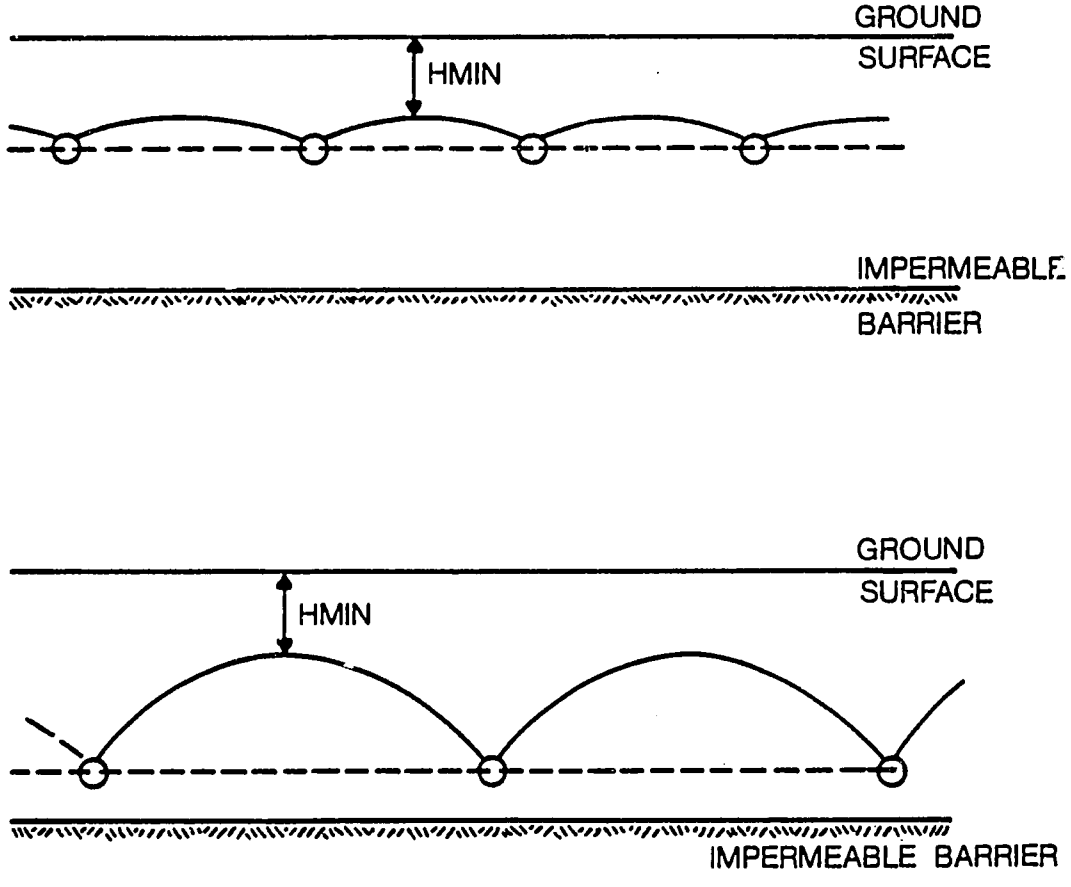


Figure 3 Alternative drain layouts with the same minimum midspan depth to water.

Hence, the extreme differences in areas shown in Figure 3 would not occur in a practical application.

2.2 PROGRAM OUTLINE:

Figure 4 shows a general flow chart of the main program, DRAINS. DRAINS controls the main loop of the program which increments HMIN. The hierarchy of subroutines is given in Figure 5 and a summary of what each subroutine does is given in Table 2.1.

The general procedure used in the program is as follows:

1. Input data is read and variables are initialized.
2. Subroutines RTZ, SUMS, and YIELD are called to evaluate the existing root zone environment and estimate crop yield for the existing field situation. From the existing field situation, an initial estimate of the deep percolation to the water table is also obtained for each irrigation.
3. At this point the main loop of the program begins with HMIN= HMINI, the initial input value for the minimum depth to water for the season. HMIN represents the level of protection to be afforded by the drain system. This main loop increases HMIN by uniform increments until a maximum HMIN input by the programmer is reached or the drains are on an impermeable lower barrier. The variable J indicates the type of system to be evaluated. If J=0, only the existing field situation is to be considered. J=1 indicates closed drains and J=2 indicates open drains are to be evaluated. The existing field situation is evaluated if J is set equal to either 1 or 2. If J=3, both open and closed systems, as well as the existing system, are considered.

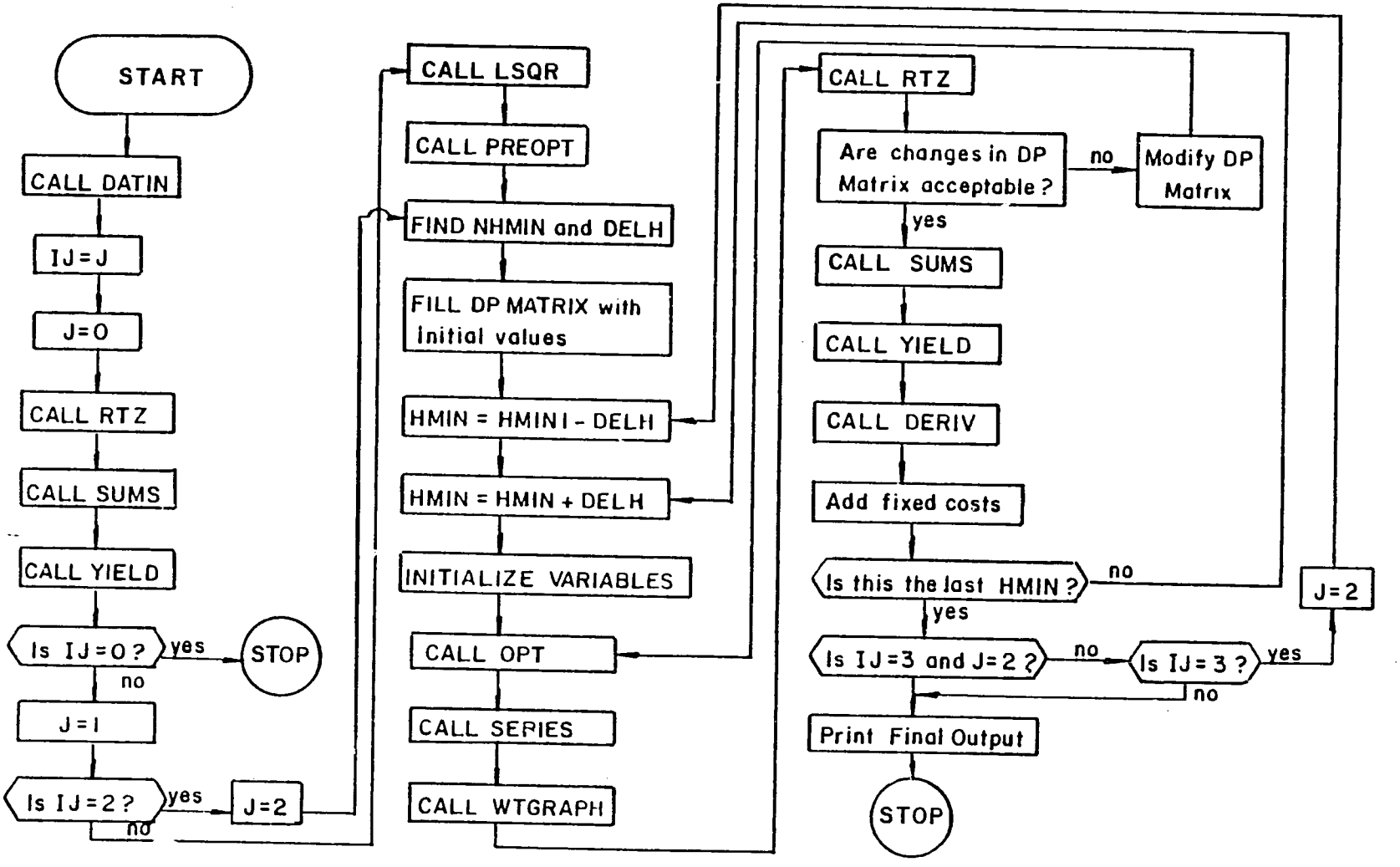


Figure 4 Flow chart of main program, DRAINS.

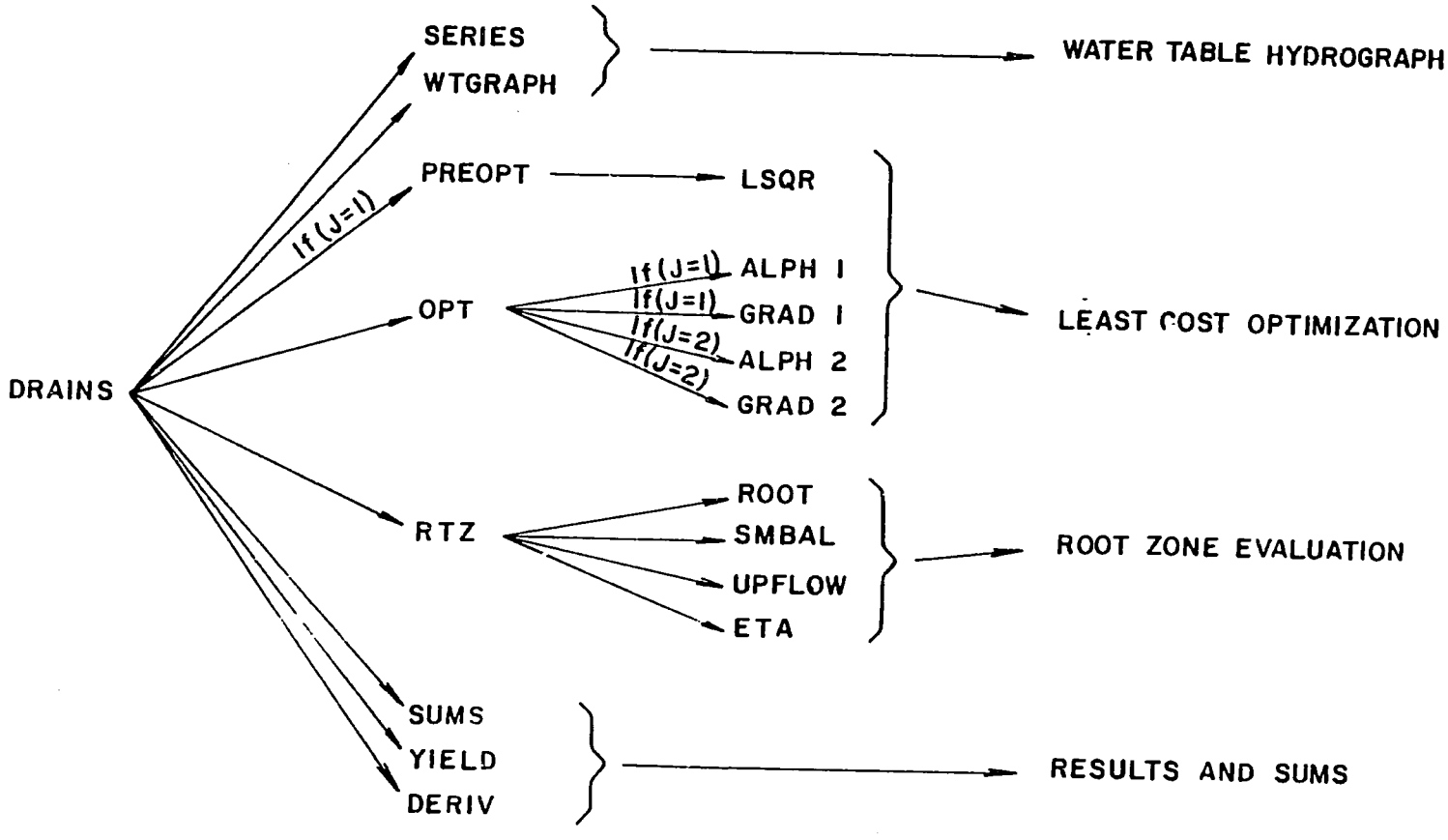


Figure 5 Hierarchy of subroutines.

Table 2.1: Subroutines

ALPH1:	Computes the drain size and maximum discharge rate for closed drains. Also computes the equivalent drain depth and alpha using Moody's convergence criteria.
ALPH2:	Computes the required ditch dimensions, flow velocity and discharge for open ditches.
ETA:	Determines the actual daily evapotranspiration from an input water availability curve and the total average soil moisture stress in the root zone.
GRAD1:	Computes the gradient matrix entries for closed drains and evaluates the cost function and the constrained derivative of the cost function.
GRAD2:	Computes the gradient matrix entries for open drains and evaluates the cost function and the constrained derivative of the cost function.
LSQR:	Determines the cost coefficients for a quadratic function that expresses closed drain cost in terms of drain diameter.
OPT:	This is the main subroutine of the least cost analysis. OPT computes the maximum allowable drain spacing, iterates until alpha and the drain depth are consistent with the spacing, checks the change in spacing and controls the convergence pattern.
PREOPT:	Simplifies the cost coefficients in the closed drain objective function.
ROOT:	Initially fills the unstressed root depth matrix from input values, checks the proximity of the bottom of the root zone to the water table and prunes the roots or delays root growth if within the input saturated height.
RTZ:	This is the main subroutine of the daily root zone status evaluation. It calls subroutines ETA, ROOT, SMBAL and UPFLOW, increments the day, computes the salinity status of the root zone, calculates the deep percolation and computes application efficiencies. An irrigation pattern can also be determined in RTZ if this option is specified by the user.
SERIES:	Computes the infinite series in the dynamic equilibrium equations for midspan water table height.

Table 2.1: Subroutines (Continued)

SMBAL:	Computes the average volumetric soil moisture content in the root zone and in the soil profile from the ground surface to the water table from input equilibrium soil moisture distributions.
SUMS:	Sums evapotranspiration rates, soil moisture contents, and the number of centimeter days the water table is above an input critical.
UPFLOW:	Calculates the limiting daily steady water flux from the water table to the root zone.
WTGRAPH:	Determines the water table hydrograph for the study period using the infinite sums computed in SERIES.
YIELD:	Calculates yield reduction from a linear production function which combines the ratio of actual to maximum evapotranspiration and a growth stage susceptibility factor.

4. For each level of protection (HMIN), the program determines a minimum cost system which will provide that level of protection and the associated yield or benefit derived. The sequence of steps is as follows:

   a. Using current values of deep percolation, subroutine OPT is called to determine the least cost drain depth and spacing combination which will provide the desired level of protection and the cost of the system is determined. Subroutines GRAD1 and ALPH1 are called from OPT if J=1 and GRAD2 and ALPH2 are called if J=2. Subroutines LSQR and PREOPT are also called once if J=1 to determine a functional cost relationship for closed drains and simplify the coefficients in the objective function.

   b. The water table hydrograph for the season is determined in subroutines SERIES and WTGRAPH for this drain depth and spacing combination and current values of deep percolation.

   c. RTZ is then called to evaluate the root zone environment created by this drain system and new estimates for the percolation values are made. If the changes in the deep percolation values are not within acceptable limits, the values are modified and steps 4 (a-c) are repeated. Subroutines ETA, UPFLOW, ROOT, and SMBAL are called from RTZ.

   d. Subroutines SUMS and YIELD are called to determine the yield (benefits) for this system.

e. Fixed costs associated with the input irrigation pattern (conveyance costs, labor costs, etc.) are added to the drain system costs determined in part a.

5. HMIN is now incremented and the sequence (a-e) in part 4 is repeated for this new level. This is repeated until a maximum HMIN occurs. At this point, the program has determined the minimum costs and benefits associated with a range of system levels, denoted by HMIN. The costs and benefits can be compared and the optimum system (maximum net benefits) determined.

6. If both open and closed systems are to be considered, the above procedure is completed for closed drains, HMIN is reset to HMINI, variables are reinitialized, and steps 4, 5 and 6 are repeated for open drains.

7. If the irrigation schedule or other input variables are design considerations, changes in the input data are made and the program must be rerun to evaluate the new conditions.

The remainder of this chapter discusses individual components of the program.

2.3 ROOT ZONE ENVIRONMENT:

The root zone environment is evaluated in subroutine RTZ and is defined in terms of three quantities:

(i) the depth of the root zone,

(ii) the average soil moisture in the root zone expressed as an average volumetric soil moisture content,

(iii) the average salinity level of the root zone expressed in terms of an electrical conductivity.

Subroutine RTZ is the primary subroutine used to determine the daily status of each of these variables. Subroutines SMBAL, ETA, ROOT, and UPFLOW are called when required to supplement subroutine RTZ. It should be recalled that when RTZ is called from the main program, DRAINS, the initial conditions, irrigation schedule and water table hydrograph are generally known. From this information, RTZ performs daily water and salt balances and estimates the percolation to and upflow from the water table, the effective root zone depth, the actual daily evapotranspiration rates and the change in the depth to water due to upflow to the root zone. The program also has the capability of choosing an irrigation schedule. This is done in subroutine RTZ if the variable ICHNG is input as 1 by the user. This option is discussed in Chapter 3. The discussion which follows assumes an input irrigation schedule. Figure 6 outlines the procedure used in RTZ.

2.3.1 The Depth Of The Root Zone: The first component of the root zone environment considered is the depth of the root zone. It is assumed that there is a height, HSAT, above the water table below which plant respiration is restricted. This limit could be designated by a bubbling pressure or air entry pressure (Corey, 1977; Brooks and Corey, 1964) or related to critical aeration levels for plant growth (Williamson and Kriz, 1970). It could also be considered to be similar to Duke's equivalent saturated height (Duke, 1973; McWhorter and Duke, 1976). In any case, an unstressed effective root growth distribution for the season is input in the program. Each time any portion of the root zone is saturated (or below HSAT), root growth is delayed and transpiration from this region ceases. If saturated conditions persist for an input number of days, based on the crop's tolerance of saturated conditions,

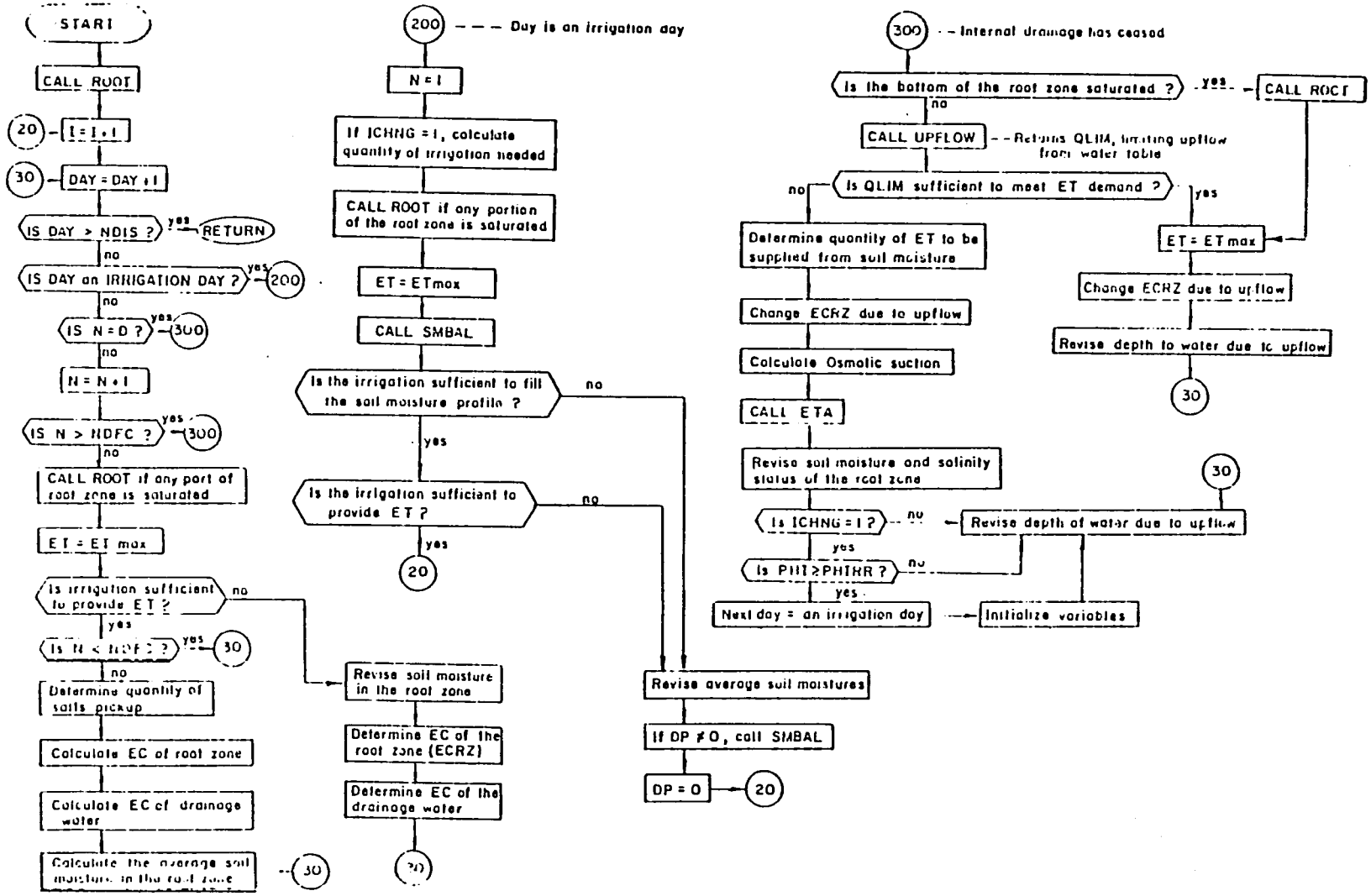


Figure 6 Flow chart of subroutine RTZ.

the roots in the saturated region are destroyed and the root depth truncated. If the water table subsequently declines, growth is resumed at a rate equal to the unstressed root growth rate before saturation occurred.

2.3.2 The Root Zone Soil Moisture Status: In RTZ, each day in the season is initially categorized as one of the following:

(i) an irrigation day,

(ii) a day following an irrigation day, but before internal drainage is assumed to cease in the root zone,

(iii) the day at which field capacity is reached in the root zone or downward flow ceases, or

(iv) a day which occurs after drainage ceases in the root zone, but before the next irrigation event.

The input irrigation water is assumed to fill the soil moisture holding capacity to an equilibrium profile and provide the evapotranspiration demand for days in periods (i), (ii) and (iii), with the excess draining to the water table. If, in fact, the irrigation quantity is insufficient to meet these demands, periods (ii) and (iii) are adjusted. The equilibrium average soil moisture status and salinity status in the root zone and in the entire profile are evaluated at the day defined in period (iii). Although, particularly for shallow water table depths, soil moisture equilibrium is not actually attained, this is assumed to be a reasonable assumption (Skaggs, 1978). Hysteresis effects, changes in soil properties and changes in infiltration rates during the season are neglected in the present form of the program.

During period (iv) all evapotranspiration demand is assumed to be provided from the available soil moisture in the root zone or upflow

from the water table. The quantity of upflow available for plant use is determined initially. Richards' equation (Corey, 1977) for vertical flow is

$$\frac{\partial}{\partial Z}\left[-K(\theta)\,\frac{d\left[\frac{p_c}{\rho g}+Z\right]}{dZ}\right] = \frac{-d\theta}{dt} \qquad (2.1)$$

θ = volumetric water content

$K(\theta)$ = the unsaturated hydraulic conductivity expressed as a function of θ

$\frac{p_c}{\rho g}$ = the pressure head

Z = vertical coordinate measured upward from the water table

t = time coordinate

Several authors have discussed steady upflow from a water table in response to evaporation at the surface (Anat et al, 1965; Corey, 1977). In this case, Richards' equation reduces to a steady state equation and upflow is uniquely determined by solution of the equation

$$L = -\int_0^{h(L)} \frac{1}{1+\frac{q}{K(h)}}\,dh \qquad (2.2)$$

where q = the steady upward flux

L = depth to the water table

h = vertical space coordinate

$h(L)$ = pressure head at the soil surface

$K(h)$ = unsaturated hydraulic conductivity as a function of h

From this equation, it can be seen that for a given water table position, the upward flux is a function of $K(h)$ and h. It has been shown that a limiting flux, q_{Lim} is approached as h becomes large, and in most soils, the actual upward flux is very close to the limiting flux because of the nonlinearity of the unsaturated conductivity. Equation 2.2 can be solved by numerical methods or solved analytically if an appropriate expression for $K(h)$ is available. Solutions by Brooks and Corey (1964) and Gardner (1958) are most notable in the latter case.

A soil containing growing plants complicates the solution of Equation 2.2 in that the location of the sink term is not a single valued function defined by L but depends on the spatial and temporal uptake distribution of the roots. This is difficult to determine even under laboratory conditions. In view of the uncertainties inherent in a field situation and the lack of available data, the problem is simplified considerably. In the program, steady upflow on a daily basis is assumed and the upflow rate is assumed equal to the limiting value. For most cases, these assumptions are reasonable. The upward flux is very close to the maximum even when the pressure head is as small as -50 to -300 centimeters of water. A table of input values of limiting upflow, q_{Lim}, versus distance, Z, is required input in the program. These relationships can be determined from a numerical or analytical

solution of Equation 2.2, or from publications such as the FAO Irrigation and Drainage Paper No. 24 by Doorenbos and Pruitt (1977). The distance, Z, is assumed to be the distance from the bottom of the effective root zone to the water table. This assumption may overestimate the upflow somewhat, particularly in high water table conditions. However, under these same conditions, an equilibrium profile would probably not be obtained, tending to offset the error introduced in the assumption. Perhaps a better assumption would be to assume there exists a plane of maximum uptake in the root zone and Z is the distance between this plane and the water table. A change in the program redefining the variable Z could be easily accomplished if data on the location of this maximum plane were available.

If the bottom of the root zone is within the saturated area above the water table, it is assumed all of the evapotranspiration demand is supplied from the water table. Otherwise, the available upflow is used for plant transpiration and evaporation and the remaining demand must be supplied by the available soil moisture in the root zone. The total integrated soil moisture suction is evaluated from the matric and solute suctions and subroutine ETA is called to evaluate the actual evapotranspiration for the day based on input water availability criteria and input maximum evapotranspiration data. Average moisture contents and salinity levels are evaluated assuming that the salts in the transpired or evaporated water are left in the root zone. Also, if upflow has occurred, the position of the water table is adjusted.

2.3.3 Root Zone Salinity Status: A portion of the water applied in an irrigation event is used to fill the soil moisture deficit, a second portion is assumed to meet the evapotranspiration demand during the

draining cycle and the remainder is assumed to percolate to the water table. For the purpose of discussion, assume that the net quantity of percolated water is positive and that the salinity of the drainage water is greater than the salinity of the irrigation water. Then, at the end of the drainage cycle, the quantity of salts in the drainage water can be expressed as:

$$S_d d_d = S_i d_i + M_i \tag{2.3}$$

where d_d = quantity of drainage expressed as a depth (L^3/L^2)

d_i = depth of irrigation (L^3/L^2)

S_d = salinity of the drainage water

S_i = salinity of the irrigation water

M_i = mass pickup

In the program, the salinities are expressed in terms of electrical conductivities. The mass pickup is the total quantity of salt removed from the soil moisture by the percolating water.

Further assume that internal drainage occurs for k days after an irrigation event and the evapotranspiration (ET) demand during this period is supplied by the percolating water. Then

$$d_d = d_i - \Delta SM - \sum_{n=1}^{k} ET_n \tag{2.4}$$

where ΔSM is the depth of water required to fill the soil moisture profile. Therefore, if the quantity of water needed to fill the soil moisture reservoir, the quantity and quality of the irrigation water and the total evapotranspiration demand for the draining period are known, the salinity of the drainage water can be determined if a reasonable estimate of the mass pickup can be obtained.

The mass pickup term, M_i, is approximated by assuming that complete mixing of the percolating water and the soil water occurs, and all salts in the soil matrix are mobile and in solution. Let d_w be the total depth of water in the soil above the water table after an irrigation event and before internal drainage is assumed to cease after k days. Then

$$d_w = d_{sm} + d_i - \sum_{n=1}^{k} ET_n \tag{2.5}$$

Precipitation of the salts is assumed negligible. Hence, the total quantity of salts is

$$Q_s = d_{sm}S_{sm} + d_iS_i \tag{2.6}$$

If, in fact, all salts are in solution, the average salinity of all the water present is

$$S_{avg} = \frac{Q_s}{d_w} = \frac{d_{sm}S_{sm} + d_iS_i}{d_{sm} + d_i - \sum_{n=1}^{k} ET_n} \tag{2.7}$$

The salinity of the drainage water is then equal to the salinity of the soil moisture and the quantity of salts leached is directly proportional to the quantity of drainage water. The mass pickup term in Equation 2.3 is

$$M_i = S_{avg}d_d - S_id_i \tag{2.8}$$

and

$$S_d d_d = S_{avg} d_d = \frac{d_{sm} S_{sm} + d_i S_i}{d_{sm} + d_i - \sum_{n=1}^{k} ET_n} d_d \tag{2.9}$$

Note that the following relationships hold:

(i) As the salts input in the irrigation event increase, the salts in the drainage water increase, but the pickup decreases.

(ii) As the salts in the soil moisture profile increase, the pickup term increases.

(iii) As the ET demand during drainage increases, the average salinity of the remaining water increases.

Further, if an entire season balance is considered and it is assumed that throughout the season the net changes in soil moisture and soil moisture salinity are zero, and no upflow from the water table occurs, then the sum of all input depths, Σd_i, minus the total ET is equal to the drainage quantity. In Equation 2.9, d_{sm} and S_{sm} are assumed constant and the total quantity of salts reaching the water table, $S_d d_d$ is given by:

$$S_d d_d = \frac{d_i S_i}{\Sigma d_i - \Sigma ET} d_d = \frac{d_i S_i}{d_d} d_d = d_i S_i \tag{2.10}$$

which is, when rearranged, the leaching fraction required for equilibrium (USDA, 1954). Similarly, if drainage is zero, the mass pickup term is simply $-S_i d_i$ which indicates all salts added in an irrigation event are stored in the soil moisture profile above the water table.

The equation for mass pickup is limited in the program if the value of S_{avg} is larger than the salt carrying capacity of the drainage water. Hence, M_i is chosen as the smaller of Equation (2.8) and

$$(M_i)_{max} = \gamma ECS - d_i S_i \tag{2.11}$$

where γ is a constant between 0 and 1 which indicates leaching efficiency and is a function of temperature, rate of percolation and soil texture and ECS is the total dissolved solids of a water saturated with indigenous soil zone salts.

The quantity of salts remaining in the soil profile is determined from the initial level of salinity before irrigation and the mass pickup term. The salinity of the root zone is adjusted for the change in average soil moisture level and the salinity of the groundwater in subsequent upflow calculations is assumed to be the larger of the input groundwater salinity and the calculated salinity of the drainage water.

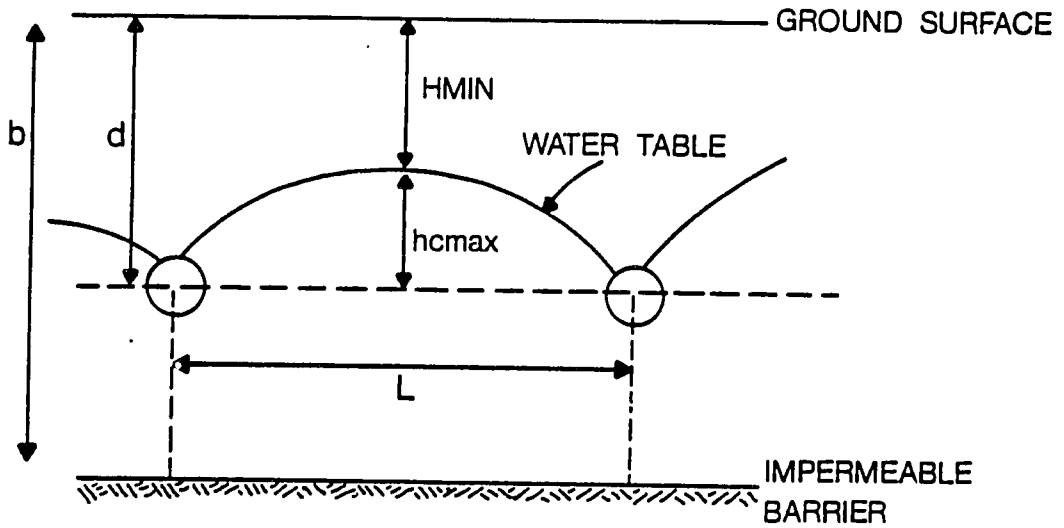
2.4 SYSTEM COSTS:

Subroutines PREOPT, OPT, GRAD1, GRAD2, ALPH1 and ALPH2 determine the minimum cost drain depth and spacing combination which will result in the specified level of protection. Cost functions for open and closed drains are the objective functions of the optimization process. The decision variable is the drain spacing, L, and the major constraint on the objective function is an approximation of the dynamic equilibrium equation for drain depth. The cost function and constraints given in the following section are those which are included in the program at this time. These can be easily changed if they are deemed inappropriate for the field case being considered. For example, any analytical drain spacing equation could be used as a constraint if dynamic equilibrium of

the water table is not the design requirement desired. The form of the cost function can be changed by simply changing the cost function and derivatives in subroutines GRAD1 and GRAD2.

An initial spacing is assumed and a compatible drain depth is estimated initially by ignoring convergence at the drain. Then subroutine ALPH1 or ALPH2 (depending on whether the drain is open or closed) is called to account for convergence using Moody's convergence criteria (Moody, 1966), determine a more appropriate drain depth, size the drain and approximate the maximum outflow for the season. Subroutines GRAD1 and GRAD2 are then called and the objective function and its gradient are evaluated. If the gradient of the cost function is found to be positive, the spacing is decreased. If the gradient is negative, the spacing is increased. The process is repeated until a minimum cost is found or the spacing is limited by the field width or the maximum allowable drain depth. The following sections delineate the cost function, constraints, and gradient matrices.

2.4.1 Costs of Closed Drains: The layout and variables used for closed drain systems are shown in Figure 7. The costs of the system which are assumed to be functions of the design variables (the depth and spacing of the drains) are the costs of the drains, filters, installation and maintenance, manholes and outlet structures. Other costs such as the cost of the irrigation water, labor for irrigations, and collection or conveyance costs of the irrigation or drainage water are not included in the optimization process. These values, however, can be included in the final cost analysis if alternate irrigation schedules are to be compared or the cost of closed drains is to be compared to other types of



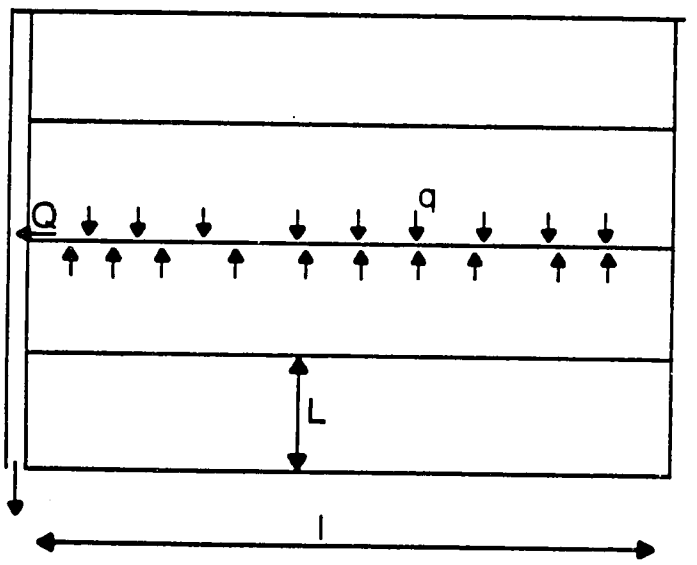


Figure 7 Elevation and plan view of closed drain system.

drainage systems. The cost function for a closed drain system in terms of dollars per annum per unit area is formulated as:

$$Z = \frac{i(C_1+C_2\phi+C_3\phi^2)}{L} + \frac{iC_4}{L} + \frac{C_5}{L} + \frac{iC_6}{DPM*L} + \frac{iC_7}{Ll} + \frac{i(C_8+C_9d)}{L} + \frac{iC_{10}}{Ll} \qquad (2.12)$$

where d = depth of the center line of the drain below ground surface

L = the spacing, center to center, of the drains

i = rate

ϕ = drain diameter

l = the length of the drains

$C_1+C_2\phi+C_3\phi^2$ = the cost of the drain expressed as a quadratic function of the diameter

C_4 = the cost of the filter per unit length of drain

C_5 = the cost of drain maintenance per unit length of drain per year

C_6 = the cost of one manhole

DPM = the length of drain per manhole

C_7 = the fixed cost of installing the drains, i.e. the cost of equipment use

C_8+C_9d = the cost of installation per unit length of drain expressed as a linear function of depth. The installation cost is assumed a function of the quantity of soil excavated for drain placement.

C_{10} = the cost of the drain outlet structure per outlet

The rate, i, converts a present cost to an annual cost for the expected life of the drain. Depending on the way the system is financed, it can be considered an interest rate on borrowed money, an opportunity cost or a discount factor. The length of the drain, l, is an input value

usually determined by external restrictions. In many cases, it will simply be the length of the field. Cost coefficients C_1, C_2 and C_3 are determined in subroutine LSQR from an input table of costs versus drain diameter. Cost coefficients C_6, C_7 and C_{10} can be included in the objective function or simply added to the final costs evaluated later. If they are included in the objective function, they are assumed to be functions of the number of drains installed. For example, if the equipment fixed cost is the same if one drain or ten are installed, this cost would be added later. However, if it costs a certain amount per hour for rental of the equipment and each drain takes an estimated number of hours, it should be included here. Similarly, if only one manhole or one outlet structure is required independent of the drain layout, these would be added in the final cost analysis. However, if manholes and outlets are required for each drain, the costs are included in the objective function. The cost of the drains in terms of depth is expressed here as a linear function. An exponential function, step function or power function can also be used by simply changing the equation and the derivatives in the program.

Consider the objective function given in Equation 2.12 in general form as:

$$\min_{L,d,\phi} \quad (Z = Z(L,d,\phi))$$

The problem is constrained by the following restrictions or relationships:

$$
\begin{aligned}
f_1 &= \phi(d,L) = 0 \\
f_2 &= d(L) = 0 \\
0 &\leq L \leq L_{max} \\
0 &\leq d \leq d_{max} \\
\phi &\geq \phi_{min}
\end{aligned}
\tag{2.13}
$$

The inequality constraints can be rewritten as equality constraints by the introduction of non-negative slack variables, denoted by $\psi_i, i=1,5$, so that the general problem formulation is:

$$\min_{L,d,\phi} \quad (Z = Z(L,d,\phi))$$

subject to

$$
\begin{aligned}
f_1 &= \phi(d,L) = 0 \\
f_2 &= d(L) = 0 \\
f_3 &= L_{max}-L-\psi_1 = 0 \\
f_4 &= L-\psi_2 = 0 \\
f_5 &= d_{max}-d-\psi_3 = 0 \\
f_6 &= d-\psi_4 = 0 \\
f_7 &= \phi-\phi_{min}-\psi_5 = 0 \\
\psi_1,\psi_2,\psi_3,\psi_4,\psi_5,d,L,\phi &\geq 0
\end{aligned}
\tag{2.14}
$$

In this form, the number of variables, N, is 8 (d, L , ϕ and the slack variables) and the number of constraints is 7. If the constraints were linear, it would be possible to use the constraint equalities to write seven of the variables in terms of an eighth independent variable. Substitution of the expressions for the dependent variables into the objective function would result in an unconstrained minimization problem in one variable. This is simply an elimination procedure. If the

function is a smooth, convex function, the stationarity conditions could then be used to determine the value of the one independent variable at the minimum point and, consequently, the minimum value of Z. However, the constraints are not all linear. In particular, the relationship between d and L is very complex. An expression for ϕ, on the other hand, can easily be developed in terms of L and d, and this variable will be eliminated from the minimization problem. The following sections modify the problem formulation given in Equation 2.13 and outline the method of solution used in the program.

The drain diameter, ϕ, could be considered a function of the drainage coefficient (the quantity of water to be drained per unit time), the overburden loads or the required flow capacity. It is assumed here that the diameter is a function of the flow capacity only and is sized to carry the maximum flow, Q_{max}, expected for the season, flowing full. This corresponds to the maximum midspan water table height, h_{cmax} or d-HMIN, at the downstream end of the drain. Manning's equation (Albertson, et al, 1960) is used to relate the required diameter of the pipe to the maximum flow, Q_{max}:

$$Q_{max} = \frac{1}{n} R^{2/3} S^{1/2} A \qquad (2.15)$$

where n = Manning's roughness coefficient

R = hydraulic radius

A = the cross sectional area of the pipe

S = the bottom slope of the pipe

For a pipe flowing full, the hydraulic radius is $\frac{\phi}{4}$ and the flow area is $\frac{\pi\phi^2}{4}$. Therefore, Equation 2.15 reduces to

$$Q_{max} = \frac{1}{n} \varphi^{8/3} S^{1/2} \left(\frac{\pi}{4^{5/3}}\right) \tag{2.16}$$

If the roughness factor, n, and the bottom slope of the pipe are known, Q_{max} is a direct function of the diameter.

Q_{max} can also be expressed as a function of the water table gradient at the ditch. Q_{max} can be approximated as

$$Q_{max} = \frac{2KK_2Dl\ h_{cmax}}{L} \tag{2.17}$$

where K = the hydraulic conductivity

K_2 = a shape factor which varies from π to 4

D = the effective flow depth

l = drain length

L = drain spacing

and h_{cmax} = midspan water table height above the drain level

The maximum drain flow from this equation corresponds to an h_{cmax} value equal to (d-HMIN) for each input level, HMIN. Combining Equations 2.16 and 2.17 and solving for φ gives:

$$\varphi = 2.008 \left|\frac{KK_2Dln}{S^{1/2}}\right|^{3/8} \left|\frac{d-HMIN}{L}\right|^{3/8} \tag{2.18}$$

The variables D, L and d are decision variables in the optimization formulation. All other variables in Equation 2.18 are assumed known or, in the case of HMIN, are assumed constant for each program loop. Therefore, the diameter, φ, can be easily eliminated from the objective function and constraints.

The objective function and constraints for closed drain systems can now be simplified. The diameter is eliminated using Equation 2.18 and the relationship between d and L approximated by an equation developed which is a simplification of the dynamic equilibrium equation (McWhorter, 1977; Maasland, 1964) for water table height. Because the variable D appears in the constraints and is a nonlinear function of d and L, the relationship for D(d,L) is included in the constraints. The minimization problem can now be written in terms of cost per unit area per year as:

$$\underset{L,d,D}{\text{Min}} \quad \left(Z = \frac{C_1^*}{L} + \frac{C_2^* D^{3/8}(d-HMIN)^{3/8}}{L^{11/8}} + \frac{C_3^* D^{3/4}(d-HMIN)^{3/4}}{L^{14/8}} + \frac{C_4^* d}{L}\right)$$

subject to:

$$f_1 = d-HMIN - \frac{8}{\pi^2 K_1 Sya} \sum_{i=1}^{m} I_i \frac{\exp\frac{-\pi^2 \alpha \tau_i'}{L^2}}{1-\exp\frac{-\pi^2 \alpha T}{L^2}} - \frac{I_m}{Sya}\left(1-\frac{1}{K_1}\right) = 0$$

and

$$f_2 = D - d_e - \sum_{i=1}^{m} \frac{I_i L^2}{12KDT} = 0 \qquad (2.19)$$

where

$$C_1^* = i(C_1+C_4+C_{6/DPM}+C_{7/1}+C_8+C_{10})/1$$

$$C_2^* = iC_2 * \frac{2.008}{126.24}\left|\frac{KK_2nl}{S^{1/2}}\right|^{3/8}$$

$$C_3^* = iC_3 * \frac{4.032}{15936.5}\left|\frac{KK_2nl}{S^{1/2}}\right|^{3/4}$$

$$C_4^* = iC_9$$

and

$$d_e = \frac{b-d}{1+\frac{b-d}{L}\left[\frac{8}{\pi}\ln\frac{2(b-d)}{\varphi} -3.55+1.6(\frac{b-d}{L}) -2(\frac{b-d}{L})^2\right]} \qquad \text{if } \frac{d}{L} \leq 0.3$$

or

$$d_e = \frac{L\pi}{8[\ln\frac{2L}{\varphi} -1.15]} \qquad \text{if } \frac{d}{L} > 0.3$$

This form of the minimization problem has one degree of difficulty although the constraints are nonlinear. To circumvent the difficulty imposed by the nonlinearity of the constraints, the objective function and two constraint equations are differentiated with respect to the variables L, d and D and evaluated at a point, say X_o. The point X_o is a feasible point in the domain. The system of differential equations for closed drains, can be written in matrix notation as:

$$\begin{bmatrix} (\frac{\partial Z}{\partial L})_{xo} & (\frac{\partial Z}{\partial d})_{xo} & (\frac{\partial Z}{\partial D})_{xo} \\ (\frac{\partial f_1}{\partial L})_{xo} & (\frac{\partial f_1}{\partial d})_{xo} & (\frac{\partial f_1}{\partial D})_{xo} \\ (\frac{\partial f_2}{\partial L})_{xo} & (\frac{\partial f_2}{\partial d})_{xo} & (\frac{\partial f_2}{\partial D})_{xo} \end{bmatrix} \begin{matrix} \partial L \\ \partial d \\ \partial D \end{matrix} = \begin{matrix} \partial z \\ 0 \\ 0 \end{matrix} \qquad (2.20)$$

Further, if the variable, L, is taken as the decision variable and d and D taken as state variables, the matrix equation can be written as

$$\begin{bmatrix} (\frac{\partial Z}{\partial L})_{xo} & (\frac{\partial Z}{\partial d})_{xo} & (\frac{\partial Z}{\partial D})_{xo} \\ (\frac{\partial f_1}{\partial L})_{xo} & (\frac{\partial f_1}{\partial d})_{xo} & (\frac{\partial f_1}{\partial D})_{xo} \\ (\frac{\partial f_2}{\partial L})_{xo} & (\frac{\partial f_2}{\partial d})_{xo} & (\frac{\partial f_2}{\partial D})_{xo} \end{bmatrix} \begin{matrix} \frac{dL}{dL} \\ \frac{dd}{dL} \\ \frac{dD}{dL} \end{matrix} = \begin{matrix} \frac{dZ}{dL} \\ 0 \\ 0 \end{matrix} \qquad (2.21)$$

or $\underline{A} \quad \underline{X} \quad = \underline{B}$

where $\underline{A}$ is a gradient matrix of known values evaluated at a point and the vector $\underline{X}$ contains the differentials. The differential dL/dL can be replaced by 1. The vector $\underline{B}$ contains the unknown value of the gradient of Z with respect to L at point X_o.

The entries in the gradient matrix are determined by evaluating the equatio s shown in Table 2.2. If the diameter is equal to the minimum allowable drain diameter, the matrix is somewhat modified from the one given here. Note that d, D and L must have feasible values and must be consistent. For a trial spacing of L, d will be a function of L and D and, conversely, D will be a function of d and L. Therefore, values of d and D which are consistent with the trial spacing and each other are determined by iteration. In OPT, an initial estimate of the depth, d, is made by ignoring convergence at the drain. The value of d is then simply a function of the trial spacing and current deep percolation values, soil properties and HMIN. Subroutine ALPH1 is then called to evaluate D, the effective flow depth, using the convergence criteria developed by Moody (1966). Using this value of D, the depth is

Table 2.2: Gradient Matrix Entries for Closed Drains

$$\frac{\partial Z}{\partial L} = -\frac{C_1^*}{L^2} - \frac{11}{8}\frac{C_2^* D^{3/8}(d-HMIN)^{3/8}}{L^{19/8}} - \frac{14}{8}\frac{C_3^*(d-HMIN)^{3/4}D^{3/4}}{L^{22/8}} - \frac{C_4^* d}{L^2}$$

$$\frac{\partial Z}{\partial d} = \frac{3}{8}\frac{C_2^* D^{3/8}(d-HMIN)^{-3/8}}{L^{11/8}} + \frac{3}{4}\frac{C_3^*(d-HMIN)^{1/4}D^{3/4}}{L^{14/8}} + \frac{C_4^*}{L}$$

$$\frac{\partial Z}{\partial D} = \frac{3}{8}\frac{C_2^* D^{-5/8}(d-HMIN)^{3/8}}{L^{11/8}} + \frac{3}{4}\frac{C_3^*(d-HMIN)^{3/4}D^{-1/4}}{L^{14/8}}$$

$$\frac{\partial f_1}{\partial L} = \frac{-16a}{SyaK_1L^3}\left(\sum_{i=1}^{m} I_i\tau_i \exp\frac{-\pi^2 a\tau_i}{L^2} + T\exp\frac{-\pi^2 aT}{L^2}\sum_{i=1}^{m} I_i \exp\frac{-\pi^2 a\tau_i}{L^2}\right)/\left(1-\exp\frac{-\pi^2 aT}{L^2}\right)$$

$$\frac{\partial f_1}{\partial d} = 1.0$$

$$\frac{\partial f_1}{\partial D} = \frac{8K}{Sya^2K_1L^2}\left|\frac{T\exp\frac{-\pi^2 aT}{L^2}\sum_{i=1}^{m} I_i\exp\frac{-\pi^2 a\tau_i}{L^2}}{1-\exp\frac{-\pi^2 aT}{L^2}} + \sum_{i=1} I_i\tau_i\exp\frac{-\pi^2 a\tau_i}{L^2}\right|$$

$$\frac{\partial f_2}{\partial L} = -\frac{1}{2}\frac{\partial d_e}{\partial L} - \frac{1}{2}\left|d_e\frac{\partial d_e}{\partial L} + \frac{\sum_{i=1}^{m} I_i L}{3KT}\right| \Big/ \left|d_e^{\,2} + \frac{\sum_{i=1}^{m} I_i L^2}{3KT}\right|^{1/2}$$

Table 2.2: Gradient Matrix Entries for Closed Drains (continued)

$$\frac{\partial f_2}{\partial d} = -\frac{1}{2}\frac{\partial d_e}{\partial d} - \frac{1}{2}\left| d_e \frac{\partial d_e}{\partial d} \right| \Big/ \left| d_e^2 + \frac{\sum_{i=1}^{m} I_i L^2}{3KT} \right|^{1/2}$$

$$\frac{\partial f_2}{\partial D} = 1.0$$

where

$$\frac{\partial d_e}{\partial L} = \frac{d_e^{\,2}}{L^2}\left| \frac{8\ \ln\frac{(b-d)}{r}}{\pi} - 3.55 + \frac{3.2(\frac{b-d}{r})}{L} - \frac{6.0(\frac{b-d}{r})^2}{L^2} \right| \text{ if } \frac{b-d}{L} \leq 0.3$$

and

$$\frac{\partial d_e}{\partial L} = \frac{d_e}{L}\left| 1 - \frac{8d_e}{\pi L} \right| \text{ if } \frac{b-d}{L} > 0.3$$

$$\frac{\partial d_e}{\partial d} = \frac{-d_e}{(b-d)}\left| 1 - \frac{d_e}{L}\left| \frac{8\ \ln(\frac{b-d}{r})}{\pi} - 3.55 + \frac{3.2(\frac{b-d}{r})}{L} \frac{-6(\frac{b-d}{r})^2}{L^2} + \frac{8}{\pi} \right| \right| \text{ if } \frac{b-d}{L} \leq 0.3$$

and

$$\frac{\partial d_e}{\partial d} = 0.0 \text{ if } \frac{b-d}{L} > 0.3$$

recomputed and so on until the changes occurring in D and d are negligible.

Solution of the matrix equation, Equation 2.21, could be accomplished by any method applicable to solution of linear, simultaneous equations including a Gauss elimination process, matrix inversion procedure, Cramer's rule or simple elimination. For closed drains, a simple elimination process is used. If the gradient of Z with respect to L is positive, the spacing is decreased. Conversely, if the gradient is negative, the spacing is increased. A maximum spacing is estimated, limited by either the input field width, a drain depth on the impermeable barrier or an input maximum depth, DMAX. This estimated maximum spacing and a minimum of zero are the initial limits on L. The first trial spacing in the first loop is an input spacing. If this is found to be feasible, the gradient matrix is determined and the derivative of Z with respect to L evaluated. Depending on whether the gradient is found to be positive or negative, the spacing is decreased by half or increased to a point intermediate between the current trial spacing and Lmax. The current trial spacing becomes the new upper or lower bound (depending on the sign of the gradient) and the process is repeated for the new trial value. The opposite bound is reset when the sign of the gradient changes. New trial spacings are always the average of the current upper and lower bounds. For subsequent loops in the program, the initial trial spacing is the final spacing from the last loop.

2.4.2 Costs of Open Drains: The minimization problem for open drains is developed in a way analogous to that of closed drains discussed in the previous sections. Let Figure 8 define the cross sectional shape of an open drain (Luthin, 1966; Schwab et al, 1957). The plan view of the open drain system is the same as that in Figure 7 for closed drains. The cost of draining using open ditches is assumed to be the sum of the excavation costs, maintenance costs and the cost of a reduction in yield due to the loss of productive land. The costs of the irrigation water, irrigation labor, collection and conveyance costs, the cost of building bridges over the ditches and the cost of the inconvenience of farming around the ditches are included in the final analysis, but are assumed constant for a particular set of irrigation data and field conditions. Hence, while these costs would be included in a comparison of open versus closed drains or one irrigation pattern versus another, they are not a factor in evaluating the trade-off of spacing-depth combinations. The cost function in terms of dollars per year per unit area drained for open ditches is:

$$Z = \frac{iC_1Al}{Ll} + \frac{C_2Wl}{Ll} + \frac{C_3l}{Ll} \tag{2.22}$$

where i = rate (interest, opportunity cost or discount rate)

C_1 = cost per unit volume excavated

C_2 = cost per unit area of land taken out of production per year, usually crop market value.

C_3 = maintenance cost per year per unit length of ditch

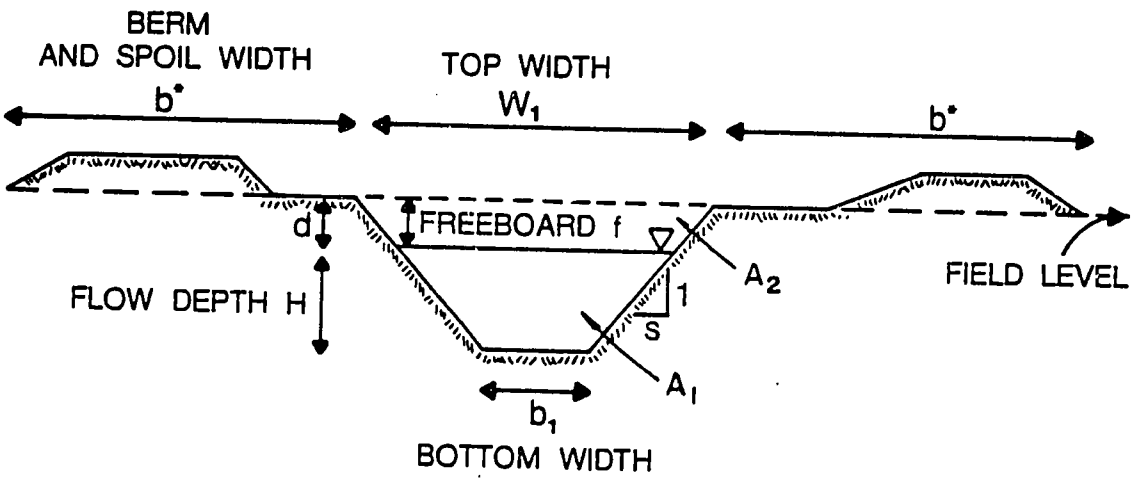


Figure 8 Elevation of open ditch.

L = drain spacing

ℓ = drain length

W = width of land taken out of production

The following relationships are obvious from the geometry assumed in Figure 8:

$$A = A_1 + A_2 = (b_1 + Hs)H + (b_1 + 2Hs) + d^2 s$$

and $$W = 2b^* + W_1 = 2b^* + b_1 + 2(H + d)s$$

The berm and spoil width, b*, and the side slope, s, are considered to be determined by the farmer or soil conditions and are input variables. In addition, minimum and maximum limits for H and a minimum value for b_1 can be specified by the programmer. Within these limits, however, the variables b_1 and H are not independent variables. They are functions of the maximum inflow into the ditch and hence, are functions of the drain spacing, depth and HMIN. The objective function, therefore, is subject to a series of constraints which specify the various relationships between the dependent variables. The simplification of the spacing-depth relationship will again be used as a constraint. The following paragraphs develop the remaining equality constraints.

The open ditch is assumed to carry the maximum flow of the season, Q_{max}, and Manning's equation (Albertson et al, 1960) can be used to size the drain. Therefore,

$$Q_{max} = 2q^*\ell = A_1 V = \frac{1}{n} R^{2/3} S^{1/2} A_1 \qquad (2.23)$$

where q^* = the inflow into the ditch from one side

ℓ = the length of the ditch

A_1 = the area of the flow region of the ditch

V = the average flow velocity

R = the hydraulic radius

S = the bottom slope of the ditch

n = Manning's roughness coefficient

The variables n and S are assumed known for a particular field. Similarly, the ditch is sized so that the flow velocity is the maximum input velocity governed by field conditions and soil properties. If the velocity equals the maximum allowable velocity, V_{max}, the area will be a minimum which corresponds to a lower cost. One exception to this is made when Q_{max} is small and Q_{max}/V_{max} results in values for b_1 and H which are less than the minimum allowable values input. In this case, b_1 and H are set equal to the minimum allowable values and a velocity less than V_{max} is computed.

Equation 2.23 can be combined with geometric equations for A_1 and R and solved for b_1 as a function of H:

$$b_1 = \frac{2q^*\ell}{VH} - Hs \tag{2.24}$$

$$\text{or} \quad b_1 = \frac{H^2 s - 2*CONST*H(1+s^2)^{1/2}}{CONST-H} \tag{2.25}$$

$$\text{where} \quad CONST = \left[\frac{Vn}{S^{1/2}}\right]^{3/2}$$

Darcy's law (McWhorter and Sunada, 1977) can be used to derive a second relationship between b_1, H and known quantities or other dependent or independent variables. The inflow into the ditch from one side is, by Darcy's law:

$$q^* = KD \left.\frac{\partial h}{\partial x}\right|_{x=0} \tag{2.26}$$

Using an approximation for q^*

$$Q_{max} = 2q^*\ell = \frac{2KK_2D\ell(d-HMIN)}{L} \tag{2.27}$$

but

$$Q_{max} = AV = (b_1 + Hs)H\ V \tag{2.28}$$

where A = the flow area

V = the average flow velocity

Therefore, solving Equations 2.27 and 2.28 for H gives:

$$H = -\frac{b_1}{2s} + \frac{1}{2}\left[\frac{b_1^2}{s^2} + \frac{4\ FUNC}{s}\right]^{1/2} \tag{2.29}$$

where $FUNC = \dfrac{2K_2KD\ell(d-HMIN)}{LV}$

Equations 2.29 and 2.25 provide relationships for H and b_1 in terms of known quantities or the other design variables, D, d and L. Elimination of b_1 and H from the objective function is now possible. However, because of the complexity of the relationships between b_1 and H and the design variables, both Equations 2.29 and 2.25 were left as equality constraints.

The simplified relationship between the depth and spacing and the equations developed for b_1 and H in this section allow the minimization problem to be formulated as follows:

$$\underset{L,d,b_1,H,D}{\text{Min}} \quad Z = \frac{1}{L}\,[iC_1(b_1H+H^2s+b_1d+2Hsd+d^2s)$$

$$+\ C_2(2b^*+b_1+2Hs+2ds)+C_3]$$

subject to

$$f_1 = D-d_e - \frac{\sum_{i=1}^{m} I_i L^2}{12KDT} = 0$$

$$f_2 = d-HMIN - \frac{8L}{\pi^2 K_1 Sya} \sum_{i=1}^{m} I_i \frac{\exp \frac{-\pi^2 \alpha \tau_i'}{L^2}}{1-\exp \frac{-\pi^2 \alpha T}{L^2}}$$

$$f_3 = H + \frac{b_1}{2s} - \frac{1}{2}\left(\frac{b_1^2}{2s} + \frac{4\ FUNC}{s}\right)^{1/2} = 0$$

$$\text{where FUNC} = \frac{2K_2K\ D\ 1\ (d-HMIN)}{LV}$$

$$f_4 = b_1(CONST-H)-H^2s+2*CONST*H*\sqrt{1+s^2} = 0 \qquad (2.30)$$

The total number of variables is 5 (L, d, b_1, H, D) and the number of constraints is 4. Therefore, the problem has one degree of difficulty. Again, the decision variable is chosen to be the spacing, L, and the constraints are linearized. The final matrix equation to be solved is

$$\begin{bmatrix} (\frac{\partial Z}{\partial L})_{xo} & (\frac{\partial Z}{\partial D})_{xo} & (\frac{\partial Z}{\partial d})_{xo} & (\frac{\partial Z}{\partial H})_{xo} & (\frac{\partial Z}{\partial b_1})_{xo} \\ (\frac{\partial f_1}{\partial L})_{xo} & (\frac{\partial f_1}{\partial D})_{xo} & (\frac{\partial f_1}{\partial d})_{xo} & (\frac{\partial f_1}{\partial H})_{xo} & (\frac{\partial f_1}{\partial b_1})_{xo} \\ (\frac{\partial f_2}{\partial L})_{xo} & (\frac{\partial f_2}{\partial D})_{xo} & (\frac{\partial f_2}{\partial d})_{xo} & (\frac{\partial f_2}{\partial H})_{xo} & (\frac{\partial f_2}{\partial b_1})_{xo} \\ (\frac{\partial f_3}{\partial L})_{xo} & (\frac{\partial f_3}{\partial D})_{xo} & (\frac{\partial f_3}{\partial d})_{xo} & (\frac{\partial f_3}{\partial H})_{xo} & (\frac{\partial f_3}{\partial b_1})_{xo} \\ (\frac{\partial f_4}{\partial L})_{xo} & (\frac{\partial f_4}{\partial D})_{xo} & (\frac{\partial f_4}{\partial d})_{xo} & (\frac{\partial f_4}{\partial H})_{xo} & (\frac{\partial f_4}{\partial b_1})_{xo} \end{bmatrix} \begin{Bmatrix} 1 \\ \frac{dD}{dL} \\ \frac{dd}{dL} \\ \frac{dH_1}{dL} \\ \frac{db_1}{dL} \end{Bmatrix} = \begin{Bmatrix} \frac{dZ}{dL} \\ 0 \\ 0 \\ 0 \\ 0 \end{Bmatrix} \tag{2.31}$$

The entries in the matrix are all known values. For a trial spacing, L_o, values of d, D, b_1, and H which are consistent with L_o are evaluated in subroutines OPT and ALPH2 prior to evaluation of the matrix. The matrix entries are then found from the equations given in Table 2.3.

Solution of the matrix for dZ/dL at L_o could be accomplished by any process which is applicable to the solution of a set of linear, simultaneous equations. In the program, a modified Gauss elimination process is used for open drains. If b_1 and H are equal to minimum allowable input values, the matrix equation reduces to one of order three rather than five. Selection of a new trial spacing and determination of a minimum point is the same as that described for closed drains in Section 2.4.1.

Table 2.3: Gradient Matrix Entries for Open Drains

$$\frac{\partial Z}{\partial L} = - iC_1 \frac{(b_1H+H^2s+b_1d+2Hsd+d^2s)}{L^2}$$

$$- C_2 \frac{(2b^*+b_1+2Hs+2ds)}{L^2} - \frac{C_3}{L^2}$$

$$\frac{\partial Z}{\partial D} = 0.0$$

$$\frac{\partial Z}{\partial d} = \frac{iC_1(b_1+2Hs+2sd)}{L} + \frac{2C_2s}{L}$$

$$\frac{\partial Z}{\partial H} = \frac{iC_1(b_1+2Hs+2sd)}{L} + \frac{2C_2s}{L}$$

$$\frac{\partial Z}{\partial b_1} = \frac{-iC_1(H+d)}{L} + \frac{C_2}{L}$$

$$\frac{\partial f_1}{\partial L} = - \frac{\partial d_e}{\partial L}$$

$$\frac{\partial f_1}{\partial D} = 1.0$$

$$\frac{\partial f_1}{\partial d} = - \frac{1}{2}\left(\frac{\partial d_e}{\partial d}\right) - \left(\frac{\partial d_e}{\partial d}\right) \frac{d_e}{2\left(d_e^2+\frac{\Sigma I_i L^2}{3KT}\right)^{1/2}}$$

$$\frac{\partial f_1}{\partial H} = 0.0$$

$$\frac{\partial f_1}{\partial b_1} = - \frac{1}{2}\left(\frac{\partial d_e}{\partial b_1}\right) - \frac{\partial d_e}{\partial b_1} \frac{d_e}{2\left(d_e^2+\frac{\Sigma I_i L^2}{3KT}\right)^{1/2}}$$

Table 2.3: Gradient Matrix Entries for Open Drains (continued)

$$\frac{\partial f_2}{\partial L} = \frac{-16\alpha}{SyaK_1L^3} \left(\sum_{i=1}^{m} I_i\tau_i \exp\frac{-\pi^2\alpha\tau_i}{L^2} + T \exp\frac{-\pi^2\alpha T}{L^2} \sum_{i=1}^{m} I_i \exp\frac{-\pi^2\alpha\tau_i}{L^2} \right) / \left(1-\exp\frac{-\pi^2\alpha T}{L^2}\right)$$

$$\frac{\partial f_2}{\partial D} = \frac{8K}{Sya^2K_1L} \left(\frac{T \exp\frac{-\pi^2\alpha T}{L^2} \sum_{i=1}^{m} I_i \exp\frac{-\pi^2\alpha\tau_i}{L^2}}{1-\exp\frac{-\pi^2\alpha T}{L^2}} + \sum_{i=1}^{m} I_i\tau_i \exp\frac{-\pi^2\alpha\tau_i}{L^2} \right)$$

$$\frac{\partial f_2}{\partial d} = 1.0$$

$$\frac{\partial f_2}{\partial H} = 0$$

$$\frac{\partial f_2}{\partial b_1} = 0$$

$$\frac{\partial f_3}{\partial L} = \frac{2.0K_2KD1(d-HMIN)}{L^2V}$$

$$\frac{\partial f_3}{\partial D} = -\frac{2KK_21(d-HMIN)}{LV}$$

$$\frac{\partial f_3}{\partial d} = 0.0$$

$$\frac{\partial f_3}{\partial H} = b_1 + 2Hs$$

$$\frac{\partial f_3}{\partial b_1} = H$$

Table 2.3: Gradient Matrix Entries for Open Drains (continued)

$$\frac{\partial f_4}{\partial L} = 0$$

$$\frac{\partial f_4}{\partial D} = 0$$

$$\frac{\partial f_4}{\partial d} = 0$$

$$\frac{\partial f_4}{\partial H} = 2\sqrt{1+s^2}\left(\frac{V*n}{S^{1/2}}\right)^{3/2} - b_1 - 2Hs$$

$$\frac{\partial f_4}{\partial b_1} = \left(\frac{V*n}{S^{1/2}}\right)^{3/2} - H$$

2.5 CROP RESPONSE TO SUBSURFACE DRAINAGE:

In order to identify an optimum drain system, it is necessary to relate the effects of drain installation to the plant environment and plant growth. That is, the mechanism of plant uptake of soil moisture, the influence of salt in the soil water on growth and the effects of the location of the water table on crop yield must be considered.

2.5.1 The Uptake of Water By Plants: Evapotranspiration is the combined process of evaporation from the soil surface and the transpiration of plants to the atmosphere. Methods currently used for evaluating the potential evapotranspiration are widely available (Jensen, 1973; Robins, 1965). The actual evapotranspiration is less than or equal to the potential, depending on the type of crop, the degree of crop cover and the availability of water. Although evaporation and transpiration occur simultaneously, the following discussion concerns the mechanism of plant transpiration without regard for the complicating aspect of evaporation which tends to dry the surface layers of the soil.

Growing plants are not in equilibrium with their environment with respect to water. The transpiration demand by the atmosphere acts as a sink and provides the driving force for the upward movement of water from the soil, through the plant, to the atmosphere. In other words, a free energy gradient or water potential exists between the soil and the atmosphere causing the upward flow of water. The main gradient is between the above ground parts of the plant and the atmosphere, not between the tops and the roots or the roots and the soil. The total potential difference in arid regions between the soil and the atmosphere can be as large as 1000 bars. Of this total, the potential drop in the

soil and the plant is of the order of, at most, several tens of bars, the remaining difference being between the leaves and the atmosphere (Hillel, 1971). The quantity of water transpired is large compared to the change in water content of the plant. Therefore, the process can be considered steady for short periods of time and the uptake of water can be considered to be directly proportional to the suctions in the root zone and inversely proportional to the resistance in the soil and in the plant to the movement of water. However, the process is not entirely steady. The soil moisture content decreases as water is withdrawn from the soil, requiring a constant readjustment by the plant and a constant redistribution of the soil moisture. Although the energy concept appropriately explains the uptake of water, the quantity of water left in the soil and the soil properties indirectly produce important effects on the energy gradient. The rate of uptake by the plant depends on the roots' ability to absorb water and the soil's ability to supply and transmit water at a sufficient rate. Because the process depends on the properties of the plant, soil, and climate, the status of which are all constantly changing, a totally quantitative analysis, even in a laboratory, is difficult.

Plants respond to the soil water environment by constantly readjusting their internal energy status. As water is withdrawn from the soil, the suction in the root zone increases, resulting in a decreased tendency for water to enter the roots. The atmospheric demand for water continues, however, causing the loss of water by transpiration to exceed the entry of water into the roots. The water content in the plant is thus decreased by this imbalance, decreasing the outward pressures on the cell walls. This readjustment allows the plant to

absorb water at higher and higher suctions. The process continues until the cells lose turgor and the plant wilts or the readjustment becomes ineffective.

The fact that often this readjustment process becomes ineffective before the cells lose turgor and wilt, is witnessed by the fact that measured transpiration rates invariably decrease between field capacity and the wilting point (Black, 1968). The decrease in the transpiration rate occurs presumably because of the inability of the soil to transport the water in the soil to the root at a fast enough rate. As moisture is removed from the root zone and the soil dries, the rate at which the water in the soil moves decreases, increasing the gradient of suctions away from the root and decreasing the rate at which equilibrium in the soil is reestablished. If the rate of equilibration in the soil does not keep pace with the uptake of the plant, the suction of the soil moisture in the vicinity of the root will be higher than that in the soil away from the root. Experiments (Black, 1968) indicate that at low suctions, the rate of equilibration is sufficient. In drier soils, however, the rate of equilibration significantly decreases the transpiration rate. These findings support the concept of a critical value of soil moisture, below which the water demand by the plant cannot be completely satisfied because water is not transported through the soil to the root fast enough to satisfy the demand. The point at which this begins to occur depends on the soil, plant and transpiration demand.

The readiness with which the plant uses available water has been the subject of a great deal of debate in the past. Hillel (1971) discusses the various theories which have been advanced. In brief, the

classical theories are as follows:

(i) Soil water is equally available to the plant between field capacity and the wilting point with no effect on plant functions.

(ii) Soil water decreases in availability as the soil moisture decreases and the plant may experience considerable stress before wilting occurs.

(iii) The available soil moisture can be divided into "readily available" and "decreasingly available" with a point existing between field capacity and the wilting point which separates the two ranges.

2.5.2 The Effects of Salts on Water Uptake and Yields: In humid areas, salinity is rarely a problem except in coastal regions or areas inundated with salt water. In arid regions, however, soil water losses through evaporation and transpiration of plants is not offset by precipitation. When soil water evaporates or is used consumptively by plants, a residue of salt is left behind in the root zone. In this case, leaching is generally used to remove the excess salt from the plant root environment. The addition of leaching water may lead to a higher water table elevation. Further, evaporation increases as capillary flow near the surface increases and hence salinity increases. The conflict between providing leaching and still maintaining the water table at a sufficient depth is often the primary reason for installing drains in arid or semiarid regions.

The physiological effect of salinity on crop yields varies greatly with the tolerance of the plant and the plant environment. At this time, however, the most generally accepted and usable theory of the

cause of detrimental effects due to soil salinity is the Water Availability Theory (Black, 1968; Hillel, 1971; Bresler, 1972; Berstein, 1974; Rhoades, 1974). According to this theory, the soluble salts in the soil water increase the solute suction of the soil water. The available water for plant use is thus reduced and the plant suffers water stress. Other theories that suggest that plant damage is due to the excess of salts inside the plant (Osmotic-Inhibition Theory) or due to specific toxicities have been advanced (Black, 1968; Hillel, 1971). In some cases, these have been shown to be more appropriate (Black, 1968). However, in view of the fact that salt tolerance data is available primarily in terms of the Water Availability Theory and that a great deal of research supports this hypothesis, this approach will be accepted here.

The solute suction is numerically equal but opposite in sign to the osmotic pressure. In general, consider two solutions of different strengths (different concentrations of solvents) separated by a semipermeable membrane. The weaker solution will move through the membrane to the stronger solution until equilibrium is established. The movement is in direct proportion to the pressure difference which is directly related to the difference in the number of solute particles in the solutions. In terms of the plant root environment, the two solutions are the soil moisture and the internal fluid in the root. Under nonsaline conditions, the plant fluid is the stronger solution. However, with saline soil water, the soil moisture has a larger number of solute particles than nonsaline soil water, thus decreasing the pressure difference and decreasing the flow of water into the root.

Physically, the solute and matric suctions are additive. This is shown in Figure 9 which shows a container of moist soil at atmospheric pressure in contact with a container of saline soil solution and one with pure water, separated by semimpermeable membranes. The manometer in the center measures the matric suction and the manometer on the left, the solute suction. Physiologically, there is evidence that the effects of these two suctions are also additive with respect to plant growth. Wadleigh and Ayers (1945) suggested that crops respond to the "integrated total soil moisture stress" which is the sum of the solute and matric suctions. In addition, there is considerable evidence that, in most cases, the effect of saline conditions on the crop was not a function of the type of salt present but only a function of the osmotic potential (Bresler, 1972; Hayward and Wadleigh, 1949). It should be noted, however, that in some cases, the situation may be more complex (see Slayter, 1967; Black, 1968; and Hillel, 1971 for more complete discussions).

The concept of an "integrated total soil moisture stress" is particularly useful in predicting crop yields since the osmotic effect on yield caused by salt concentrations can be evaluated by the same mechanisms as the matric or soil moisture effect. The two suctions are simply added and the uptake of the plant is a function of the resulting total potential gradient between the soil and the atmosphere. This provides a convenient procedure for incorporating the effects of salinity on plant growth.

The most common method of measuring soil salinity is to determine the electrical conductivity of saturation extracts, EC_e, from the effective root zone. Electrical conductivity is directly related to the

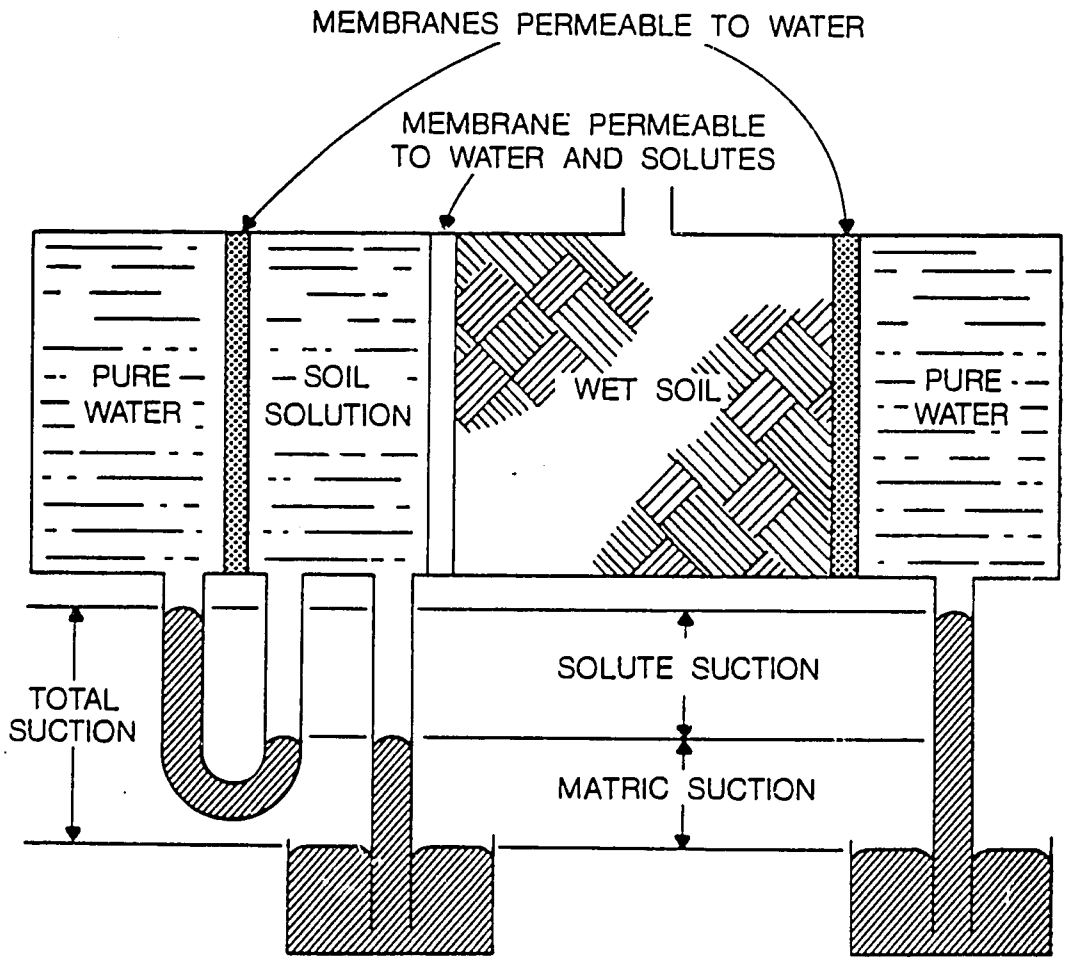


Figure 9 Membrane system illustrating concepts of matric suction, solute suction and total suction of soil water (after Richards, 1965).

soluble salts in the soil solution and the osmotic potential. Extensive reviews of literature giving yield decreases in terms of average EC values for various crops can be found in Bernstein (1974) and Maas and Hoffman (1977). These references also rate crops in terms of salinity tolerance and discuss general aspects of crop response to salinity, particularly the sensitivity variation of some crops during different stages of development. Much of the data cited was obtained from experiments using artificially salinized plots where the salt concentrations were uniform with depth and time. Maas and Hoffman (1977) and the U.S. Salinity Laboratory staff (1954) discuss application of the data to field situations where salinity distributions are neither spatially uniform nor constant over time.

In arid irrigated regions, the most obvious effects of a transient high water table are the development of nonaerated conditions in the root zone and the rise of salts from the groundwater table into the plant environment. The effect of saline conditions has been discussed previously. Temporarily high water tables do not necessarily inhibit plant growth. However, if they remain high for even a few days, they can cause nonaerated conditions to develop and this condition can severely restrict respiration and plant and root growth. Plants absorb oxygen and release carbon dioxide in the process of respiration. The exchange of these gases between the atmosphere and the roots takes place through interconnected air spaces open to the atmosphere or in a dissolved form through the soil water. However, the rate of diffusion in the air phase is generally much higher than in the water phase. High moisture contents in the region above the water table interfere with

this gas exchange and decreased respiration and accumulation of carbon dioxide in the root zone result.

Williamson and Kriz (1970) provide an extensive review of the effects of excess water in the root zone. In summarizing pertinent research, some aspects cited are:

(i) Root respiration is the most sensitive aspect of plant activity with respect to soil aeration and a reduction in respiration is the first step in growth limiting effects.

(ii) Poor aeration increases the resistance of water movement through the roots.

(iii) The exchange of oxygen and carbon dioxide is inhibited by excess water and carbon dioxide can accumulate to toxic levels.

The length of time until respiration ceases is a function of how much air is entrapped in the soil and the transpiration demand on the plant. The effect that nonaeration has on crop growth is a function of the plant species, soil conditions and micrometeorological conditions. It is also widely acknowledged that, in most cases, plant response to nonaerated root zone conditions varies with the stage of growth of the crop (Williamson and Kriz, 1970; Russell, 1977).

Very little data is available on the effects of fluctuating water tables on plant growth. Data that is available (Bouwer, 1974; Tovey, 1964; Tondreau, et al, 1977) is primarily related to temporary waterlogging conditions and specifies how fast the water table must be lowered to prevent crop damage. Some attempts have been made to quantify the effects of a fluctuating water table on crop yields. Sieben (Bouwer, 1974) constructed water table hydrographs for an area in

the Netherlands and determined the area under the curve above a depth of 30 cm, expressed in cm-days and called SEW_{30} (sum of excess water table rises above 30 cm). A study of crop yields indicated that if the SEW_{30} levels did not exceed 200 cm-days, yields were near optimum. Hiler proposes a similar method for evaluating crop damage (Hiler, 1969; Hiler and Clark, 1971; Hiler, et al, 1971). He suggests using a stress day index. The plant growth is maximized when the stress day index is minimized. The advantage of Hiler's method is that not only the type of plant is considered but the stage of growth is incorporated.

2.6 SYSTEM BENEFITS:

The purpose of an agricultural subsurface drain system is to improve the root zone environment and, consequently, increase yields. In arid regions, high water tables are generally due to application of quantities of irrigation water that exceed the natural drainage rate. Salinity is an almost universal problem and excess water is applied for leaching. If the water table is allowed to rise too high, upflow from a groundwater table that may be saline, ineffectiveness of leaching, nonaerated conditions in the root zone and truncation of the root system occur. The problem addressed here then, is to establish a methodology which will quantitatively characterize yields or alternatively, yield reductions, for arid irrigated areas which incorporates the drainage requirements prevalent in arid regions. A plant growth model would satisfy this requirement. However, the physiology of crop growth is complex and the computer time required for a detailed model is usually unjustified. Nevertheless, some basis for comparison of the effects of drain systems on crop yield is required which will incorporate the effects of a saline root zone environment, high water table conditions

and possible soil moisture deficits on crop growth. To this end, a methodology is used which modifies a procedure promoted by Doorenbos and Kassam (1979). In this paper, a crop production function which expresses crop yield as a linear function of the ratio of actual to potential evapotranspiration for the season is determined. The differing effects of reduced evapotranspiration in various growth stages is incorporated by using a multiplier, k_y, developed for each stage.

The computer program in the current study estimates yield using a similar production function. However, the actual evapotranspiration is determined using an average total integrated soil moisture suction, that is, the solute and matric suctions are assumed additive and the availability of soil moisture is a function of the average sum of the solute and matric suctions in the root zone.

Subroutine RTZ is the main component of the evaluation. This subroutine was described in Section 2.3. Daily average salinity and soil moisture statuses are computed using volume balances. Subroutines UPFLOW and SMBAL are called from RTZ to determine the upflow quantities of water and salts from the water table and evaluate average soil moisture values from input equilibrium soil moisture profiles. In addition, subroutine ROOT delays root elongation if a portion of the root zone is saturated and destroys the roots in the saturated area if saturated conditions persist for a specified number of days (depending on crop tolerances of nonaerated conditions). The effect of this root adjustment is a smaller depth of accessible soil moisture and hence, possibly, reduced evapotranspiration due to water stress. Subroutine ETA evaluates the actual daily evapotranspiration. At the end of the season, subroutines SUMS and YIELD sum the total evapotranspiration for

each growth stage and the season and approximate the yield from a linear input production function.

This procedure would not be expected to be adequate for a true crop yield evaluation. However, it does have advantages over other currently used methods in that it provides a basis for comparing various root zone conditions in terms of the variables which are generally the major considerations of a drainage study in arid regions.

The yield of a particular crop is assumed to be a direct function of its aerial and root environment. Further, it is assumed that the aerial environment and all aspects of the root environment except the soil water status, salinity level and the location of the water table are uncontrollable or nonlimiting to growth. In addition, the following general assumptions are made:

(i) Crop yield is directly related in some definitive way to plant growth.

(ii) Plant growth is limited only by the availability of soil water for plant uptake and use.

(iii) The availability of soil water is a function of the soil moisture content, salinity in the root zone and the depth of the effective roots.

In general algebraic form, yield is assumed to be a function of an index, S, of the total integrated soil moisture suction in the root zone (Wadleigh and Ayers, 1945; Wadleigh, 1946; Bresler and Yaron, 1972) with all other growth factors, K, assumed constant, i.e.

$$Y = Y[S/K] \tag{2.32}$$

The index S is an explicit function of the water content in the soil, the salinity in the root zone and the effective depth of the roots. Assuming that plants respond to average values of suctions integrated over time and space but that this response varies with the growth stage of the plant, S is defined for each growth stage, i, as

$$S_i = \frac{1}{T_i} \int_0^{T_i} \frac{1}{Z_i(t)} \int_0^{Z} s(z,t)dzdt \qquad (2.33)$$

where $s(z,t) = \tau(\theta)+\pi(c)$; the sum of the matric suction, $\tau(\theta)$, and the solute suction, $\pi(c)$, in bars.

$Z_i(t)$ = the effective root depth

T_i = the length of growth stage i

This formulation follows the Water Availability Theory discussed in Section 2.5.2 and combines the soil moisture and salinity effects on crop growth by assuming that the suctions are physically and physiologically additive and yield reduction is due to water stress. Further, it accounts for different crop responses at different growth stages and also for the variation in root depth with time. High water table effects are incorporated indirectly by considering their effect on the root depth and the contribution of salts to the root zone due to upflow from the water table. If the water table is at a level sufficiently below the root zone so that root elongation and respiration are not impeded and upflow of saline groundwater is negligible, yields will be a function of the frequency and quantity of irrigations, soil properties and initial root zone conditions. However, if the water table or the saturated region above the water table infringes on the root zone, water uptake is assumed to cease in the region below the

level at which interconnected air passages open to the atmosphere exist. This restriction in the depth of respiring roots will decrease the available soil moisture. Further, if the saturated region remains in the root zone for an extended period of time, the roots in this region are killed. Crop growth will be affected by the diminished depth of available soil moisture. Further, subsequent root elongation is delayed by the saturated conditions. After the water table falls, the roots are assumed to resume growth in a manner parallel to an input unstressed root distribution pattern with time. This is not entirely accurate since a regeneration component of root adaptation exists. However, experimental data on the magnitude of this regeneration capacity of crop plants is generally unavailable at this time. For a more complete discussion of the effects of oxygen deficiency on root growth, the reader is referred to de Wit (1978) and Russell (1977).

The second effect of high water tables indirectly incorporated into Equation 2.33 is the increase in upflow from the water table into the root zone as the distance between the root zone and water table decreases. If the groundwater is saline, the increase in upflow of water and salts into the root zone and subsequent evaporation of the water will result in increased root zone salinity levels and, hence, increased suction levels.

Yields or yield reductions are quantified as a function of the index S by relating the total soil moisture suction in the root zone to the uptake of the soil moisture by the plant (actual evapotranspiration). Plant use is then related to yield.

Consider the definition of the instantaneous total soil moisture suction given previously as

$$s(z,t) = \tau(\theta)+\pi(c) \tag{2.34}$$

The matric component $\tau(\theta)$ is not a single valued function of the moisture content θ since the relationship depends on the previous soil moisture history. However, for practical purposes, it is assumed that at an assigned time (2-3 days after an irrigation event) drainage has essentially ceased and soil moisture at a point can be adequately determined from an equilibrium soil moisture profile.

The solute suction or osmotic pressure is a function of the concentration of soluble salts present. The most common method of measuring salinity is to determine the electrical conductivity of the saturated extracts, EC_e. The conversion from EC values to suction values can be made using the following equation developed from data published by the U. S. Salinity staff (1954).

$$\text{Solute suction in bars} = \pi(C) = .325\ EC^{1.065} \tag{2.35}$$

In the program, average root zone soil moisture and salinity statuses are computed from volumetric balance methods. These are converted to solute and matric suctions and added to get the total average integrated soil moisture suction. In other words, the salinity in the root zone simply increases the total suction in the root zone. This is shown in Figure 10.

Daily actual evapotranspiration values are computed using any of the three soil moisture availability alternatives discussed in Section 2.5 and total actual evapotranspiration for each growth stage is determined. The final step in the process is to relate yields to the evapotranspiration of the plant. This could be accomplished using any of the several forms of production functions currently in use. The

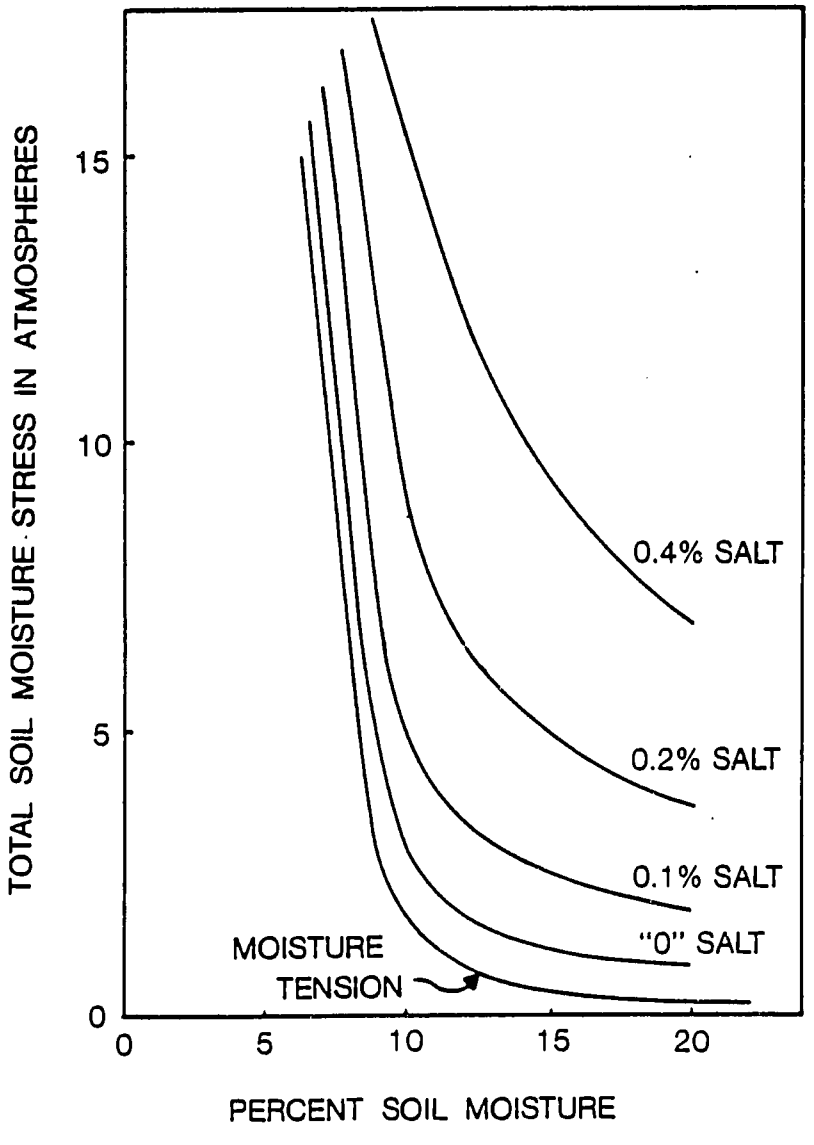


Figure 10 Illustration of effect of salt content on total soil moisture suction.

most common forms are linear (Barrett, 1977). A significant amount of data is available to estimate function coefficients for most crops. However, much of the data is site specific or production functions given are expressed in terms of net or gross total seasonal water application without differentiating between differing growth stage responses. For these reasons, the formulation given by Doorenbos and Kassam (1979) is used in the program.

The effect of water stress is quantified in terms of yield reductions with a linear equation of the form:

$$(1 - \frac{Ya}{Ym}) = \sum_{i=1}^{n} k_{yi} \, (1 - \frac{ETa_i}{ETm_i}) \qquad (2.36)$$

where Ya = actual harvested yield

Ym = maximum harvested yield

k_{yi} = response factor for each growth stage i

ETa_i = actual evapotranspiration in growth stage i

ETm_i = maximum evapotranspiration in growth stage i

n = number of growth stages

The use of a yield reduction relationship rather than absolute yields makes the specific relationships reported more transferable to other locations. The response factor, k_y, is an empirical coefficient which is estimated by Doorenbos and Kassam (1979) for a variety of crops grown in arid irrigated areas. It is estimated for the individual growth periods of the crop as well as for the total growing season.

CHAPTER III

PROGRAM APPLICATION

The purpose of this chapter is to illustrate the capabilities of the program. A set of input data is assumed which is typical of conditions in an arid, irrigated area. Corn is assumed to be grown in the summer with Berseem planted in September on this field. For the purpose of illustrating the program's capabilities, only the summer crop, corn, is considered initially. However, the analysis is then extended to a two crop period (one year) and a four crop period (two years).

3.1 EXISTING FIELD SITUATION--ONE CROP:

The first evaluation made by the computer program is of the existing field situation. The irrigation schedule, water table elevations, soil properties, and initial conditions are input. The daily average soil moisture and salinity status of the root zone, evapotranspiration rates, seepage to and upflow from the water table, the alteration of the unstressed input effective root depths due to extended nonaerated conditions and a relative crop yield are determined. A summary of the input values used is shown in Table 3.1 and the irrigation and seasonal results obtained are summarized in Table 3.2. Of the 74.9 cm applied, the program estimated that 65.5 cm or 87 percent were used for evapotranspiration (ET). In this example, the soil moisture available for plant use was assumed to decrease linearly from a soil suction of .34 bars to 15 bars. This resulted in the computed ET being less than the maximum ET demand for 85 days during the 116 day season and reduced the maximum ET demand of 71.24 cm to a computed total seasonal ET of 65.5 cm. It should be noted that the

Table 3.1 Summary of Program Input Data

Area	Beni Magdoul Summer season, 1978
Site	Farm 5, Field 2
Crop	Corn
Number of days in season	116
Number of days to field capacity	2
Number of days to root death	3
Saturated height above water table	30.0 cm
EC of the irrigation water	0.32 mmhos/cm
EC of the ground water	6.5 mmhos/cm
Hydraulic conductivity	3.5 cm/day
Apparent specific yield	0.06
Initial volumetric soil moisture	.47
Saturated volumetric soil moisture	.54
Initial salinity of soil moisture	3.64 mmhos/cm

Plant growth stage susceptibility factors:

Growth stage	First Day	Factor
0	1	0.0
1	21	0.4
2	64	1.5
3	69	0.5
4	102	0.2

Irrigation schedule and measured depths to water:

Day	Date	Irrigation Quantity (cm)	Depth to Water (cm)
1	4/18	16.6	78.
29	5/16	8.1	66.
45	6/1	5.0	77.
54	6/10	6.0	90.
62	6/18	6.2	56.
69	6/25	7.0	50.
76	7/2	6.0	62.
83	7/9	5.0	71.
93	7/19	8.0	64
102	7/28	7.0	55.

Total applied: 74.9

Table 3.2: Summary of Computed Results for Summer Season, 1978

Irrigation Number	Irrigation Period	Net Application (cm)	Seepage (cm)	Upflow (cm)	ET Demand (cm)	ET Actual (cm)	Change in Soil Moisture (cm)
1	4/18-5/15	16.6	10.77	2.46	8.36	7.04	1.25
2	5/16-5/31	8.1	2.85	3.03	9.65	8.98	-.70
3	6/1 -6/9	5.0	0.0	2.05	5.66	5.43	1.62
4	6/10-6/17	6.0	1.3	1.82	6.85	6.54	-.02
5	6/18-6/24	6.2	1.18	1.75	6.48	6.14	+.63
6	6/25-7/1	7.0	2.68	1.74	6.17	5.82	+.24
7	7/2 -7/8	6.0	2.00	1.55	6.06	5.73	-.18
8	7/9 -7/18	5.0	.97	1.45	8.14	7.17	-1.69
9	7/19-7/27	8.0	2.47	1.69	6.33	5.89	1.33
10	7/28-8/11	7.0	3.16	2.60	7.53	6.75	-.31
		74.9	27.38	20.14	71.23	65.5	2.17

evapotranspiration values computed are highly dependent on the soil moisture availability assumption used.

The purpose of evaluating the existing field case is to determine a base by which the advantages of installing drains can be quantified. In this study, that basis is the yield or plant growth which is assumed decreased by:

(i) soil moisture deficits experienced by the plant

(ii) unfavorable salinity levels in the root zone

(iii) waterlogging or nonaerated conditions in the root zone

In order to evaluate these three conditions, their effects on corn growth separately, and in conjunction, must be explored.

In general, 50-80 cm of water, depending on the climate, is required for a maximum yield of corn (Doorenbos and Kassam, 1979). In areas with high, nonsaline water tables, a portion of this requirement may be supplied from the groundwater reserve. Under ideal conditions, yields of up to 10 metric tons/hectare can be achieved. Studies of corn yields in Egypt have shown the average from 1970-72 was 3.74 metric tons/ha although average yields of 4.33 metric tons/ha occurred in some regions.

Gross water applications are not entirely satisfactory in estimating yield deficits for corn because the crop's response to its environment is highly dependent on growth stage. To incorporate these differing responses, growth stages suggested by Doorenbos and Kassam (1979) were adjusted to correspond to the season length in the current study. Adjusting the lengths of these suggested periods to the current study, the following values are assumed:

Establishment (0)	20 days
Vegetative (1)	33 days
Flowering (2)	15 days
Yield Formation (3)	33 days
Ripening (4)	15 days
Total	116 days

Figure 11 shows these growth stages and the soil moisture status of the root zone during the season as determined by the computer program. The vertical axis of this curve is the ratio of the average soil moisture in the root zone to the average soil moisture if the equilibrium soil moisture profile was filled. This ratio is used rather than the more standard saturation index to eliminate variations due to the changing water table position. Figure 11 shows that every irrigation except the third filled the soil moisture reservoir. The interval between the first and second irrigations was relatively long (29 days) but this interval decreased to about 7 to 10 days by the beginning of the flowering stage. Near the end of the season, soil moisture was again allowed to deplete slightly. Corn is relatively tolerant to water deficits during the vegetative (1) and ripening stages (4). The greatest decrease in yields has been shown to occur due to water deficits during the flowering period (2) including tasselling, silking, and pollenation, due mainly to a reduction in the grain number per cob. To a somewhat lesser extent, deficits in period (3) are important. However, the effects of deficits in periods (2) and (3) are less pronounced if water deficits occurred in the earlier stages, presumably because root growth is encouraged by the earlier deficits. Therefore, the slight soil moisture depletion early in the season shown in

Figure 11 may be advantageous to crop growth. The frequent irrigations in stages (2) and (3) follow generally accepted patterns. Therefore, the decreases in soil moisture would decrease evapotranspiration somewhat but severe growth reduction would not be expected due to water deficits if all other growth factors are favorable.

The second consideration pertaining to yields included in this study is root zone salinity levels. Corn is moderately sensitive to salinity. Doorenbos and Kassam (1979) cite yield decreases for corn under increasing soil salinity as: 0 percent at an EC_e value of 1.7 mmhos/cm, 10 percent at 2.5, 25 percent at 3.8, 50 percent at 5.9 and 100 percent at 10 mmhos/cm. The values are the same as those given by Maas and Hoffman (1977) although they assume a linear decrease in yields below a threshold value of 1.7 mmhos/cm. Bernstein (1974) cites yield decreases of: 10 percent at an EC_e value of 5 mmhos/cm, 25 percent at 6 mmhos/cm and 50 percent at 7 mmhos/cm.

Figure 12 shows the seasonal variation of the root zone salinity levels. The values shown here are the electrical conductivities of the soil moisture in the root zone, not the electrical conductivities of the saturated extracts. Therefore, the peaks shown are due to depletion of the soil moisture by evapotranspiration. The conductivities of the saturated extracts are approximately the minimum values shown immediately following the irrigations.

The initial preirrigation salinity level input was 3.64 mmhos/cm. The average salinity of the soil moisture for the season was 4.67 mmhos/cm with a maximum of 7.02 mmhos/cm reached at the end of the season. The actual change in total salt content can be seen by examining the salinities immediately following the irrigation events.

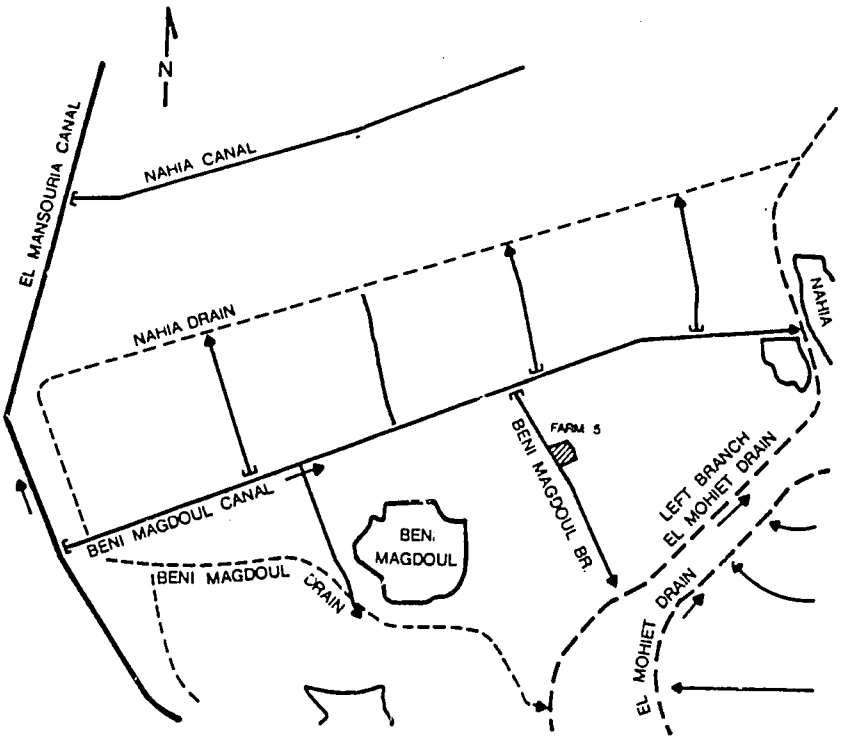


Figure 11 Location of study area, Farm 5.

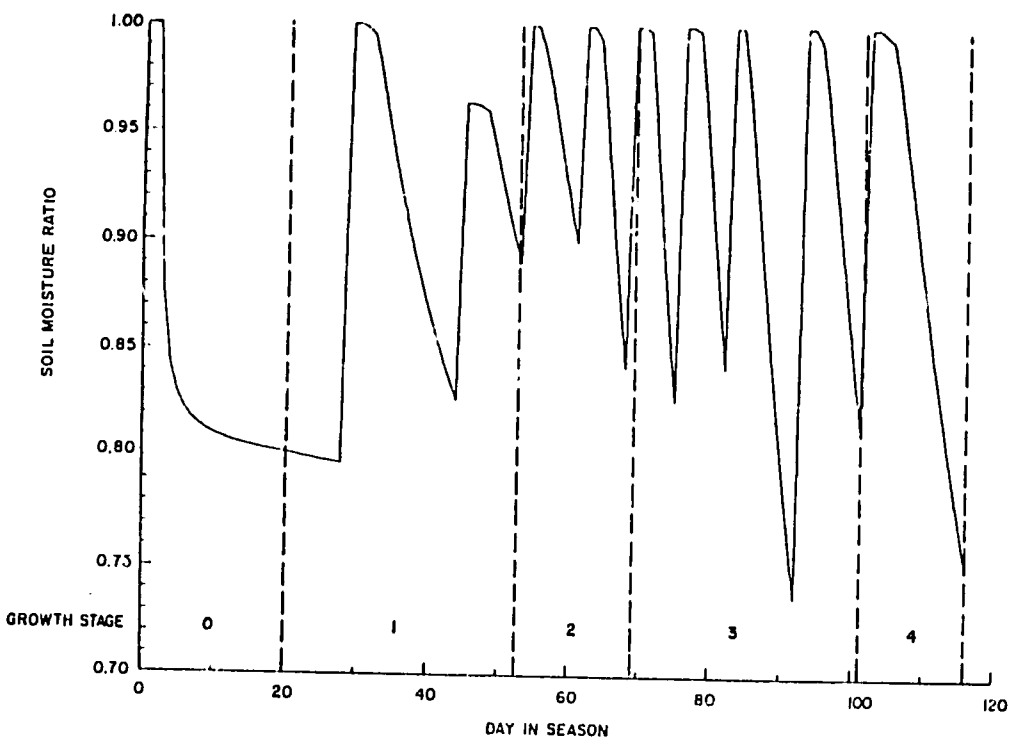


Figure 12 Soil Moisture status computed for the summer season, 1978.

As the curve shows, there is not a significant build up in the quantity of salts in the root zone during the season. At the last irrigation, the computed salinity is 4.0 mmhos/cm, or only 10 percent higher than the preseason salinity of 3.64 mmhos/cm.

The third aspect of growth considered in this study is the effect of nonaerated conditions on root growth and hence yields. Corn is very susceptible to waterlogging, particularly during the flowering stage. The corn root system is highly branched and can be deep. Roots which develop early in the season may extend to a depth of 1 meter or more if soil conditions are favorable. However, these roots are sparse. Later in the season, a highly branched secondary root system develops which extends 0.8 to 1 meter if unrestricted. Eighty percent of the water uptake for respiration occurs in this main root zone depth.

Figure 13 shows the input effective root depths for the season, the measured water table elevations and the adjusted effective root depths determined by the program. Ground surface elevation is 16.58 m. It was assumed the area for 30 cm above the water table was saturated. This value is probably low for a soil with a high clay content and a larger height may in fact be saturated. The curve in Figure 13 shows that on day 62, a significant increase in water table elevation occurs. This increase occurs during the flowering growth stage (2). The flowering and yield formation periods, growth stages 2 and 3, are the most critical and waterlogging during flowering can reduce grain yields by 50 percent or more (Doorenbos and Kassam, 1979). Waterlogging of a large portion of the root zone during these critical growth stages is shown in Figure 13 and root growth is severely retarded or truncated for the rest of the season due to high water tables. Using 30 cm of saturated height

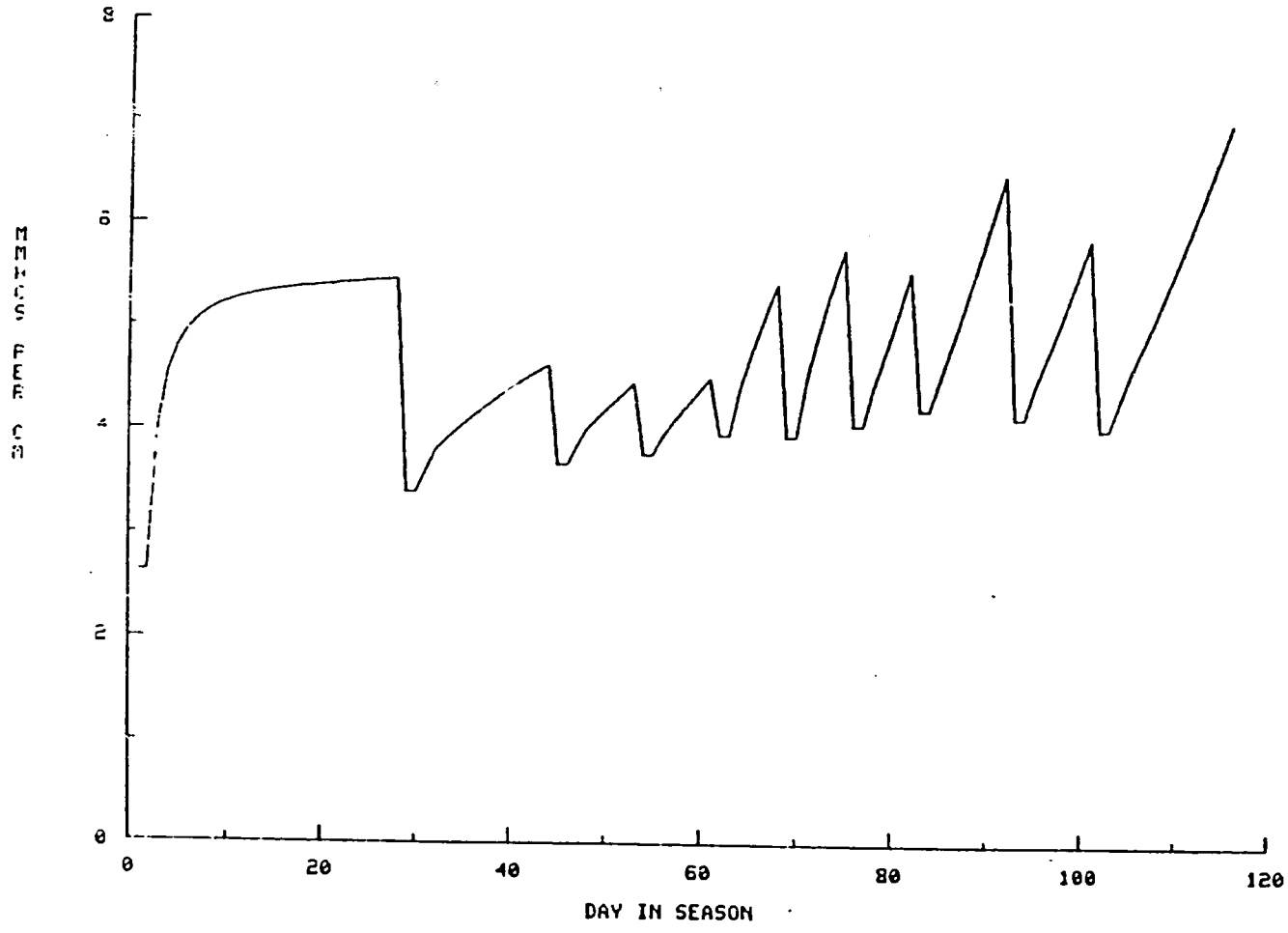


Figure 13 Salinity levels computed for the summer season, 1978.

above the water table, the root depths at the end of the season are limited to within 25 cm from the ground surface.

The actual measured yield for the corn crop on this field was 3.97 metric tons/ha. The program also computed a yield of 3.97 tons/ha, which is a 16 percent reduction from the input obtainable yield of 4.75 tons/ha. It should be noted that this assumed obtainable yield is lower than an optimum yield which could be realized for corn grown on this land, if all factors such as water management, seed variety, fertilizer application, soil treatment and land leveling are considered in conjunction with proposed drainage systems or the existing field case. It simply represents an obtainable yield if the three factors considered in this analysis, i.e., soil moisture levels, salinity levels and root depths, are not limiting plant growth. Further, the computed yield is related to the obtainable yield by a linear production function. Therefore, the computed yields given in the following sections are direct functions of the input obtainable yield assumed for the cases illustrated.

3.2 EXISTING FIELD CASE - TWO CROPS:

In the field situation assumed, two crops are planted yearly: corn in the spring and Berseem clover in September. The analysis of this case is examined in this section. Soil properties and initial conditions input are the same as those given in Table 3.1. The irrigation schedule, input depth to water and maximum evapotranspiration rates were extended to a one year period (two crop seasons). In the preliminary analyses made for one crop, it appeared that the assumed curve of soil moisture availability for plant use was very significant in the final results. Therefore, three cases are investigated in this

section. These are:

Case I: Soil moisture availability for plant use is assumed to decrease linearly from a soil suction of .34 bars to the wilting point at 15 bars.

Case II: Soil moisture is readily available for plant use until a soil suction value of 8.4 bars. At suctions above this value, soil moisture availability decreases linearly to zero at the wilting point (15 bars).

Case III: All the soil moisture held at suctions less than 15 bars is readily available for plant use.

The seasonal results from these three cases are summarized in Figure 14. As shown in this figure, as more of the moisture in the profile is assumed readily available for plant use, the seasonal evapotranspiration rates increase and the seepage to the water table decreases. Upflow from the water table is a function of the soil properties and the distance between the water table and the root zone. Since water table elevations are input and truncation of the effective root depths is a direct function of the location of the water table, the quantity of seasonal upflow is the same for each case. The salt balance shown assumes that the net change in root zone salinity for the year is zero.

Several factors are noteworthy. Case III will be used to illustrate these considerations. Figure 15 shows the root growth and the water table elevations. As this figure shows, the high water table conditions are clearly a major factor in considering the plant environment since root growth is restricted and nonaerated conditions would be expected to occur at critical times during both crop seasons.

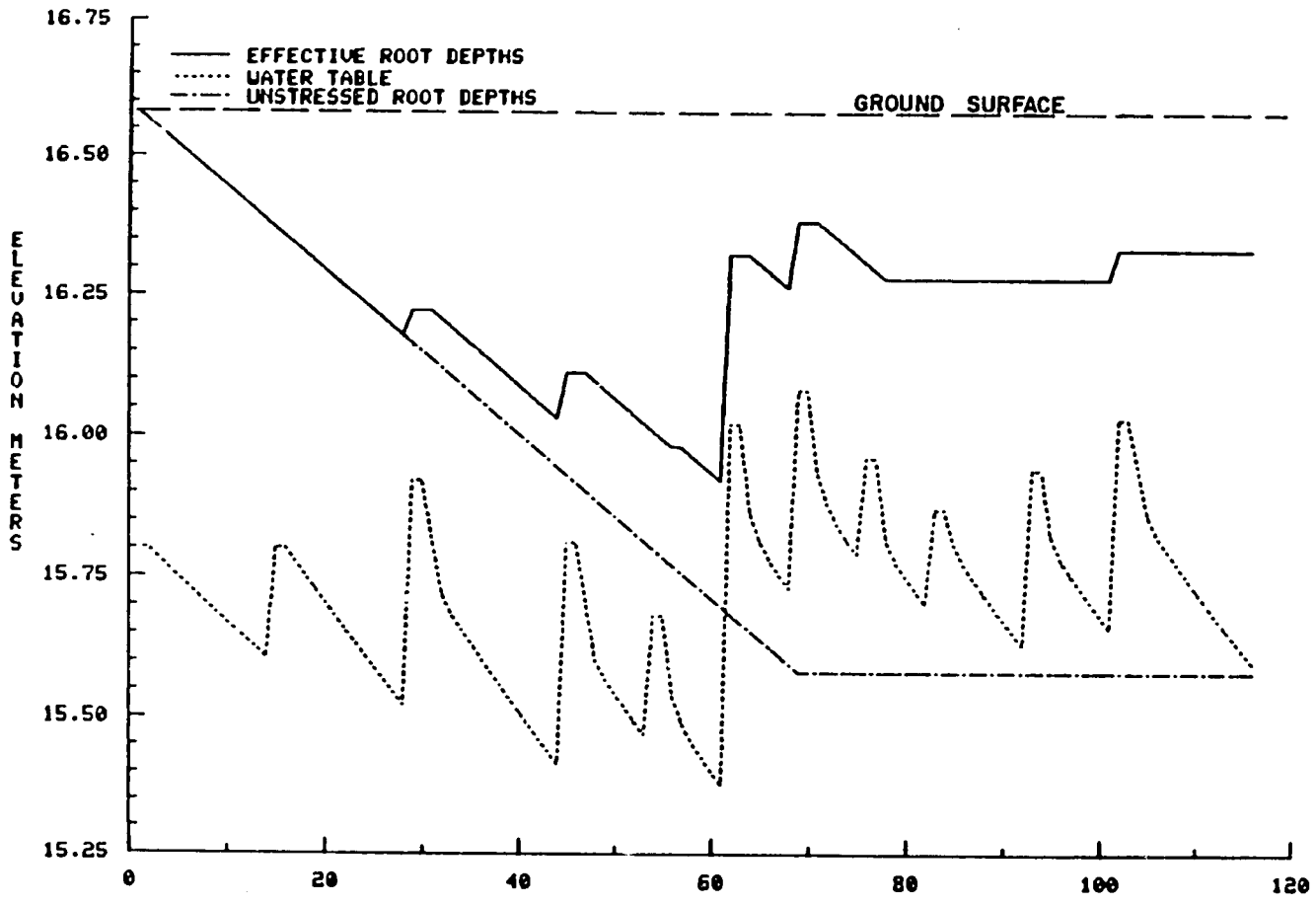


Figure 14 Effective and input root distribution and water table evaluations for the summer season, 1978.

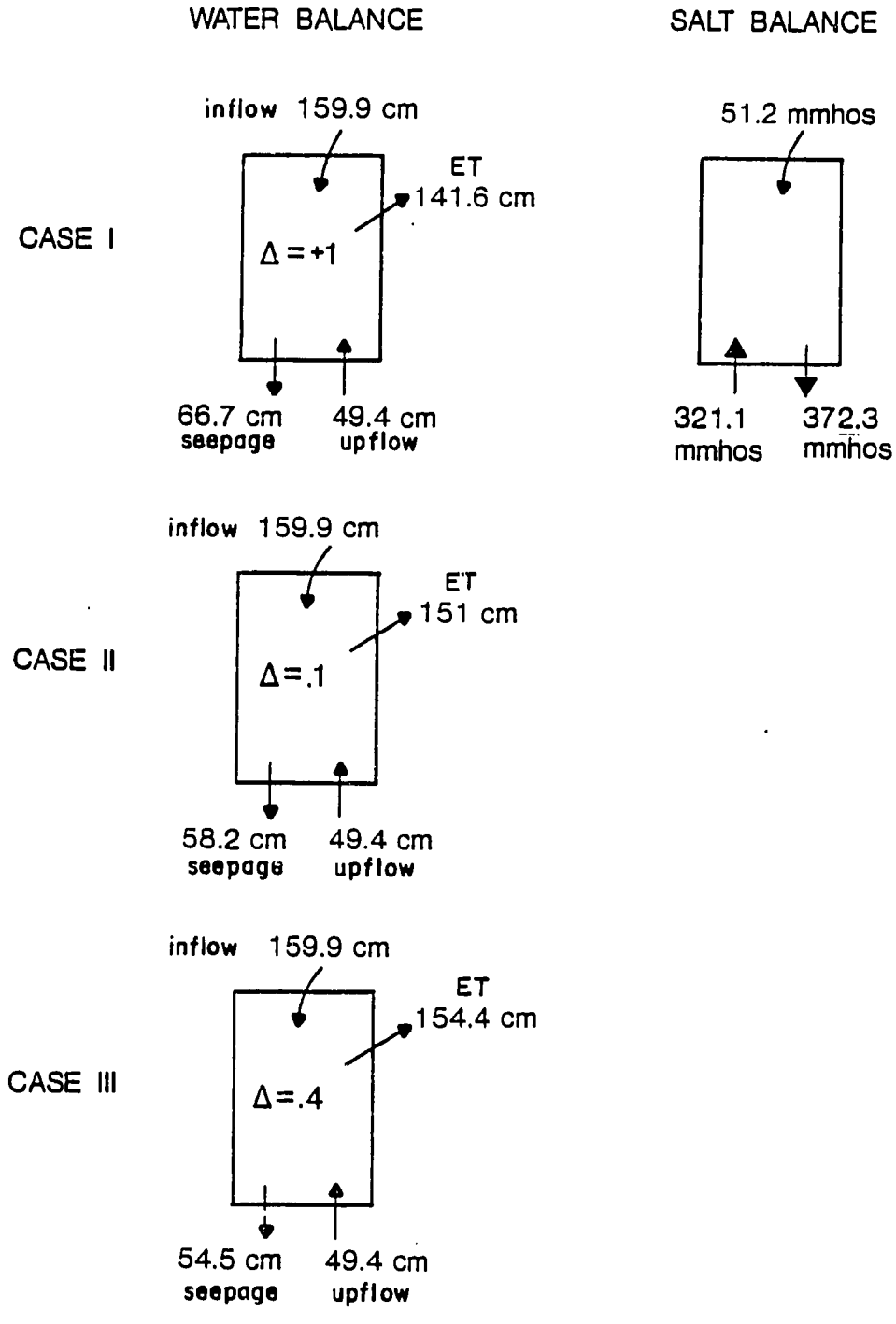


Figure 15 Water and salt balances for two crop seasons and three soil moisture availability assumptions.

On the other hand, the water table supplies approximately 30 percent of the total seasonal evapotranspiration. If the water table is lowered significantly, additional water for plant use would need to be applied by irrigation.

Characteristics of a soil with a high clay content are also a consideration. If the water table is lowered, the surface layer of the soil may dry excessively, causing cracking and poor leaching. In addition, the infiltration rate is low. Increased irrigation applications may result in higher losses due to surface evaporation, runoff, and so forth.

Figure 16 shows the electrical conductivities of the soil moisture in the root zone for the two crop period. Again, the minimum values shown immediately following the irrigation events are approximately the electrical conductivities of the saturated extracts. These values show that there is only a slight net build-up of total salts in the one year period. However, 160 cm of irrigation water with a salinity about .32 mmhos/cm were applied during this same period. If the total quantity of salts (corresponding to 51.2 mmhos per year) is added to the groundwater and the system is a closed system (i.e. no drainage), then a gradual decline in the quality of the groundwater would be expected. The rate at which this deterioration occurs is a function of the quantity of groundwater. For example, if the depth of the aquifer is approximately 7 meters and the fraction of soil voids filled with water is .54, then the total quantity of soil water below the water table is about 380 cm and the net change in salinity per year is approximately 0.13 mmhos/year. At this rate, if the current value of groundwater salinity is 6.5 mmhos/cm, it would have taken almost 50 years to obtain this

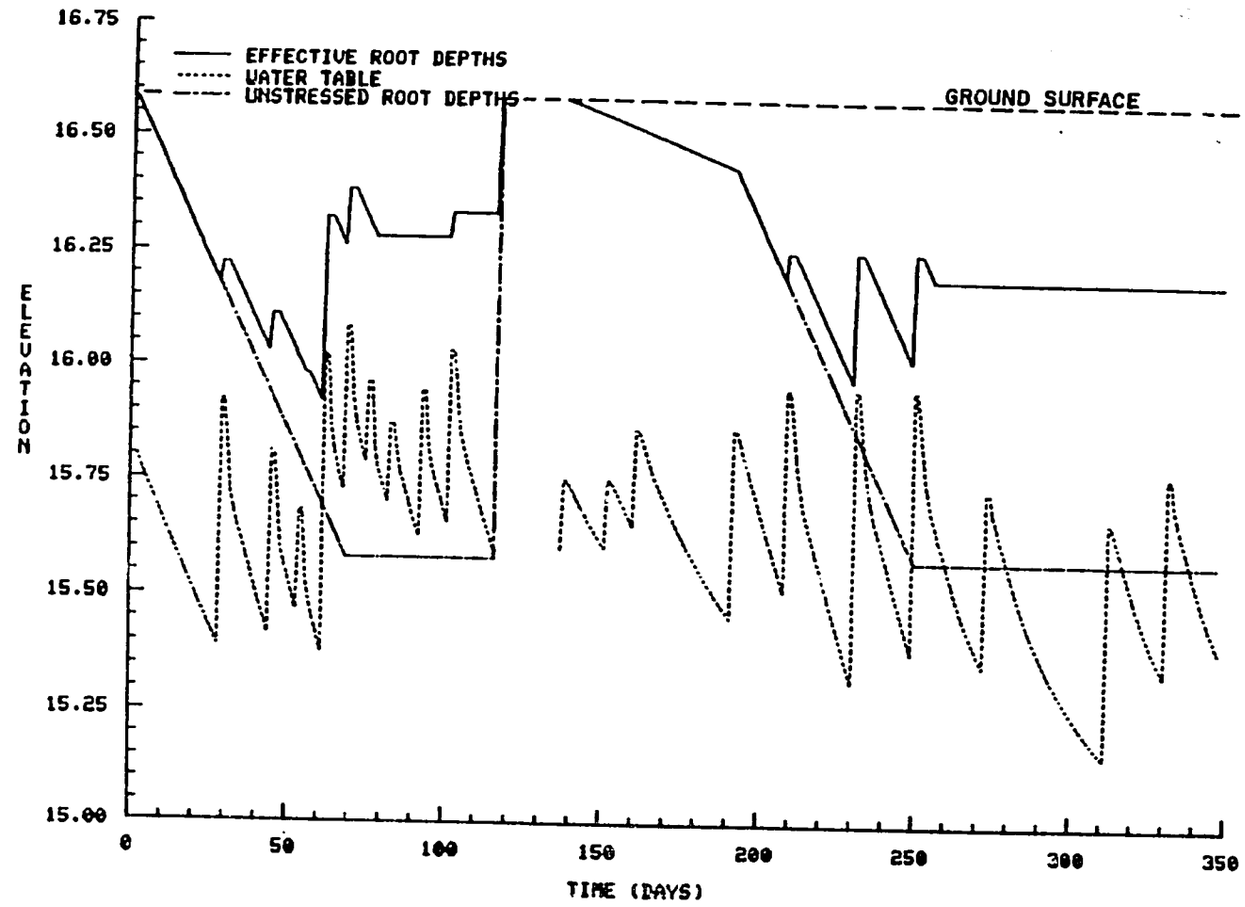


Figure 16 Root depths and water table elevations for one year period.

level. If the depth of the aquifer is 3 meters, the salt build up would be occurring at a rate of about 0.3 mmhos/year. Only 20 years of adding salts at this rate would increase the aquifer's salinity to 6.5 mmhos/cm.

3.3 EXISTING FIELD CASE - FOUR CROPS:

In order to further investigate the trends indicated in Section 3.2 for two crops, data for a two-year period (four crop seasons) was input. Irrigation data, maximum evapotranspiration values and water table elevations were input for the period. Initial values of salinity, soil moisture and soil properties remained the same. Three cases of soil moisture availability were considered. Case I assumes the soil moisture is decreasingly available for plant use between field capacity and wilting point. Case II assumes the soil moisture is readily available to a suction of 8.4 bars and decreasingly available above this point to 15 bars. Case III assumes the soil moisture held at suctions below 15 bars is readily available for plant use. Water and salt balances for these three cases for the two-year period are shown in Figure 17. Figures 18, 19, and 20 show the daily soil moisture status, salinity status, and root growth curves for Case II. It was found that no net build-up of salinity occurred and no net build-up of water elevations occured for the two-year period. For Case II, the root zone salinity level at the last irrigation was computed as 3.57 mmhos/cm which is about the same as the initial measured value of 3.64 mmhos/cm.

Case II was rerun assuming 25 percent of the applied irrigation water was lost through surface evaporation before it infiltrated. The total evapotranspiration for the two year period decreased by only one percent. However, in this case, the net quantity of water added to the

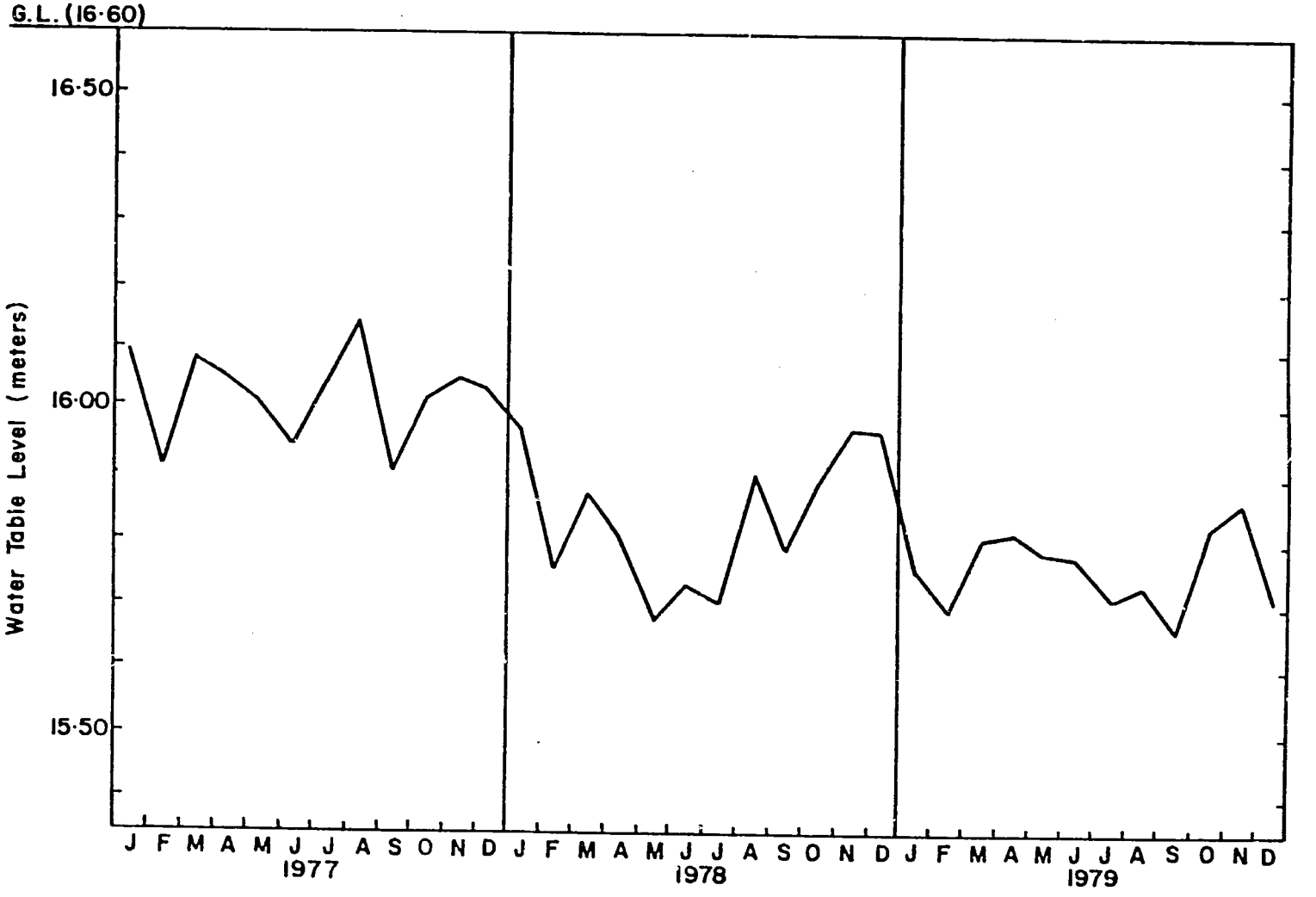


Figure 17 Measured water table elevations for three year period at Beni Magdoul.

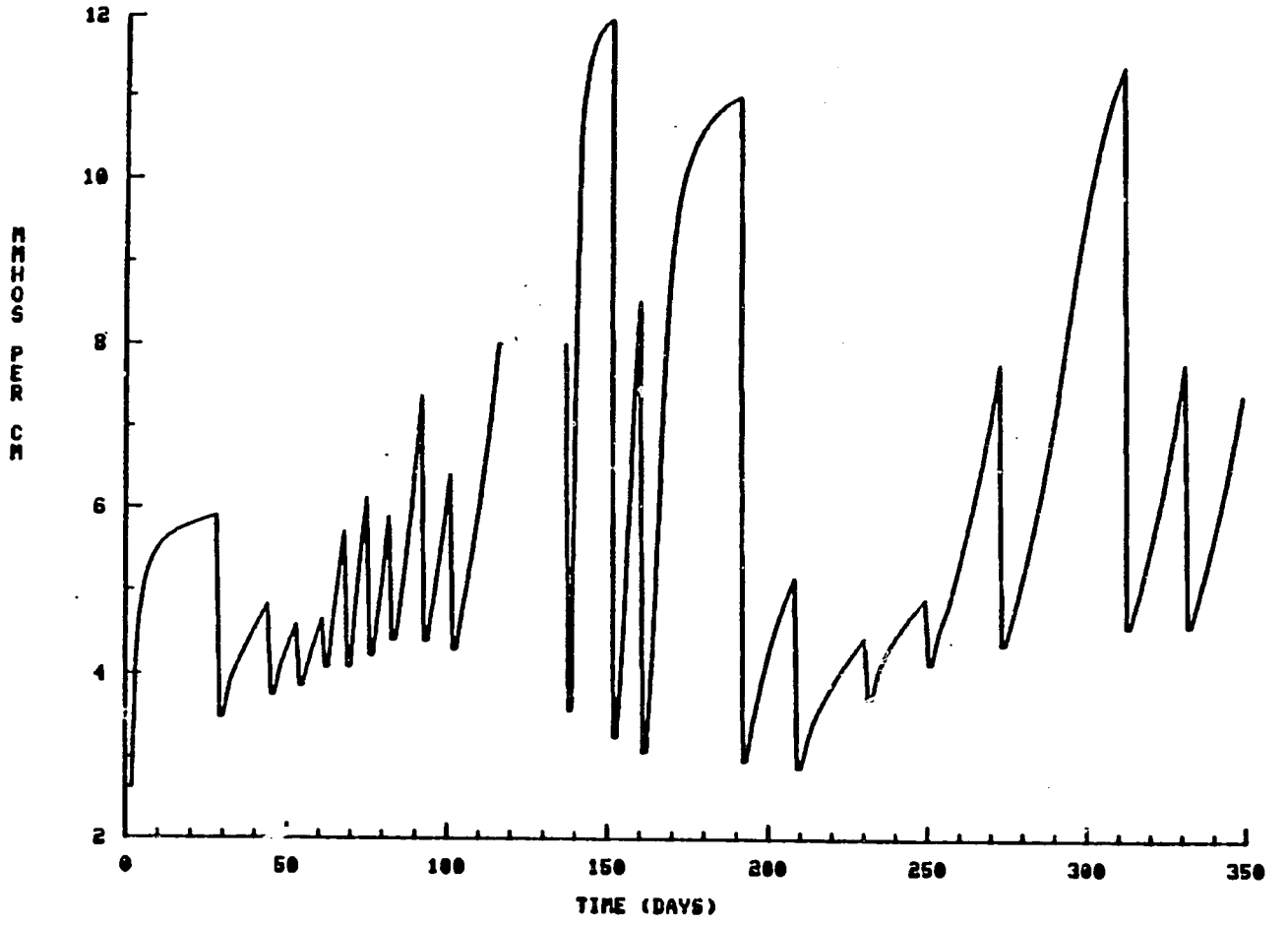


Figure 18 Root zone salinity levels for one year period.

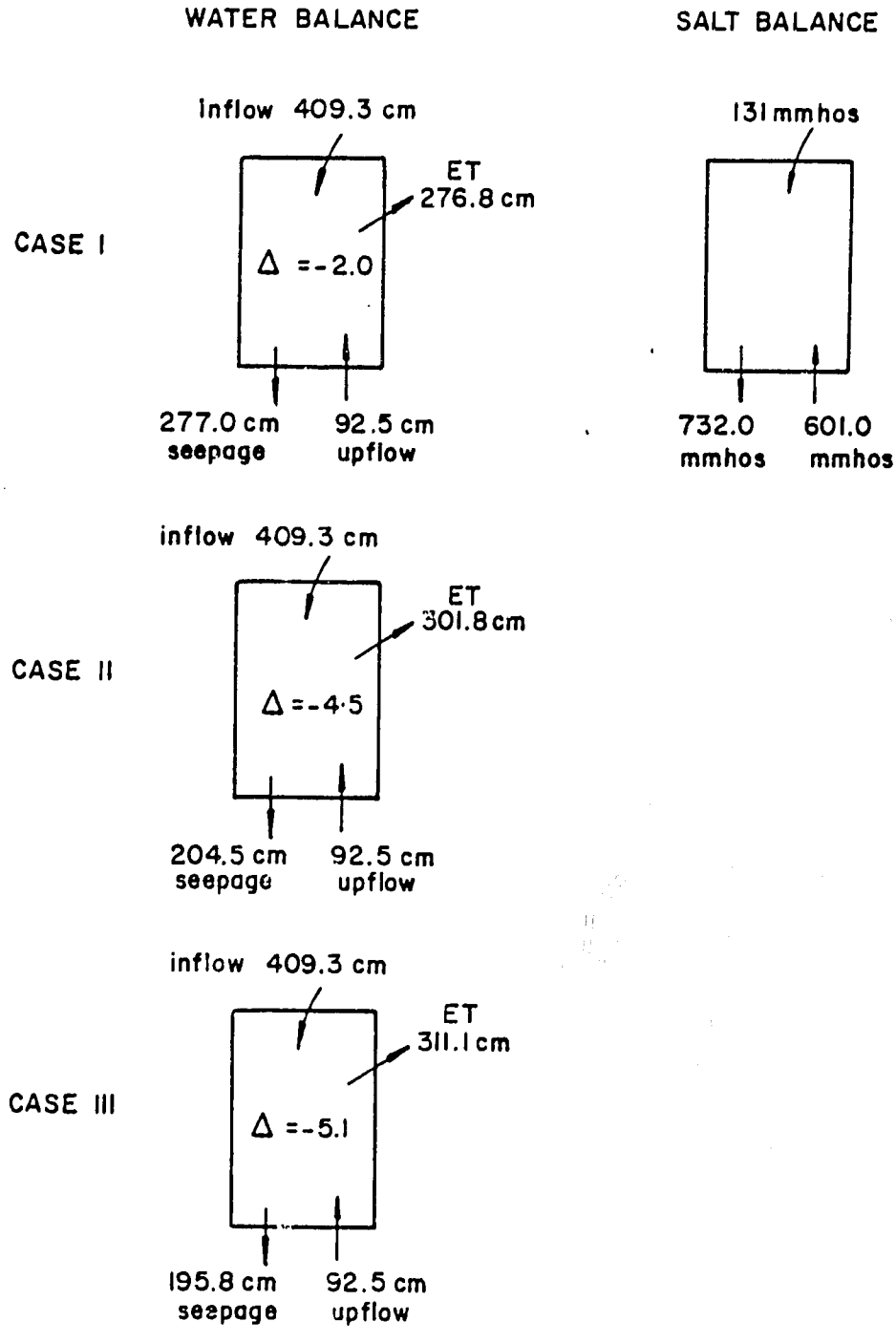


Figure 19 Water and salt balances for two year period and three soil moisture availability assumptions.

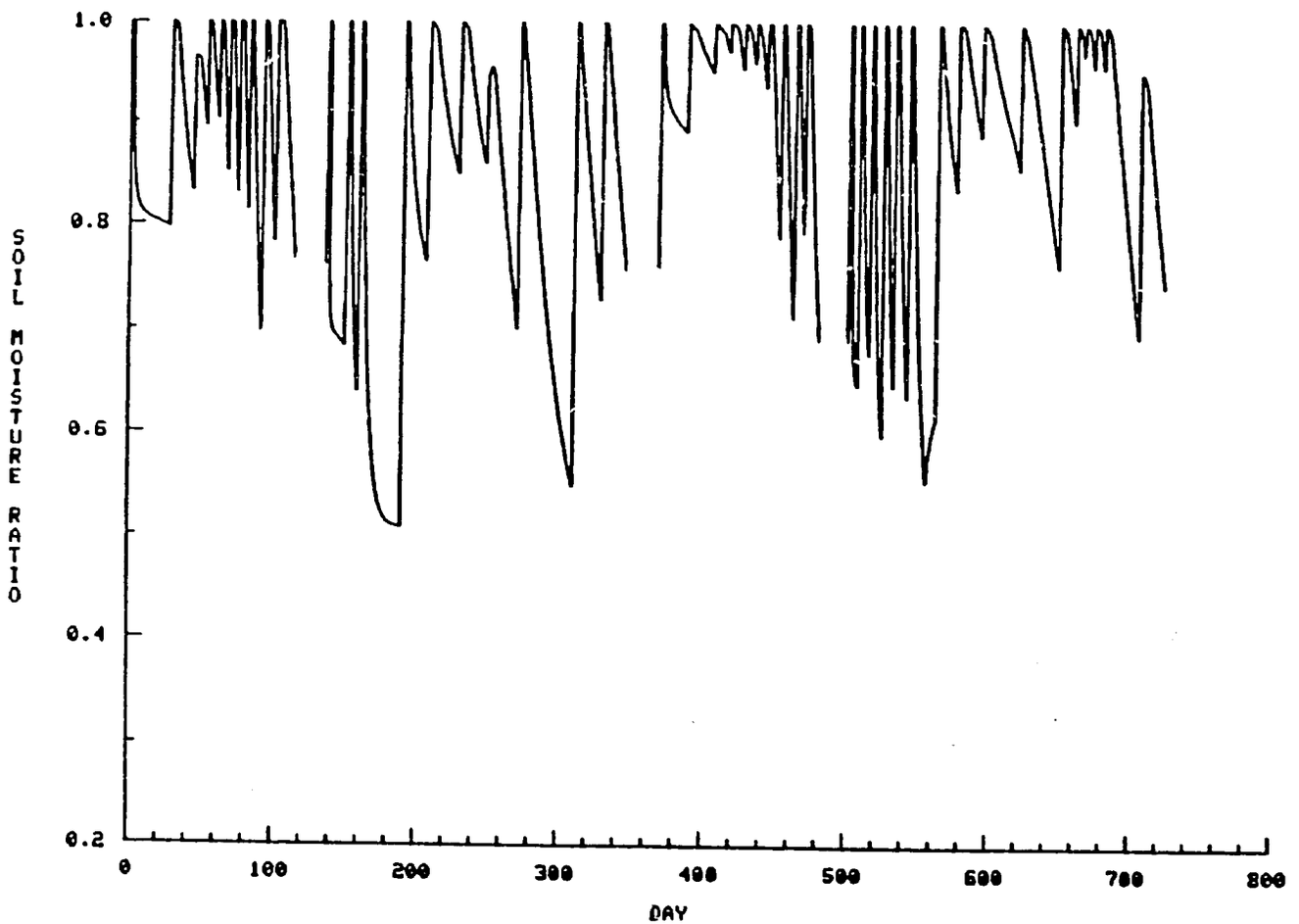


Figure 20 Soil moisture status for two year period.

groundwater reservoir was reduced to 15.6 cm. Because less leaching occurred, the root zone salinity levels were found to be slightly higher. However, at the last irrigation, the computed level was only 5.3 mmhos/cm. Assuming, for simplicity, that this net change in the salinity levels is negligible, and the 131 mmhos of salt in the irrigation water were added to the water table, the ratio of salt added to water added is 8.4 mmhos/cm or about 30 percent higher than the input preseason groundwater salinity level of 6.5 mmhos/cm. If the entire ET demand were met, there would be a negative net change in the water table elevation of 2.75 cm (assuming 25 percent surface loss). Similar trends were found when Case I and Case III were run with decreased irrigation applications. If the 25 percent surface loss is reasonable, two trends are indicated. First, the actual salinity levels in the root zone would be higher than those in the program output. A constant input groundwater salinity is assumed in the program. In the upper regions of the water table, salinity levels would probably be higher near the end of the period studied. Secondly, a general build-up in the aquifer salinity level would be expected over time, eventually causing higher yield reductions.

3.4 CLOSED DRAIN SELECTION - ONE CROP:

After the existing field case is analyzed, the program selects closed drain spacings and depths for each level of protection (HMIN) considered. The drain design selected is the least cost system for that protection level based on the input cost data, soil conditions and the irrigation schedule. The procedure is an iterative process. For illustration, assume that only the corn crop is planted each year. The costs for a closed drain system are as shown in Table 3.3. The analysis

Table 3.3: Costs Assumed for Closed Drains

Variable	Cost Assumed	Units	Explanation
C1	.526	$/m	C1 + C2 * Ø + C3 * Ø^2 is the material cost of the drains per meter expressed as a quadratic function of the drain diameter in cm
C2	-.119	$/(m*cm)	
C3	0.017	$/(m*cm^2)	
C4	0.1	$/m	Cost of the filter per meter of drain
C5	0.01	$/m	Maintenance cost per meter of drain per year
C6	0.0	$	Cost of one manhole
C7	0.0	$	Fixed cost of drain installation, i.e. minimum cost
C8	0.3	$/m	C8 + C9 * depth is the variable cost of drain installation per meter expressed as a linear function of drain depth
C9	0.3	$/m^2	
C10	0.0	$	Cost of one outlet structure
RATE	0.202		Interest rate, discount rate or opportunity cost converts present cost to an annual cost

of the existing system determined an initial set of deep percolation values. Using these values and an initial trial spacing of 10 m, the program determines that a drain depth of 1.30 m is required from the dynamic equilibrium equation to limit the minimum depth to water to 100 cm. The cost for the system is evaluated as $380/ha and the gradient of the cost function with respect to the spacing is $-.298 \times 10^{-4}$. Since the gradient is negative, the cost will decrease if the spacing is increased. When the change in the spacing is less than one percent or less than an input epsilon, the system is chosen as the least cost combination which will satisfy the protection requirements, assuming the current deep percolation values and input data. In this case a spacing of 145.9 m and a drain depth of 5.59 m is chosen. The cost for this system is $43.9/ha and the gradient is $-.5718 \times 10^{-9}$. At this point, a new water table hydrograph is developed, the root zone conditions are reestimated, new values for the seepage to the water table are determined, and the process is repeated. When the change in seepage values is within acceptable limits, the final spacing and depth of 107.6 m and 5.7 m, respectively, is chosen for HMIN=100 cm.

The crop yield determined by the program for HMIN=100 cm only increased slightly from the 3.97 metric tons/ha for the existing case when the drains were installed. However, the plant root environment changed significantly. By comparing Figures 21, 22 and 23 which show the computed soil moisture levels, salinity levels and root zone depths for the field with drains installed, with corresponding curves for the existing case, the changes in the root zone environment are evident. First, by installing the drain system, the minimum depth to water is increased from 50 cm to 120 cm. For the existing system, the water

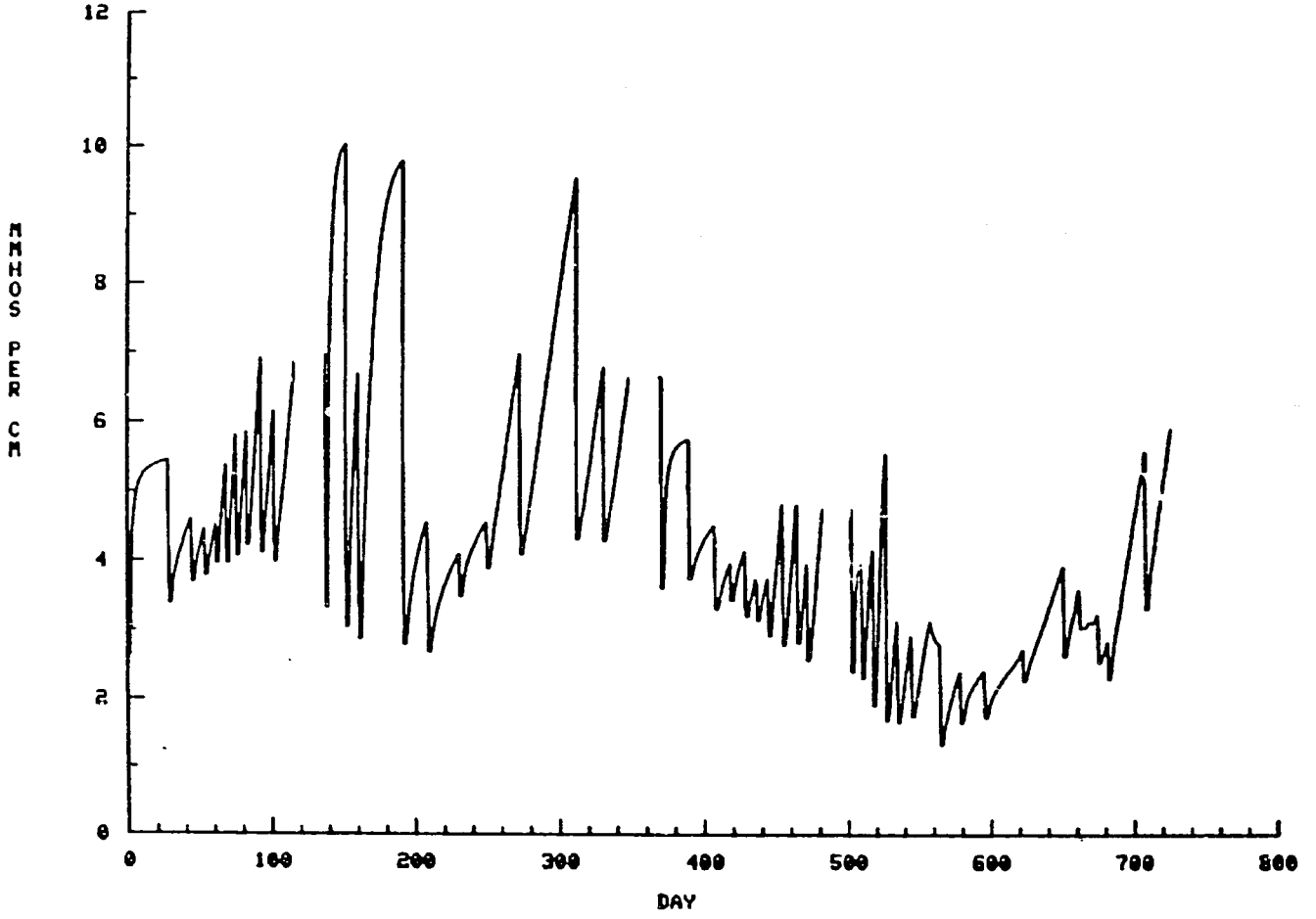


Figure 21 Salinity levels for two year period.

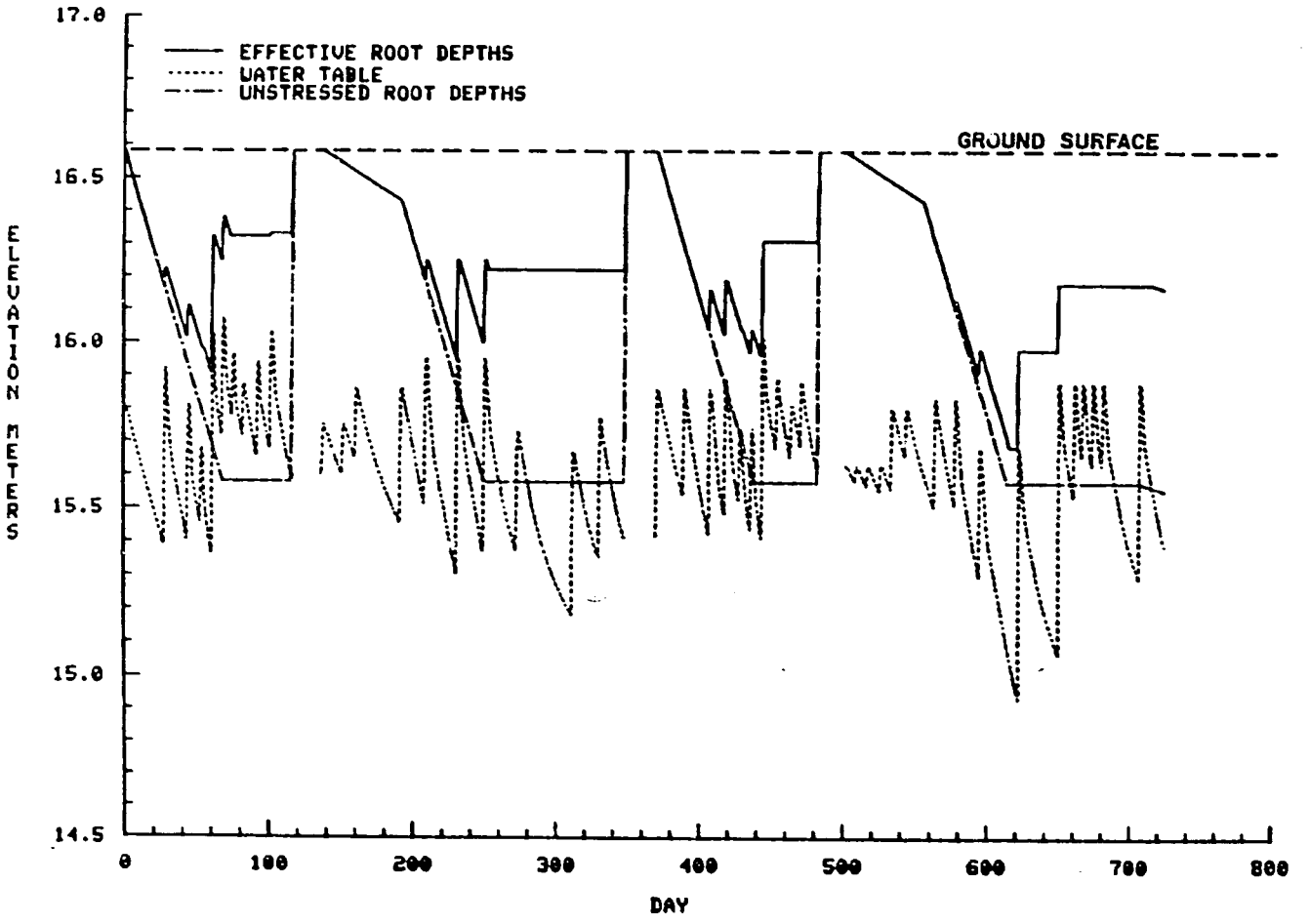


Figure 22 Root depths and water table elevations for two year period.

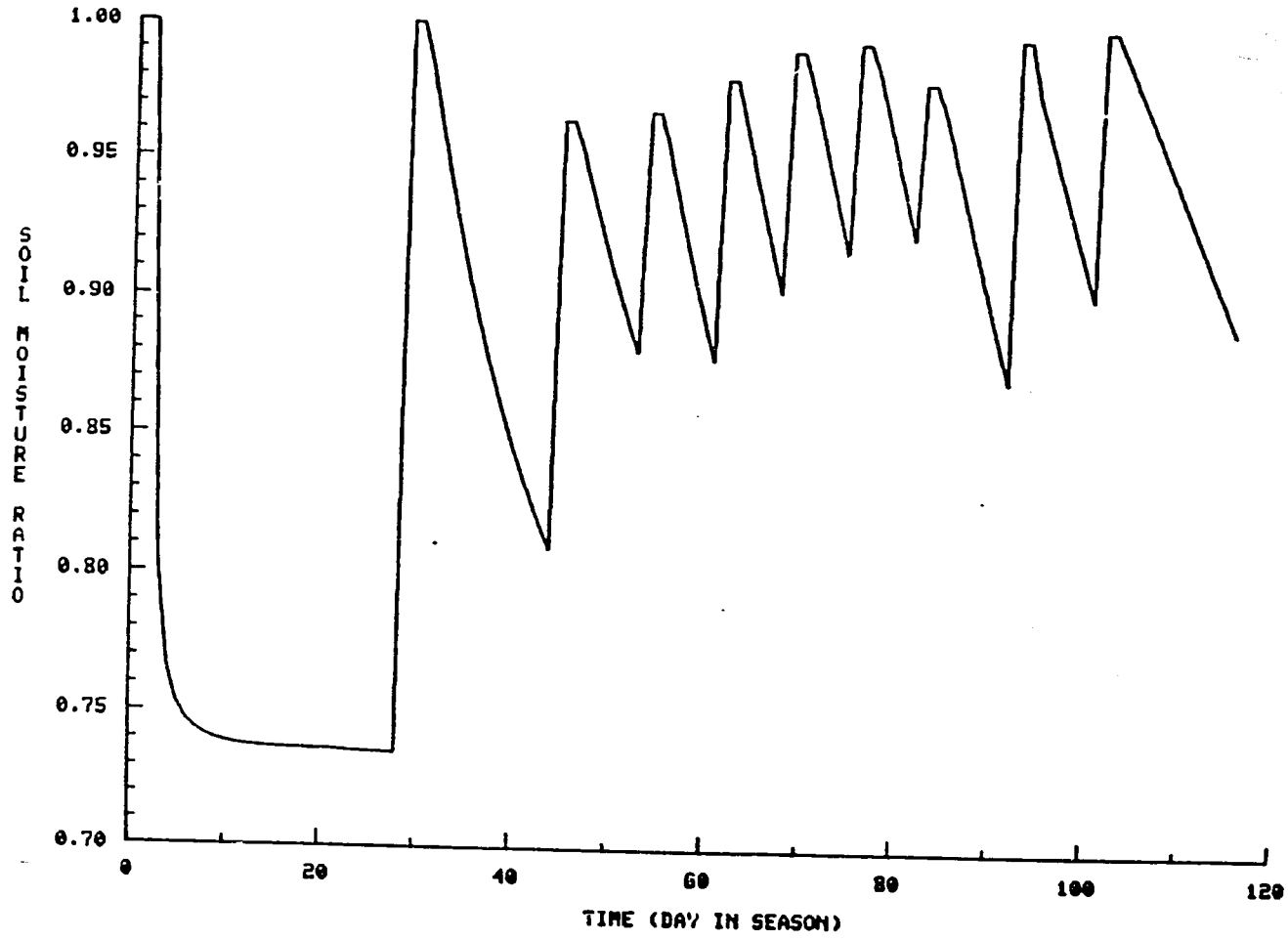


Figure 23 Soil moisture ratio computed for summer, 1978, with drains installed, HMIN = 100 cm.

table was at a depth of less than 100 cm from the surface 85 days during the 116 day season. This change causes a series of alterations in the field situation and plant growth environment. First of all, there is no truncation of the root zone as there is in the existing field case. Secondly, the lower water table elevations reduce the upflow from the water table to the root zone, decreasing the groundwater aquifer's total computed seasonal contribution to evapotranspiration from 31 percent to 7.6 percent of the total. With the decrease in upflow of the poorer quality water from the water table, the salinity levels in the root zone begin to approach the salinity of the irrigation water which is low in salts. In the existing field case, the average salinity of the root zone soil moisture was approximately 4.8 mmhos/cm. Figure 21 shows the salinity levels which would be expected after drain installation. The maximum salinity shown here is 4.09 mmhos/cm and the average is 3.2 mmhos/cm.

The third aspect considered in the yield determination is the occurrence of soil moisture deficits in the root zone. The lower water table position with drains results in a decrease in upflow to the root zone, higher matric suctions between irrigations and lower soil moisture holding capacity in the root zone. The decrease in upflow means that a larger percentage of the evapotranspiration demand must be supplied by the soil moisture reservoir. This, of course, causes more drying of the root zone and, hence, lower computed ET values. This trend can be seen more clearly in Tables 3.4 and 3.5 which summarize the complete run for the closed drain case. The most significant drying occurs early in the season. This is due to both the small root zone area and the lowered soil moisture holding capacity compared to a higher water table

Table 3.4: Summary of Results for Closed Drain Analysis--One Crop

Level	Drain Spacing (m)	Drain Depth (m)	Cost ($/ha)	Yield (Tons/ha)
Existing				3.97
100 cm	107.64	5.70	60.16	4.01
150 cm	103.28	5.96	64.22	3.97
200 cm	95.19	6.22	71.34	3.94
250 cm	85.90	6.48	80.81	3.80
300 cm	75.77	6.67	93.15	3.64

Table 3.5: Seasonal Summary of Computed Results for Closed Drain Analysis --One Crop.

Level	Net Application (cm)	Total ET (cm)	Seepage (cm)	Upflow (cm)	Minimum Soil Moisture	Average EC (mmhos/cm)	Minimum Depth to Water (cm)
Existing	74.9	65.5	27.4	20.14	.3955	4.76	50
100 cm	74.9	65.0	12.8	4.91	.3873	3.25	121
150 cm	74.9	64.8	12.7	2.99	.3832	2.87	145
200 cm	74.9	64.6	12.5	.77	.3762	2.32	188
250 cm	74.9	63.8	12.5	0	.3696	2.09	239
300 cm	74.9	62.9	12.5	0	.3633	1.91	285

elevation. Later in the season, the frequent irrigations and increased root zone depth result in satisfactory levels of soil moisture availability.

The yield computed with drains installed is still considerably below the maximum value input. Since the roots were not truncated and the salinity levels in the root zone are low with the drain system, the reduction in plant uptake and use (hence yield) is now a result of a less than optimum irrigation schedule. At this point, selection of a new irrigation regime becomes the responsibility of the programmer. The program includes an option which will aid the designer in choosing a better irrigation pattern. In addition, some comments should be made regarding the large spacing and depths selected. The depths selected are not feasible in terms of construction, nor are they desirable in terms of total field conditions. The area above the drains would be expected to have severe soil moisture drying which would result in crop yield reductions. There are primarily three reasons for the program's choice of this type of layout. First, although the soil has a low conductivity in the example given above, it was assumed for illustration that only one crop was planted each year and a long drainout period occurs following harvest. Secondly, as mentioned previously, the irrigation schedule is input and not selected by the program. The installation of the drains significantly lowered the water table. This reduced upflow from the water table to the root zone and increased the percentage of the evapotranspiration demand supplied by the available root zone soil moisture. More of the input water was used to fill the soil moisture deficit and the seepage to the water table was significantly reduced. Third, the cost structure used greatly influences

the final layout chosen. In the case presented above, there is a very small cost penalty on the drain depth. Perhaps a better cost function form would be an exponential or power function of depth. This would increase the penalty as drain depth increased.

3.5 OPEN DRAIN SELECTION - ONE CROP:

The costs assumed for open drains are:

C1 = \$1.05/m^3 = the cost of excavation

C2 = \$.1/m^2 = the value of the land taken out of production per year

C3 = \$1.0/m = the annual cost of maintenance per length of drain.

The irrigation pattern, soil properties and so forth are the same as those given in Table 3.1. Note that the cost structure has a high penalty in C2 and C3 for decreasing the spacing. The drain coefficient, C1 is multiplied by an interest or discount rate whereas C2 and C3 are annual costs. Therefore, the drain layouts are again wide and deep. The results are summarized in Table 3.6

Generally, the same patterns as those found in the closed drain selection are evident. As the drain system becomes more restrictive, the upflow and hence, salinities, decrease. However, due to the decreased upflow, the soil dries more between irrigations and yields subsequently begin to decline. The costs of the open drains are also higher than the corresponding costs of the closed drains.

3.6 EXPANDED PROGRAM USE - ONE CROP:

The examples in this section illustrate a procedure which can be used to extend the program capabilities by varying the irrigation regime. Again, however, the illustrations are meant as examples only. As mentioned previously, with drains installed, as the spacing increases

Table 3.6: Summary of Results for Open Drain Analysis--One Crop

Level	Spacing (m)	Drain Depth (m)	Cost ($/ha)	Yield (Tons/ha)
Existing				3.97
100 cm	116.0	6.4	86.22	4.11
150 cm	108.7	6.5	92.05	4.11
200 cm	100.4	6.82	99.57	4.00
250 cm	89.9	6.92	111.12	3.91
300 cm	79.2	6.92	130.00	3.73

with HMIN, the costs increase but the yields eventually decrease. This trend indicates that by installing more restrictive drain systems, one problem is solved but another is created. Although salinity levels are low and no truncation of the root zone occurs, the upflow from the water table is decreased and the depth of the soil moisture profile is increased. Hence, water deficits are more frequent and severe, excess application values are reduced, and the result is lower yields.

There are three possible procedures which can be used to modify the irrigation pattern. First, irrigation timing may be controlled by outside factors such as availability. Therefore, one option is to maintain the same irrigation timing but increase the application quantities. A second possible procedure is to use the ICHNG option available in the program. This option will schedule irrigations within the program when the evaluated total soil suctions reach prespecified input levels. For example, the program may be instructed to irrigate when soil suctions reach 10 bars in the first growth stage and 5 bars in all subsequent stages. The leaching fraction is also input. The timing of an irrigation, then, is determined by the average total integrated root zone suctions and the application quantity is determined by the program to fill the soil moisture profile and supply the input leaching requirement. For deep water table conditions, only one run is required to determine the irrigation timing and application intensity required to meet the input specifications. However, for high water table conditions, the process is a trial and error procedure because the soil moisture status in the root zone is highly dependent on the position of the water table. As the proximity of the water table changes, upflow values change and the equilibrium soil moisture values in the root zone

vary (versus an assumed constant value of field capacity for deep water tables). Two methods are available to estimate the water table position for the season. A constant depth to water can be specified at the beginning of subroutine RTZ or an initial water table elevation can be input and the change in water table elevations determined in the program.

The third possible procedure available to the designer in determining an irrigation schedule is using engineering judgment and the soil moisture status output from previous runs of the computer to make an educated guess at a better irrigation system. This alternative can also be combined with output from the ICHNG option.

3.7 SUMMARY AND DISCUSSION:

This chapter illustrates the procedure used in the computer program. The root zone evaluation uses water and salt balances to estimate daily root zone soil moisture and salinity levels. The cost coefficients used in the program are delineated and the method used for approximating crop yields is summarized.

I would like to emphasize that the model can be easily modified if the assumptions made in the program development are deemed inappropriate for the field situation being considered. For example, the cost function assumed should be considered to be an example of a possible cost function. The form can be easily modified by simply changing the cost function and derivatives in the program. Similarly, the program determines drain layouts using the dynamic equilibrium equations for the drain spacing - depth relationship as a constraint on the cost objective function. Any other drain spacing equation can be substituted for the dynamic equilibrium equation if it is more appropriate. The form of the

crop yield production function can also be modified by simply changing the form of the equation used in the program.

CHAPTER IV

SUMMARY

A computer model is presented which can be used to choose an optimal layout for relief open or closed drain systems in irrigated areas. The optimal design is defined as the drain spacing and depth combination which returns maximum net benefits, that is, the difference between the increased crop yield minus the drain cost. The program increments the variable HMIN, the minimum allowable depth to water for the season. For each level of HMIN, a least cost drain layout is determined by minimizing a cost function subject to equality constraints which specify approximate relationships between the drain spacing, depth and size required to result in the specified minimum depth to water. After the drain layout is chosen, the water table hydrograph is developed and the root zone environment evaluated from daily water and salt volumetric balances. Upflow of water and salts from the groundwater aquifer to the root zone and root truncation or delayed root growth due to nonaerated conditions are incorporated in the balances. The actual evapotranspiration rates for each day are estimated using an integrated total soil moisture suction, i.e., the sum of the average matric and solute suctions in the root zone, and an input water availability function.

Crop yield is estimated from a linear production function which equates relative yield decreases in each plant growth stage to relative evapotranspiration deficits multiplied by a yield response factor. Total yield is the maximum attainable yield under favorable root zone conditions minus the sum of the yield reductions for each growth stage.

For each increment of HMIN, a yield and least cost drain layout are determined. The optimal system is then chosen which corresponds to the level which maximizes the net benefit obtained.

Improvements in the program would be expected to occur from additional use of the program. The following changes or modifications should be considered:

(i) Incorporate soil layers in the root zone analysis. This would probably improve the soil moisture and salinity balances. In addition, a pattern of root uptake could be included and modified during the season. The root zone environment analysis could even be extended to a two or three dimensional analysis.

(ii) The upflow from the water table to the root zone could be improved as information on this process becomes available.

(iii) Expand subroutine YIELD to accommodate alternate forms of the production function. This could be accomplished easily and would extend the applicability of the program. A crop yield model could also be used conjunctively with the program.

(iv) Incorporate a more sophisticated root zone salinity analysis, including chemical interactions. Volumetric salt balances are easy to use and indicate general trends. However, in many cases the chemical constituency and interactions can not reasonably be ignored.

(v) Incorporate a water quality analysis of the water below the water table and interface this analysis with the root zone analysis.

For many applications, only parts of the program are needed. To

save compilation time and reduce storage requirements, the program can be decomposed into the following subprograms:

(i) A subprogram which includes only the root zone evaluations in subroutines RTZ, ROOT, ETA, SMBAL, and UPFLOW. Soil properties, irrigation data, water table depths, upflow rates and an unstressed root growth curve would be required input. This subprogram could then be used to evaluate the root zone environment, determine actual evapotranspiration rates and determine changes in the effective root depths due to nonaerated conditions. Alternative irrigation schedules, in particular, could be evaluated.

(ii) A subprogram which evaluates the effects of drain cost coefficients. This subprogram would include subroutines OPT, ALPH1 and GRAD1 or ALPH2 and GRAD2 only. The recharge values from each irrigation would need to be approximated. However, the influence of the cost coefficients, soil properties such as the hydraulic conductivity, specific yield and depth to the impermeable sublayer, the form of the cost function and the estimation of recharge values could be checked with a minimum amount of calculation required.

(iii) Subroutines SERIES and WTGRAPH could be used separately to determine the water table hydrograph for input drain depth and spacing combinations and a required minimum allowable depth to water. The output from these subroutines could also be used as input to the root zone evaluation subprogram (part i) to evaluate the effects on the plant environment of installing a prespecified drain spacing and depth combination.

REFERENCES

Albertson, M. L., J. R. Barton and D. B. Simons. 1960. Fluid mechanics for engineers. Prentice-Hall, Englewood Cliffs, N. J. 567 p.

Anat, A., H. R. Duke and A. T. Corey. 1965. Steady upward flow from water tables. Hydrology paper No. 7. Colorado State University. Fort Collins, Colorado. 88 p.

Arar, A. and B. G. Bishay. 1975. Drainage. In: Aboukhaled, A., A. Arar, A. M. Balba, B. G. Bishay, L. T. Kadry, P. E. Rijtema and A. Taher. Research on crop water use, salt affected soils and drainage in the Arab Republic of Egypt. Food and Agriculture Organization of the United Nations, Rome. p. 80-92.

Balba, A. M., L. T. Kadry and A. Taher. 1975. Salt affected soils. In: Aboukhaled, A., A. Arar, A. M. Balba, B. G. Bishay, L. T. Kadry, P. E. Rijtema and A. Taher. Research on crop water use, salt affected soils and drainage in the Arab Republic of Egypt. Food and Agriculture Organization of the United Nations, Rome. p. 62-79.

Barrett, J. W. H. 1977. Crop yield functions and the allocation and use of irrigation water. Ph.D. dissertation. Colorado State University. Fort Collins, Colorado. 210 p.

Bernstein, L. 1974. Crop growth and salinity. In: van Schilfgaarde, J. (ed.). Drainage for agriculture. Agronomy 17: 39-54. American Society of Agronomy. Madison, Wisconsin.

Black, C. A. 1968. Soil-plant relationships. John Wiley and Sons, Inc., New York. 792 p.

Bouwer, H. 1974. Developing drainage design criteria. In: van Schilfgaarde, J. (ed.). Drainage for agriculture. Agronomy 7: 67-79. American Society of Agronomy. Madison, Wisconsin.

Bresler, E. 1972. Control of soil salinity. In: Hillel, D. (ed.). Optimizing the soil physical environment toward greater crop yields. Academic Press. New York, New York. p 101-132.

Bresler, E. and D. Yaron. 1972. Soil water regime in economic evaluation of salinity in irrigation. Water Resources Research 8 (4): 791-800.

Brooks, R. H. and A. T. Corey. 1964. Hydraulic properties of porous media. Hydrology Paper No. 3. Colorado State University. Fort Collins, Colorado. 27 p.

Corey, A. T. 1977. Mechanics of heterogeneous fluids in porous media. Water Resources Publications. Fort Collins, Colorado. 259 p.

de Wit, M. C. J. 1978. Morphology and function of roots and shoots of crop plants under oxygen deficiency. In: Hook, D. D. and R. M. M. Crawford (eds.). Plant life in anaerobic environments. Ann Arbor Science Publishers, Inc. Ann Arbor, Michigan. p. 333-350.

Donnan, W. W. 1977. An overview of drainage worldwide. Third National Drainage Symposium Proceedings. ASAE. St. Joseph, Michigan. p. 6-9.

Doorenbos, J. and W. O. Pruitt. 1977. Guidelines for predicting crop water requirements. Irrigation and Drainage Paper No. 24. Food and Agriculture Organization of the United Nations, Rome. 144 p.

Doorenbos, J. and A. H. Kassam. 1979. Yield response to water. Irrigation and Drainage Paper No. 33. Food and Agriculture Organization of the United Nations, Rome. 193 p.

Dotzenko, A. D., M. Zanati, A. A. Abdel-Wahed and A. M. Keleg. 1979. Preliminary soil survey report for the Beni Magdoul and El Hammami Areas. Egypt Water Use and Management Technical Report No. 2. Colorado State University. Fort Collins, Colorado. 43 p.

Duke, H. R. 1973. Drainage design based on aeration. Hydrology Paper No. 61. Colorado State University. Fort Collins, Colorado. 59 p.

Durnford, D., 1982. Optimal drain design: An incremental net benefit approach. Ph.D. dissertation. Colorado State University. Ft. Collins, Colorado. 269 p.

El-Tobgy, H. A. 1974. Contemporary Egyptian agriculture. Ford Foundation. Beirut, Lebanon. 226 p.

Gardner, W. R. 1958. Some steady state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Science 85: 228-232.

Hayward, H. E. and C. H. Wadleigh. 1949. Plant growth on saline and alkali soils. Advances in Agronomy 1: 1-38.

Hiler, E. A. 1969. Quantitative evaluation of crop drainage requirements. Transactions ASAE 12 (4): 499-505.

Hiler, E. A. and R. N. Clark. 1971. Stress day index to characterize effects of water stress on crop yields. Transactions ASAE 14 (4): 757-761.

Hiler, E. A., R. N. Clark and L. J. Glass. 1971. Effect of water table height on soil aeration and crop response. Transactions ASAE 14 (5): 879-882.

Hillel, D. 1971. Soil and water: physical principles and processes. Academic Press. New York. 288 p.

Ibrahim, W. R. 1977. Drainage effects on soil characteristics and crop production. Third National Drainage Symposium Proceedings. ASAE. St. Joseph, Michigan. p 117-122.

Jensen, M. E. (ed.). 1973. Consumptive use of water and irrigation water requirements. Technical committee on irrigation water requirements of the Irrigation and Drainage Division. ASCE. New York. 215 p.

Luthin, J. N. 1966. Drainage engineering. John Wiley and Sons, Inc. New York. 281 p.

Maas, E. V. and M. Hoffman. 1977. Crop salt tolerance - Current assessment. Journal of Irrigation and Drainage Division, ASCE. 103 (IR2): 115-134.

Maasland, M. 1964. Water table fluctuations induced by irrigation. Paper No. 3423. Transactions, ASCE 128 (III): 142-161.

McWhorter, D. B. 1977. Drain spacing based on dynamic equilibrium. J. Irrig. and Drain. Div. ASCE 103(IR2): 259-271.

McWhorter, D. B. and H. R. Duke. 1976. Transient drainage with nonlinearity and capillarity. J. Irrig. and Drain. Div. ASCE 102(IR2): 193-204.

McWhorter, D. B. and D. K. Sunada. 1977. Ground water hydrology and hydraulics. Water Resources Publications, Ft. Collins, Colorado. 290 p.

Moody, W. T. 1966. Nonlinear differential equation of drain spacing. Proceedings, ASCE 92(IR2): 1-9.

Rhoades, J. D. 1974. Drainage for salinity control. In: van Schilfgaarde J. (ed) Drainage for agriculture. Agronomy 17: 433-468. Amer. Soc. Agron. Madison, Wisconsin.

Richards, L. A. 1965. Physical condition of water in soil. In: Black, C. A. (ed.). Methods of soil analysis I. Agronomy 9: 128-152. American Society of Agronomy. Madison, Wisconsin.

Rijtema, P. E. and A. Aboukhaled. 1975. Crop water use. In: Aboukhaled, A., A. Arar, A. M. Balba, B. G. Bishay, L. T. Kadry, P. E. Rijtema and A. Taher. Research on crop water use, salt affected soils and drainage in the Arab Republic of Egypt. United Nations Food and Agriculture Organization, Rome. p. 5-61.

Robins, J. S. 1965. Evapotranspiration. In: Black, C. A. (ed.). Methods of soil analysis I. Agronomy 9: 286-298. American Society of Agronomy. Madison, Wisconsin.

Russell, R. S. 1977. Plant root systems: their function and interaction with the soil. McGraw Hill Book Company (U. K.) Limited. Maidenhead and Berkshire, England. 298 p.

Schwab, G. O., P. W. Manson, J. N. Luthin, R. C. Reeve and T. W. Edminster. 1957. Engineering aspects of land drainage. In: Luthin, J. N. (ed.) Drainage of agricultural lands. Agronomy 7: 287-394. American Society of Agronomy. Madison, Wisconsin.

Skaggs, R. W. 1978. A water management model for shallow water table soils. Report No. 134. Water Resources Research Institute, North Carolina State University. Raleigh, North Carolina. 178 p.

Slayter, R. O. 1967. Plant-water relationships. Academic Press, Inc. London. 366 p.

Thorne, D. W. and M. D. Thorne. 1979. Soil, water and crop production. AVI Publishing Company, Inc. Westport, Connecticut. 358 p.

Tondreau, J. E., L. S. Williardson, B. D. Meek and L. B. Grass. 1977. Soil aeration response to a fluctuated water table. Third National Drainage Symposium Proceedings. ASAE. St. Joseph, Michigan. p. 130-134.

Tovey, R. 1964. Alfalfa growth as influenced by static and fluctuating water tables. Transactions ASAE 7 (3): 310-312.

U. S. Salinity Laboratory Staff. 1954. Diagnosis and improvement of saline and sodic soils. Agriculture Handbook No. 60. United States Department of Agriculture. Washington, D. C. 160 p.

Wadleigh, C. H. 1946. The integrated soil moisture stress upon a root system in a large container of saline soil. Soil Science 61: 225-238.

Wadleigh, C. H. and A. D. Ayers. 1945. Growth and biochemical composition of bean plants as conditioned by soil moisture tension and salt concentration. Plant Physiology 20: 106-132.

Williamson, R. E. and G. J. Kriz. 1970. Response of agricultural crops to flooding, depth of water table and soil gaseous composition. Transactions ASAE. 13 (2): 216-220.

APPENDIX A

PROGRAM DOCUMENTATION

A.1 PROGRAM LISTING

```
      PROGRAM DRAINS
     1(INPUT,OUTPUT,DAT2,STORE,RES,TAPE5=DAT2,TAPE6=RES,TAPE7=STORE)
C
C     ******************************************************************
C     DRAINS
C     ******************************************************************
C
      COMMON /EC/          ECMAX(30,3) , ECRZ(731)    , ECRZI        ,
     1       ECS         , ECIRR
      COMMON /LIMIT/       DIMP        , FLNTH        , FWDTH        ,
     1       VMAX        , RN          , FSLPE        , SSLPE        ,
     2       B1          , DMAX
      COMMON /SER/         TSUM(731)   , WTH(731)     , ZERO
      COMMON /GS/          IGSB(30)    , ETP(731)     , CKO(731)     ,
     1       GAMMA(30)   , YK(30)      , YA(5)        , YM(5)        ,
     2       JCROP(5)
      COMMON /SOIL/        HYDK        , SMFC         , SMWP         ,
     1       NDFC        , SMBEG       , SYA
      COMMON /SHAPE/       SFK1        , SFK2         , T
      COMMON /MISC/        NDIS        , NGS          , NIRR         ,
     1       NCROPS      , INOUT
      COMMON /IRR/         IRDAY(50)   , QIRR(50)     , DP(50)
      COMMON /WBAL/        RD(731)     , ET(731)      , INDAY(50)    ,
     1       OPTRD(50)   , DTW(731)    , NRDIN        , FL
      COMMON /DCOST/       C1(10)      , C2(3)        , RATE         ,
     1       CM(12)      , DPM         , DDEDD        , DEL2         ,
     2       DEL3
      COMMON /SUM/         ETMAX(30)   , ETSUM(30)    , ECSUM(30,3)
      COMMON /MOIS/        AW(731)     , SM(731)      , Z(20)        .
     1       SMC(20)     , NSMIN       , PHICR        , PHIRR        ,
     2       JCHNG
      COMMON /FLOW/        ZQ(20)      , Q(20)        , NQS          ,
     1       NDRD        , HSAT        , QFLOW(731)   , APEFF(50)    ,
     2       LDS(5)
      COMMON /PLOT/        IJT         , IJJ          , IJP          ,
     1       A1(3000,8)
      COMMON /GRAD/        TEXP        , FSUM         , TFSUM        ,
     1       T1          , T2          , PI           , B1MIN        ,
     2       HMAX        , BERM        , HMNM
      COMMON /DAT/         NETIN       , NWTIN        , CETP(731)    ,
     1       CCKO(731)   , NET(731)    , CDTW(731)    , INDTW(731)
      DIMENSION            TCOST(2,100), SPACE(100)   , CDP(50)      ,
     1       DEPTH(100)  , CCDP(50)    , AREA(80)     , SITE(80)     ,
     2       PHI(20)     , CPHI(20)
```

```
      REAL                    LMAX
      N = 1 - NDIS
      IJJ = N
      IJP = 0
C
C     ****************************************************************
C     READ INPUT DATA
C     ****************************************************************
C
      READ (5,300) (AREA(I),I = 1,80)
      READ (5,300) (SITE(I),I = 1,80)
      WRITE (6,480) (AREA(I),I = 1,80)
      WRITE (6,490) (SITE(I),I = 1,80)
      READ (5, * ) NDIS,NGS,NIRR,NCROPS,INOUT
      READ (5, * ) HMINI,DELH,J
      READ (5, * ) IT,DSPCE,DDPTH,SFK1,SFK2,X
      READ (5, * ) HYDK,SMFC,SMWP,NDFC,SMBEG,SYA
      READ (5, * ) ECRZI,ECS,ECIRR,A,B
      READ (5, * ) FSLPE,FLNTH,FWDTH,DIMP,DMAX,EPS
      READ (5, * ) HSAT,PHICR,NDRD,PHIRR,FL,ICHNG
      READ (5, * ) (IRDAY(I),QIRR(I),GAMMA(I),I = 1,NIRR)
      READ (5, * ) (IGSB(I),I = 1,NGS)
      READ (5, * ) (JCROP(I),LDS(I),I = 1,NCROPS)
      READ (5, * ) (YK(I),I = 1,NGS)
      READ (5, * ) (YM(I),I = 1,NCROPS)
      READ (5,340) NETIN
      READ (5, * ) (NET(I),CETP(I),CCKO(I),I = 1,NETIN)
      READ (5,340) NSMIN
      READ (5,330) (Z(I),SMC(I),I = 1,NSMIN)
      READ (5,340) NQS
      READ (5,330) (ZQ(I),Q(I),I = 1,NQS)
      READ (5,340) NRDIN
      READ (5,350) (INDAY(I),OPTRD(I),I = 1,NRDIN)
      READ (5,340) NWDIN
      READ (5, * ) (INDTW(I),CDTW(I),I = 1,NWDIN)
      I = 1
      II = 1
      DO 120 N = 1,NDIS
         IF (I.GT.NWDIN) GO TO 100
         IF (N.EQ.INDTW(I).AND.I.LE.NWDIN) I = I + 1
 100     IF (II.GT.NETIN) GO TO 110
         IF (N.EQ.NET(II).AND.II.LE.NETIN) II = II + 1
 110     DTW(N) = CDTW(I - 1)
         ETP(N) = CETP(II - 1)
         CKO(N) = CCKO(II - 1)
 120  CONTINUE
      IF (J.EQ.0.OR.J.EQ.2) GO TO 140
      READ (5, * ) (C1(I),I = 1,10)
      READ (5, * ) NPHIS
      IF (NPHIS.EQ.0) GO TO 130
      READ (5, * ) (PHI(I),CPHI(I),I = 1,NPHIS)
      CALL LSQR (NPHIS,PHI,CPHI)
 130  READ (5, * ) RMIN,RN1,RATE1,DPM
 140  IF (J.EQ.0.OR.J.EQ.1) GO TO 150
```

```
      READ (5, * ) (C2(I),I = 1,3)
      READ (5, * ) B1MIN,HMAX,HMNM,BERM,RN2,VMAX,SSLPE,RATE2
  150 SUMI = 0.0
      DO 160 I = 1,NIRR
         SUMI = SUMI + QIRR(I)
  160 CONTINUE
      T = IT
      IF (INOUT.NE.0) CALL DATIN (J,HMINI,DELH,SUMI,RN1,RN2,RATE1,RATE2,
     1X,RMIN)
      FLNTH = FLNTH * 100.
      FWDTH = FWDTH * 100.
      IJ = J
      J = 0
      NHMIN = (DIMP - HMINI)/DELH
      NHMIN1 = (DMAX - HMINI)/DELH
      IF (HMIN1.LE.HMIN) HMIN = HMIN1
      IF (NHMIN.LE.1) NHMIN = 1
C
C     ******************************************************************
C     ANALYSIS OF EXISTING FIELD CASE
C     ******************************************************************
C
      WRITE (6,310)
      CALL RTZ (J)
      CALL SUMS (X,A,B)
      CALL YIELD
      DO 170 ICROP = 1,NCROPS
         WRITE (6,390) ICROP
         WRITE (6,370) YA(ICROP),YM(ICROP)
  170 CONTINUE
      IF (IJ.NE.0) J = 1
      IF (IJ.EQ.2) J = 2
      WRITE (7,500) ((A1(II,JJ),JJ = 1,8),II = 1,IJT)
      IF (J.EQ.0) STOP
      IC = 0
      DO 180 N = 1,NIRR
         CCDP(N) = DP(N)
         CDP(N) = DP(N)
         DP(N) = .1 * QIRR(N)
  180 CONTINUE
  190 HMIN = HMINI - DELH
      IF (J.EQ.1) RATE = RATE1
      IF (J.EQ.1) RN = RN1
C
C     ******************************************************************
C     BEGIN MAIN LOOP OF PROGRAM WHICH INCREMENTS HMIN
C     ******************************************************************
C
      IF (J.EQ.2) RATE = RATE2
      IF (J.EQ.2) RN = RN2
      DO 270 I = 1,NHMIN
         IC = 0
         TCOST(J,I) = 0.0
         DEPTH(I) = 0.0
```

```
      HMIN = HMIN + DELH
      WRITE (6,320) HMIN
200   ZP = 0.0
      SPACE(I) = DSPCE
      LMAX = 0.0
      CALL PREOPT (J,HMIN,IP,SCM2,SCM3)
      CALL OPT (J,DSPCE,DDPTH,HMIN,EPS,RMIN,R,Q1,D,DE,ALPHA,LMAX,ZP,I
     1 P,SCM2,SCM3)
      IF (INOUT.EQ.2) WRITE (6,360) DSPCE,DDPTH,ALPHA,ZP,R,Q1
      CALL SERIES (DSPCE,IT,ALPHA)
      CALL WTGRAPH (DSPCE,DDPTH,IT,ALPHA)
      CALL RTZ (J)
      IK = 0
C
C     ***********************************************************  *****
C     THIS SECTION CONTROLS  ITERATION OF  DEEP PERCOLATION VAL ...
C     IT MAY BE CHANGED IF CONVERGENCE WILL OCCUR MORE QUICKLY WITH AN
C     ALTERNATE SCHEME.  THIS DEPENDS ON THE CASE BEING CONSIDERED.
C     ***************************************************************
C
      DO 220 N = 1,NIRR
         IF (DP(N).EQ.CCDP(N)) GO TO 220
         CKK = CCDP(N) - DP(N)
         CCDP(N) = DP(N)
         CK = CDP(N) - DP(N)
         ACK = ABS(CK)
         ACKK = ABS(CKK)
         IF (ACKK.LE.(0.01 * QIRR(N))) GO TO 220
         IF (ACK.LE.(0.01 * QIRR(N))) GO TO 220
         IF (IC.EQ.0) GO TO 210
         DP(N) = (2.0 * DP(N) + CCDP(N))/3.0
210      CONTINUE
         IK = IK + 1
220   CDP(N) = DP(N)
      IC = IC + 1
      IF (IC.GT.5) GO TO 230
      DEL = ABS(SPACE(I) - DSPCE)
      IF (DEL.LE.(0.01 * DSPCE)) GO TO 230
      IF (IK.NE.0) GO TO 200
230   CALL SUMS (X,A,B)
      CALL YIELD
      WRITE (6,440)
      WRITE (6,450)
      DO 240 II = 1,NDIS
         WTCONT = (QFLOW(II)/ET(II)) * 100.
         WRITE (6,460) II,SM(II),ET(II),ECRZ(II),RD(II),DTW(II),QFLOW
     1   (II),WTCONT
240   CONTINUE
      DO 250 II = 1,NIRR
         WRITE (6,470) II,IRDAY(II),QIRR(II),DP(II),APEFF(II)
250   CONTINUE
      DO 260 ICROP = 1,NCROPS
         WRITE (6,390) ICROP
         WRITE (6,370) YA(ICROP),YM(ICROP)
```

```
  260     CONTINUE
          IF (J.EQ.1) CALL DERIV (J,DDPTH,DSPCE,SUMI,ALPHA,D,DE,R,HMIN)
          TCOST(J,I) = ZP * FLNTH * FWDTH
          SPACE(I) = DSPCE
          DEPTH(I) = DDPTH
  270 CONTINUE
C
C     ******************************************************************
C     END MAIN LOOP.
C     ******************************************************************
C
      IF (J.EQ.1) WRITE (6,380)
      IF (J.EQ.2) WRITE (6,430)
      WRITE (6,400)
      WRITE (6,420)
      DO 280 I = 1,NHMIN
         SPACE(I) = SPACE(I)/100.
         DEPTH(I) = DEPTH(I)/100.
         WRITE (6,410) I,SPACE(I),DEPTH(I),TCOST(J,I)
  280 CONTINUE
      WRITE (7,500) ((A1(II,JJ),JJ = 1,8),II = 1,IJT)
      IF (IJ.EQ.3.AND.J.EQ.2) GO TO 290
      IF (IJ.EQ.3) J = 2
      IF (IJ.EQ.3) GO TO 190
C
C     ******************************************************************
C     FORMAT STATEMENTS
C     ******************************************************************
C
  290 STOP
C
  300 FORMAT (80A1)
  310 FORMAT (1H1, 26HANALYSIS OF EXISTING FIELD,/1H ,26(  1H-)/)
  320 FORMAT (1H1,19H ANALYSIS FOR HMIN=,F10.5/1H ,29(  1H-)/)
  330 FORMAT (2F10.4)
  340 FORMAT (I5)
  350 FORMAT (I5,F10.3)
  360 FORMAT (1H0,9H SPACING=,F10.4,4H CM,,7H DEPTH=,F10.4,4H CM,,7H ALP
     1HA=,F10.4,3H Z=,E10.4,8H  /M**2,,3H R=,F4.1,4H CM,,3H Q=,F10.2,9H
     2M**3/SEC)
  370 FORMAT (1H0,14H ACTUAL YIELD=,F6.2,15H MAXIMUM YIELD=,F6.2)
  380 FORMAT (1H0,31H COST SUMMARY FOR CLOSED DRAINS)
  390 FORMAT (1H0,17H YIELD DATA, CROP,I3)
  400 FORMAT (1H0,6H LEVEL,4X,8H SPACING,4X,6H DEPTH,5X,15H COST FOR FIE
     1LD)
  410 FORMAT (I5,F15.4,F10.4,2X,E15.7)
  420 FORMAT (1H0,10X,7H METERS,5X,7H METERS,5X,8H DOLLARS)
  430 FORMAT (1H0,29H COST SUMMARY FOR OPEN DRAINS)
  440 FORMAT (1H0,32H SUMMARY OF ROOT ZONE CONDITIONS)
  450 FORMAT (1H0,17H   DAY   AVG SMRZ,3X,3HETA,6X,6HECRZ   ,10HROOT DEPT
     1H,4X,3HDTW,4X,18H W.T. CONTRIBUTION/1H ,20X,  2HCM,6X,  5HMMHOS,6X
     2,  2HCM,8X,  2HCM,9X,  2HCM,7X,  7HPERCENT)
  460 FORMAT (I5,6F10.4,F12.2)
  470 FORMAT (1H0,5H IRR=,I2,5H DAY=,I3,9H APPLIED=,F8.4,12H PERCOLATED=
```

```
   1,,F8.4,17H APPLICATION EFF=,F8.4)
480 FORMAT (1H1,  5HAREA=,80A1/)
490 FORMAT (1H0.  5HSITE=,80A1/)
500 FORMAT (8F10.4)
    END
```

```
      SUBROUTINE DATIN(J,HMINI,DELH,SUMI,RN1,RN2,RATE1,RATE2,X,RMIN)I
C
C     ******************************************************************
C     DATIN WRITES OUT THE INPUT DATA IF INOUT IS NOT EQUAL TO 0.
C     ******************************************************************
C
      COMMON /EC/          ECMAX(30,3) , ECRZ(731)    , ECRZI        ,
     1        ECS         , ECIRR
      COMMON /DAT/         NETIN       , NWTIN        , CETP(731)    ,
     1        CCKO(731)   , NET(731)    , CDTW(731)    , INDTW(731)
      COMMON /LIMIT/       DIMP        , FLNTH        , FWDTH        ,
     1        VMAX        , RN          , FSLPE        , SSLPE        ,
     2        B1          , DMAX
      COMMON /GS/          IGSB(30)    , ETP(731)     , CKO(731)     ,
     1        GAMMA(30)   , YK(30)      , YA(5)        , YM(5)        ,
     2        JCROP(5)
      COMMON /SOIL/        HYDK        , SMFC         , SMWP         ,
     1        NDFC        , SMBEG       , SYA
      COMMON /SHAPE/       SFK1        , SFK2         , T
      COMMON /MISC/        NDIS        , NGS          , NIRR         ,
     1        NCROPS      , INOUT
      COMMON /IRR/         IRDAY(50)   , QIRR(50)     , DP(5)
      COMMON /WBAL/        RD(731)     , ET(731)      , INDAY(50)    ,
     1        OPTRD(50)   , DTW(731)    , NRDIN        , FL
      COMMON /DCOST/       C1(10)      , C2(3)        , RATE         ,
     1        CM(12)      , DPM         , DDEDD        , DEL2         ,
     2        DEL3
      COMMON /MOIS/        AW(731)     , SM(731)      , Z(20)        ,
     1        SMC(20)     , NSMIN       , PHICR        , PHIRR        ,
     2        ICHNG
      COMMON /FLOW/        ZQ(20)      , Q(20)        , NQS          ,
     1        NDRD        , HSAT        , QFLOW(731)   , APEFF(50)    ,
     2        LDS(5)
      COMMON /GRAD/        TEXP        , FSUM         , TFSUM        ,
     1        T1          , T2          , PI           , B1MIN        ,
     2        HMAX        , BERM        , HMNM
      REAL                 LMAX
      IT = T
      WRITE (6,140)
      WRITE (6,150) J,HMINI,DELH
      WRITE (6,160) NDIS,NGS,NIRR,NCROPS,NDFC,NDRD,IT,HSAT,ECIRR,ECS,SFK
     11,SFK2,X,PHICR
      WRITE (6,170)
      WRITE (6,180)
      WRITE (6,190) (IRDAY(I),QIRR(I),GAMMA(I),I = 1,NIRR)
      IF (ICHNG.EQ.1) GO TO 100
      WRITE (6,200)
      GO TO 110
  100 WRITE (6,210) PHIRR
  110 CONTINUE
      WRITE (6,220)
      WRITE (6,230) FLNTH,FWDTH,FSLPE,DIMP,SYA,HYDK,SMBEG,ECRZI
      WRITE (6,240)
```

```
      WRITE (6,250) (Z(I),SMC(I),I = 1,NSMIN)
      WRITE (6,260)
      WRITE (6,270) (ZQ(I),Q(I),I = 1,NQS)
      WRITE (6,280)
      WRITE (6,290) (I,JCROP(I),YM(I),I = 1,NCROPS)
      WRITE (6,300)
      WRITE (6,320) (I,IGSB(I),YK(I),I = 1,NGS)
      WRITE (6,310)
      WRITE (6,330) (INDAY(I),OPTRD(I),I - 1,NRDIN)
      IF (J.EQ.0.OR.J.EQ.2) GO TO 120
      WRITE (6,340)
      WRITE (6,350) (C1(I),I = 1,10)
      WRITE (6,360) RMIN,RN1,RATE1,DPM
  120 IF (J.EQ.0.OR.J.EQ.1) GO TO 130
      WRITE (6,370)
      WRITE (6,380) (C2(I),I = 1,3)
      WRITE (6,390) RN2,SSLPE,VMAX,B1MIN,HMAX,BERM,HMNM
  130 RETURN
C
  140 FORMAT (1H0, 10HINPUT DATA,/1H ,10(  1H=)//)
  150 FORMAT (1H0,  3HJ =,I2,8X, 14HINITIAL HMIN =,F6.2,,1X,  2HCM,5X, 1
     15HHMIN INTERVAL =,F6.2)
  160 FORMAT (1H0, 23HNO. OF DAYS IN SEASON =,I5,12X, 22HNO. OF GROWTH S
     1TAGES =,I5/1H , 20HNO. OF IRRIGATIONS =,I5,15X, 14HNO. OF CROPS =,
     2I5/1H , 31HNO. OF DAYS TO FIELD CAPACITY =,I5,4X, 30HNO. OF DAYS U
     3NTIL ROOT DEATH =,I5/1H ,  8HPERIOD =,I5,27X, 26HSATURATED HT. ABO
     4VE W.T. =,F5.1,  2HCM,/1H , 28HEC OF THE IRRIGATION WATER =,F5.2,7
     5X,  5HECS =,F5.2,1X, 12HMMHOS PER CM,/1H , 19HSHAPE FACTORS: K1 =,
     6F5.2,3X,  4HK2 =,F5.2,4X,  9HSEWX: X =,F8.2/1H , 14HPHI CRITICAL =
     7,F5.2)
  170 FORMAT (1H0, 19HIRRIGATION SCHEDULE,/1H ,19(  1H-))
  180 FORMAT (1H0,4X,  3HDAY,5X, 12HQUANTITY(CM),4X,  5HGAMMA)
  190 FORMAT (1H ,3X,I4,8X,F6.2,9X,F5.3)
  200 FORMAT (1H0, 12HNOTE:ICHNG=0)
  210 FORMAT (1H0, 22HNOTE:ICHNG=1    PHIRR =,F5.2)
  220 FORMAT (1H0, 34HFIELD GEOMETRY AND SOIL PROPERTIES,/1H ,34(  1H-))
  230 FORMAT (1H0, 14HFIELD LENGTH =,F9.2,1X,  6HMETERS,10X, 13HFIELD WI
     1DTH =,F9.2,1X,  6HMETERS,/1H , 13HFIELD SLOPE =,F8.5,19X, 28HDEPTH
     2 TO IMPERMEABLE LAYER =,F8.2,1X,  6H CMS  ,/1H , 25HAPPARENT SPECI
     3FIC YIELD =,F5.3,10X, 24HHYDRAULIC CONDUCTIVITY =,F6.2,1X, 10HCM P
     4ER DAY,/1H , 23HINITIAL SOIL MOISTURE =,F5.3,12X, 18HINITIAL SALIN
     5ITY =,F6.3,1X, 12HMMHOS PER CM)
  240 FORMAT (1H0, 22HSOIL MOISTURE PROFILE:,6X,  1HZ,7X,  3HSMC)
  250 FORMAT (22X,F8.3,2X,F8.5)
  260 FORMAT (1H0,  7HUPFLOW:,6X,  1HZ,6X,  4HQLIM)
  270 FORMAT (8X,F8.3,2X,F8.5)
  280 FORMAT (1H0,  9HCROP DATA,/1H ,9(  1H-))
  290 FORMAT (1H ,  4HCROP,I2,1X, 14HPLANTED ON DAY,I4,1X,  1H,, 17HMAXI
     1MUM YIELD  IS,F6.2)
  300 FORMAT (1H0,3X, 12HGROWTH STAGE,5X,  9HFIRST DAY,7X,  2HYK)
  310 FORMAT (1H0, 16HROOT DEPTHS(CM):,5X, 16HDAY   ROOT DEPTH)
  320 FORMAT (1H ,I8,17X,I3,6X,F5.2)
  330 FORMAT (21X,I3,5X,F6.2)
  340 FORMAT (1H0, 17HCLOSED DRAIN DATA,/1H 17(  1H=))
```

```
350 FORMAT (1H0, 13HCOSTS:    C1 =,F8.4,1X, 17HDOLLARS PER METER,/1H,,9
   1X,  4HC2 =,F8.4,1X, 24HDOLLARS PER METER PER CM,/1H ,9X,  4HC3 =,F
   28.4,1X, 32HDOLLARS PER METER PER CM SQUARED,/1H ,9X,  4HC4 =,F8.4,
   31X, 17HDOLLARS PER METER,/1H ,9X,  4HC5 =,F8.4,1X, 26HDOLLARS PER
   4METER PER YEAR,/1H ,9X,  4HC6 =,F8.4,1X,  7HDOLLARS,/1H ,9X,  4HC7
   5 =,F8.4,1X,  7HDOLLARS,/1H ,9X,  4HC8 =,F8.4,1X, 17HDOLLARS PER ME
   6TER,/1H ,9X,  4HC9 =,F8.4,1X, 25HDOLLARS PER METER SQUARED,/1H ,9X
   7,  4HC10=,F8.4,1X,  7HDOLLARS)
360 FORMAT (1H0,  6HRMIN =,F8.4,1X,  2HCM,/1H0, 32HMANNINGS ROUGHNESS
   1COEFFICIENT =,F6.4/1H0,  6HRATE =,F6.4/1H0, 22HDISTANCE PER MANHOL
   2E =,F8.2,1X,  6HMETERS)
370 FORMAT (1H0, 15HOPEN DITCH DATA,/1H ,15(  1H=))
380 FORMAT (1H0, 13HCOSTS:    C1 =,F8.4,1X, 23HDOLLARS PER METER CUBED,
   1/1H ,9X,  4HC2 =,F8.4,1X, 25HDOLLARS PER METER SQUARED,/1H ,9X,  4
   2HC3 =,F8.4,1X, 26HDOLLARS PER METER PER YEAR)
390 FORMAT (1H0, 32HMANNINGS ROUGHNESS COEFFICIENT =,F6.4/1H0, 18HDITC
   1H SIDE SLOPE =,F6.4/1H0, 28HMAXIMUM ALLOWABLE VELOCITY =,F8.4,1X,
   217HMETERS PER SECOND,/1H0, 22HMINIMUM BOTTOM WIDTH =,F6.2,1X,  6HM
   3ETERS,/1H0, 20HMAXIMUM FLOW DEPTH =,F8.4,1X,  6HMETERS,/1H0, 12HBE
   4RM WIDTH =,F8.4,1X,  6HMETERS,/1H0, 20HMINIMUM FLOW DEPTH =,F8.4,1
   5X,  6HMETERS)
    END
```

```
      SUBROUTINE SERIES (DSPCE,IT,ALPHA)
C
C     ******************************************************************
C     THIS SUBROUTINE COMPUTES THE INFINITE SERIES IN THE DYNAMIC
C     EQUILIBRIUM EQUATIONS
C     ******************************************************************
C
      COMMON /MISC/          NDIS          , NGS          , NIRR         ,
     1        NCROPS       , INOUT
      COMMON /SER/           TSUM(731)     , WTH(731)     , ZERO
      PI = 3.14159
      A = ((PI *  * 2) * ALPHA)/(DSPCE *  * 2)
      TEXP1 = EXP(A)
      X = 1.0/TEXP1
      TEMP2 = X *  * IT
      ZERO = 1.0
      DO 140 NTAU = 1,NDIS
 100     IC = 0
         SIGN = 0.0 - 1.0
         SUM = 0.0
         YN = 0.0
 110     YN = YN + 1.0
         IC = IC + 1
         IF (IC.GT.5) GO TO 130
         YM = YN * 2.0 - 1.0
         YM2 = YM *  * 2
         SIGN = SIGN * ( - 1.0)
         DSUM = SUM
         TEMP1 = X *  * NTAU
         IF (YM.GT.5.0) TEMP3 = 0.0
         IF (YM.GT.5.0) GO TO 120
         TEMP3 = TEMP2 *  * YM2
 120     SUM = SUM + (SIGN * TEMP1 *  * YM2)/(YM * (1.0 - TEMP3))
         TDEL = SUM - DSUM
         DEL = ABS(TDEL)
         IF (DEL.GT.0.0001) GO TO 110
 130     IF (ZERO.EQ.0.0) GO TO 150
         TSUM(NTAU) = SUM
 140 CONTINUE
     ZERO = 0.0
     NTAU = 0
     GO TO 100
 150 ZERO = SUM
     RETURN
     END
```

```
      SUBROUTINE WTGRAPH (DSPCE,DDPTH,IT,ALPHA)
C
C     ******************************************************************
C     THIS SUBROUTINE DETERMINES THE WATER TABLE HYDROGRAPH
C     ******************************************************************
C
      COMMON /SER/          TSUM(731)    , WTH(731)     , ZERO
      COMMON /WBAL/         RD(731)      , ET(731)      , INDAY(50)    ,
     1        OPTRD(50)    , DTW(731)    , NRDIN        , FL
      COMMON /SOIL/         HYDK         , SMFC         , SMWP         ,
     1        NDFC         , SMBEG       , SYA
      COMMON /IRR/          IRDAY(50)    , QIRR(50)     , DP(50)
      COMMON /MISC/         NDIS         , NGS          , NIRR         ,
     1        NCROPS       , INOUT
      COMMON /SHAPE/        SFK1         , SFK2         , T
      WTMAX = 0.0
      PI = 3.14159
      DO 130 I = 1,NDIS
         SUM = 0.0
         DO 100 J = 1,NIRR
            NTAU = I - IRDAY(J)
            IF (NTAU.EQ.0) GO TO 110
            IF (NTAU.LE.0) GO TO 100
            SUM = SUM + DP(J) * TSUM(NTAU) * 4.0/(PI * SYA)
  100    CONTINUE
         GO TO 120
  110    SUM = SUM + (DP(J) * 4.0 * ZERO)/(PI * SYA)
  120    WTH(I) = SUM
         IF (I.EQ.IRDAY(NIRR)) WTMAX = WTH(I)
         DTW(I) = DDPTH - WTH(I)
  130 CONTINUE
C
C     ******************************************************************
C     THIS SECTION CHECKS THE APPROXIMATION FOR THE MAXIMUM ALLOWABLE
C     MIDSPAN WATER TABLE HEIGHT USED IN SUBROUTINES OPT AND GRAD.
C     IF THE DIFFERENCE IS GREATER THAN 1%, NO CHANGE IS MADE BUT THE
C     USER IS ALERTED AND ASKED TO CHANGE SFK1.  THIS SECTIONS ALSO
C     CHECKS TO SEE IF THE MAXIMUM WATER TABLE HEIGHT OCCURRED AT
C     THE END OF THE SEASON.
C     ******************************************************************
C
      SUM = 0.0
      A = EXP(( - 1.0) * PI *  * 2 * ALPHA/DSPCE *  * 2)
      DO 140 I = 1,NIRR
         IDAY = IRDAY(I)
         PERK = DP(I)
         NTAU = IRDAY(NIRR) - IDAY
         SUM = SUM + PERK * A *  * NTAU
         IF (WTH(I).GT.WTMAX) WTMAX = WTH(I)
  140 CONTINUE
      CWTH = (8.0 * SUM)/((PI *  * 2 * SFK1 * SYA) * (1.0 - A *  * IT))
      CWTH = CWTH + (PERK/SYA) * (1.0 - 1.0/SFK1)
      K = 0
```

```
      CHECK = CWTH - WTMAX
      IF (CHECK.LT.0.0) K = 1
      CHECK = ABS(CHECK)
      IF (CHECK.LT.0.01 * WTMAX) GO TO 170
      IF (K.EQ.0) GO TO 150
      WRITE (6,220) CHECK
      GO TO 160
  150 WRITE (6,200) CHECK
  160 WRITE (6,210)
  170 WRITE (6,190) CWTH,WTMAX
      ICDAY = IRDAY(NIRR)
      IF (WTMAX.GT.WTH(ICDAY)) WRITE (6,180)
      RETURN
C
  180 FORMAT (1H0,64H THE MAXIMUM W.T. HEIGHT DOES NOT OCCUR AT THE END
     1OF THE SEASON)
  190 FORMAT (1H0,14H APPROX HCMAX=,F10.4,14H ACTUAL HCMAX=,F10.4)
  200 FORMAT (1H0,24H THE APPROX FOR HCMAX IS,F10.4,9H TOO HIGH)
  210 FORMAT (1H0,42H CHANGE SFK1 IF BETTER ACCURACY IS DESIRED)
  220 FORMAT (1H0,24H THE APPROX FOR HCMAX IS,F10.4,8H TOO LOW)
      END
```

```
      SUBROUTINE SUMS (X,A,B)
C
C     ******************************************************************
C     THIS SUBROUTINE SUMS THE OUTPUT FOR ET AND SALINITY FROM RTZ.
C     IF THE USER WANTS ANY OTHER INFORMATION SUMMARIZED, THIS
C     SUBROUTINE CAN BE EXPANDED.
C     ******************************************************************
C
      COMMON /MISC/          NDIS         , NGS          , NIRR         ,
     1        NCROPS       , INOUT
      COMMON /SER/           TSUM(731)    , WTH(731)     , ZERO
      COMMON /SOIL/          HYDK         , SMFC         , SMWP         ,
     1        NDFC         , SMBEG        , SYA
      COMMON /EC/            ECMAX(30,3)  , ECRZ(731)    , ECRZI        ,
     1        ECS          , ECIRR
      COMMON /GS/            IGSB(30)     , ETP(731)     , CKO(731)     ,
     1        GAMMA(30)    , YK(30)       , YA(5)        , YM(5)        ,
     2        JCROP(5)
      COMMON /MOIS/          AW(731)      , SM(731)      , Z(20)        ,
     1        SMC(20)      , NSMIN        , PHICR        , PHIRR        ,
     2        ICHNG
      COMMON /WBAL/          RD(731)      , ET(731)      , INDAY(50)    ,
     1        OPTRD(50)    , DTW(731)     , NRDIN        , FL
      COMMON /SUM/           ETMAX(30)    , ETSUM(30)    , ECSUM(30,3)
      INTEGER                SSMD         , ESUM
      ISUM = 0
      ESUM = 0
      SSMD = 0
      DO 100 I = 1,NDIS
         IF (SM(I).LE.SMWP) SSMD = SSMD + 1
         XCHEK = DTW(I)
         IF (XCHEK.GE.X) GO TO 100
         ISUM = ISUM + 1
  100 CONTINUE
      WRITE (6,160) X,ISUM
      WRITE (6,170) SSMD
      I = 1
      DO 130 K = 1,NDIS
         IF (I.EQ.NGS) GO TO 110
         IF (K.EQ.IGSB(I + 1)) I = I + 1
  110    DO 120 J = 1,3
            ECTEMP = ECRZ(K)
            N = 4 - J
            IF (ECTEMP.LE.ECMAX(I,N)) GO TO 200
            GO TO 120
  200       ECSUM(I,N)=ECSUM(I,N)+1.0
  120    CONTINUE
         ETSUM(I) = ETSUM(I) + ET(K)
         ETM = CKO(K) * ETP(K)
         ETMAX(I) = ETMAX(I) + ETM
  130 CONTINUE
C
C     ******************************************************************
```

```
C     THIS SECTION COMPUTES THE EQUATION FOR YIELD REDUCTION DUE TO
C     SALINITY GIVEN BY MASS AND HOFFMAN.
C     ***********************************************************************
C
      SUM = 0.0
      DO 140 I = 1,NDIS
         SUM = SUM + ECRZ(I)
  140 CONTINUE
      DIS = NDIS
      SUM = SUM/DIS
      Y = B * (SUM - A)
      WRITE (6,190) Y
      DO 150 K = 1,NDIS
         ETM = CKO(K) * ETP(K)
         IF (ET(K).LT.(ETM - .0001)) ESUM = ESUM + 1
  150 CONTINUE
      WRITE (6,180) ESUM
      RETURN
C
  160 FORMAT (1H0,35H THE SUM OF EXCESS WATER DAYS ABOVE,F10.2,3H IS,I5)
  170 FORMAT (1H0,46H THE SOIL MOISTURE CONTENT IS AT WILTING POINT,I5,5
     1H DAYS)
  180 FORMAT (1H0,26H ET IS LESS THAN POTENTIAL,I5,5H DAYS)
  190 FORMAT (1H0,57H YIELD REDUCTION DUE TO SALINITY, PER MAAS,ET.AL.,1
     1977 IS,F6.2,8H PERCENT)
      END
```

```
      SUBROUTINE PREOPT (J,HMIN,IP,SCM2,SCM3)
C
C     ******************************************************************
C     SUBROUTINE PREOPT COMBINES THE TEN COST COEFFICIENTS FOR CLOSED
C     DRAINS INTO FOUR AND CONVERTS UNITS.
C     ******************************************************************
C
      COMMON /LIMIT/        DIMP        , FLNTH       , FWDTH       ,
     1        VMAX        , RN          , FSLPE       , SSLPE       ,
     2        B1          , DMAX
      COMMON /DCOST/        C1(10)      , C2(3)       , RATE        ,
     1        CM(12)      , DPM         , DDEDD       , DEL2        ,
     2        DEL3
      COMMON /SHAPE/        SFK1        , SFK2        , T
      COMMON /SOIL/         HYDK        , SMFC        , SMWP        ,
     1        NDFC        , SMBEG       , SYA
      IF (J.EQ.2) GO TO 110
C
C     ******************************************************************
C     J=1:CLOSED DRAIN COEFIICIENTS FOR Z
C     COST ARRAY FOR CLOSED DRAINS
C       C1(1)+C1(2)*DIAMETER+C1(3)*DIAMETER**2=THE MATERIAL COST
C          OF THE DRAINS AS A QUADRATIC FUNCTION OF THE DIAMETER--
C          EVALUATED IN LSQR
C       C1(4)=THE COST OF THE FILTER PER LENGTH OF DRAIN
C       C1(5)=MAINTENANCE COST PER LENGTH OF DRAIN PER YEAR
C       C1(6)=COST OF ONE MANHOLE----DPM=DISTANCE PER MANHOLE
C       C1(7)=FIXED COST OF INSTALLING DRAINS,I.E.MINIMUM COST
C       C1(8)+C1(9)*DEPTH=VARIABLE COST OF INSTALLATION PER LENGTH
C          OF DRAIN EXPRESSED AS A LINEAR FUNCTION OF DEPTH
C       C1(10)=COST OF ONE OUTLET STRUCTURE
C
C       RATE=DISCOUNT RATE PER YEAR
C
C     ******************************************************************
C
      FLNTH = FLNTH/100.
      CM(1) = RATE * (C1(1) + C1(4) + C1(6)/DPM + C1(7)/FLNTH + C1(8) +
     1C1(10)/FLNTH) + C1(5)
      CM(2) = RATE * C1(2)
      CM(3) = RATE * C1(3)
      CM(4) = RATE * C1(9)/100.
      K = 0
      IP = 0
      FLNTH = FLNTH * 100.
      CM(1) = CM(1)/100.
      DO 100 I = 2,4
         CM(I) = CM(I)/100.
         IF (CM(I).EQ.0.0) K = K + 1
  100 CONTINUE
      SCM2 = CM(2)
      SCM3 = CM(3)
      IF (K.EQ.3) WRITE (6,120)
```

```
      IF (K.EQ.3) IP = 1
  110 RETURN
C
  120 FORMAT (1H0,91H THE OBJ FUNCTION IS A LINEAR FUNCTION OF L**-1,I.E
     1. INDEPENDENT OF THE DEPTH OF THE DRAINS)
      END
```

```
      SUBROUTINE OPT (J,DSPCE,DDPTH,HMIN,EPS,RMIN,R,Q1,D,DE,ALPHA,LMAX,Z
     1,IP,SCM2,SCM3)
C
C     ****************************************************************
C     SUBROUTINE OPT IS THE MAIN SUBROUTINE IN THE LEAST COST ANALYSIS.
C     SUBROUTINES GRAD1,GRAD2,ALPH1 AND ALPH2 ARE CALLED FROM OPT.
C     ***************************************************************
C
      COMMON /IRR/          IRDAY(50)    , QIRR(50)     , DP(50)
      COMMON /MISC/         NDIS         , NGS          , NIRR         ,
     1        NCROPS       , INOUT
      COMMON /GRAD/         TEXP         , FSUM         , TFSUM        ,
     1        T1           , T2           , PI           , B1MIN        ,
     2        HMAX         , BERM         , HMNM
      COMMON /SHAPE/        SFK1         , SFK2         , T
      COMMON /SOIL/         HYDK         , SMFC         , SMWP         ,
     1        NDFC         , SMBEG        , SYA
      COMMON /LIMIT/        DIMP         , FLNTH        , FWDTH        ,
     1        VMAX         , RN           , FSLPE        , SSLPE        ,
     2        B1           , DMAX
      COMMON /PLOT/         IJT          , IJJ          , IJP          ,
     1        A1(3000,8)
      COMMON /DCOST/        C1(10)       , C2(3)        , RATE         ,
     1        CM(12)       , DPM          , DDEDD        , DEL2         ,
     2        DEL3
      DIMENSION             TAU(50)      , TL(100)
      REAL                  LINIT        , LMAX         , INT
C
C     ****************************************************************
C     INITIALIZATION
C     ****************************************************************
C
      LINIT = 0.0
      R = 0.0
      HMNM = .4
      DL = 0.0
      DH = DMAX
      VALU = 0.0
      H = 0.0
      ICK = 0
      SUMI = 0.0
      DO 100 I = 1,NIRR
  100 SUMI = SUMI + DP(I)
      DO 110 I = 1,NIRR
  110 TAU(I) = IRDAY(NIRR) - IRDAY(I)
      PI = 3.14159
      T1 = 8.0/(PI *  * 2 * SYA * SFK1)
      T2 = DP(NIRR) * (1.0 - 1.0/SFK1)/SYA
      D1 = DDPTH
      I = 1
      STORE = 1000.
      IPSTOR = 1
C
```

```
C     ******************************************************************
C     COMPUTE THE MAXIMUM ALLOWABLE SPACING LMAX EQUAL TO THE LARGER OF
C     THE FIELD WIDTH AND THE SPACING CORRESPONDING TO A DRAIN ON THE
C     IMPERMEABLE BARRIER OR LIMITED BY DMAX.
C     ******************************************************************
C
      IF (LMAX.NE.0.0) GO TO 120
      DIS = NDIS
      ROOT = SQRT(SUMI/(12.0 * HYDK * DIS))
      ROOT2 = SQRT((DMAX - HMIN) * (DIMP - HMIN))
      LMAX = (DIMP - HMIN)/ROOT
      IF (DMAX.NE.DIMP) LMAX = ROOT2/ROOT
      IF (LMAX.GT.FWDTH) LMAX = FWDTH
      HINIT = LMAX
      IF (INOUT.EQ.2.AND.LMAX.EQ.FWDTH) WRITE (6,200)
      IF (INOUT.EQ.2.AND.LMAX.LT.FWDTH) WRITE (6,210)
      IF (INOUT.EQ.2) WRITE (6,220) LMAX
      DSMAX = LMAX
      IF (DSPCE.GT.LMAX) DSPCE = LMAX/1.1
C
C     ******************************************************************
C     THE PROGRAM ITERATES IN THIS SECTION UNTIL ALPHA AND DDPTH
C     CORRESPOND TO L.  ALPHA IS APPROXIMATED INITIALLY IGNORING CONVER-
C     GENCE AND DDPTH IS COMPUTED.  USING THIS NEW ESTIMATE OF DDPTH,
C     THE EFFECTIVE DEPTH AND ALPHA ARE RECOMPUTED AND SO FORTH UNTIL
C     THE CHANGE IN DDPTH IS LESS THAN 1 PERCENT.
C     ******************************************************************
C
  120 IF (DMAX.LE.DDPTH) DDPTH = DMAX - RMIN
      DE = DIMP - DDPTH
      B = SUMI * DSPCE *  * 2/(12.0 * HYDK * T)
      C = SQRT(B + DE *  * 2/4.0)
      D = DE * 0.5 + C
      ALPHA = HYDK * D/SYA
  130 IF (I.GE.500) GO TO 190
      IF (DDPTH.GE.DMAX.AND.DSPCE.NE.LMAX) DSPCE = DSPCE/1.1
      IF (DDPTH.GT.DMAX) DDPTH = DMAX
      IF (DDPTH.EQ.DMAX) DDPTH = DMAX
  140 TFSUM = 0.0
      FSUM = 0.0
      D2 = D1
      A = (PI *  * 2 * T * ALPHA)/DSPCE *  * 2
      DO 150 M = 1,NIRR
         X = A * TAU(M)/T
         TEXP = EXP( - X)
         TEMP = TEXP * DP(M)
         TFSUM = TFSUM + TAU(M) * TEMP
  150 FSUM = FSUM + TEMP
      ICK = ICK + 1
      IF (ICK.GT.500) GO TO 190
      TEXP = EXP( - A)
      FSUM = FSUM/(1.0 - TEXP)
      TFSUM = TFSUM/(1.0 - TEXP)
      D1 = HMIN + T1 * FSUM + T2
```

```
      DDPTH = D1
      DEL = ABS(D1 - D2)
      DDPTH = (D1 + D2)/2.0
      IF (DDPTH.GT.DMAX.AND.DSPCE.NE.LMAX) GO TO 130
      IF (DDPTH.LE.HMIN) DDPTH = HMIN
      DELL = D
C
C     ******************************************************************
C     CALL SUBROUTINE ALPH1 FOR CLOSED DRAINS AND ALPH2 FOR OPEN.
C     ******************************************************************
C
      IF (J.EQ.1) CALL ALPH1 (J,DSPCE,DDPTH,SUMI,ALPHA,DE,D,Q1,HMIN,R,RM
     1IN)
      IF (J.EQ.2) CALL ALPH2 (J,DSPCE,DDPTH,H,SUMI,ALPHA,DE,D,Q1,HMIN,R,
     1RMIN,VEL)
      SR = R
      SFSUM = FSUM
      D = ALPHA * SYA/HYDK
      DELTA = ABS(DELL - D)
      IF (DELTA.GE.0.001 * D) GO TO 140
      IF (DEL.GT.(0.001 * DDPTH)) GO TO 140
C
C     ******************************************************************
C     THE CONSTRAINED DERIVATIVE OF THE OBJECTIVE FUNCTION IS COMPUTED
C     IN GRAD AND RETURNED AS VALU...CONVERGENCE IS ASSUMED IF ABS(VALU)
C     IS LESS THAN 0.0001..AND ABS(VALU)IS LESS THAN 0.1% OF Z.
C     ******************************************************************
C
      IF (J.EQ.1) CALL GRAD1 (HMIN,DSPCE,DDPTH,D,ALPHA,DE,R,SUMI,VALU,Z,
     1SCM2,SCM3,RMIN)
      IF (J.EQ.2) CALL GRAD2 (HMIN,DSPCE,DDPTH,D,ALPHA,DE,R,SUMI,VALU,Z,
     1H,VEL)
      DEL = 0.0
      IF (Z.LT.STORE) STORE = Z
      IF (Z.EQ.STORE) STGRAD = VALU
      IF (Z.EQ.STORE) STORS = DSPCE
      IF (IPSTOR.EQ.0) DSPCE = DSPCE + INT
      IF (DSPCE.GE.DSMAX) GO TO 180
      IF (IPSTOR.EQ.0) GO TO 120
      IF (VALU.GT.0.0) GO TO 160
C
C     ******************************************************************
C     THE CONSTRAINED DERIVATIVE O F THE OBJECTIVE FUNCTION WITH RESPECT
C     TO L IS NEGATIVE...INCREASE L
C     ******************************************************************
C
      LINIT = DSPCE
      DL = DDPTH
      TL(I) = DSPCE
      IF (TL(I).EQ.TL(I - 1)) GO TO 190
      IF (I.GT.3) DIFF = ABS(TL(I) - TL(I - 2))
      IF (I.GT.3.AND.DIFF.LE.0.001 * DSPCE) GO TO 190
      DDPTH = 0.5 * (DDPTH + DH)
      IF (DSPCE.GE.LMAX.OR.DDPTH.GE.(DMAX - RMIN)) GO TO 190
```

```
      IF (J.EQ.2.AND.DDPTH.GE.(DMAX - HMNM * 100.)) GO TO 190
      IF (DDPTH.LE.DL) GO TO 190
      DSPCE = 0.5 * (HINIT + DSPCE)
      IF (DH.EQ.DMAX) DDPTH = DL
      GO TO 170
C
C     ******************************************************************
C     THE DERIVATIVE OF Z WITH RESPECT TO L IS POSITIVE...DECREASE L
C     ******************************************************************
C
  160 HINIT = DSPCE
      DH = DDPTH
      TL(I) = DSPCE
      DSPCE = 0.5 * (LINIT + DSPCE)
      DDPTH = 0.5 * (DDPTH + DL)
  170 DEL = ABS(DSPCE - TL(I))
      I = I + 1
C
C     ******************************************************************
C     CHECK...IF THE CHANGE IN L IS GREATER THAN 1 PERCENT OR GREATER
C     THAN EPS, REITERATE TO CHANGE L
C     ******************************************************************
C
      EPS1 = 0.01 * DSPCE
      IF (DEL.GT.EPS1.OR.DEL.GT.EPS) GO TO 120
      IPSTOR = 0
      IF (STORE.EQ.DSPCE) GO TO 190
      INT = 0.001 * DSPCE
      DSPCE = DSMAX
      IF (STORS.LE.DSPCE) DSPCE = STORS - (DSPCE - STORS)
      IF (DSMAX.LE.DSPCE) DSMAX = DSPCE
      GO TO 120
  180 DSPCE = STORS
      Z = STORE
      VALU = STGRAD
      DEL = 0.001 * DSPCE
  190 IF (INOUT.EQ.2) WRITE (6,230) VALU
      IF (INOUT.EQ.2) WRITE (6,240) DEL
      IF (INOUT.EQ.2) WRITE (6,250) DSPCE,HMIN
      IF (R.EQ.0.0) R = SR
      IF (FSUM.EQ.0.0) FSUM = SFSUM
      RETURN
C
  200 FORMAT (1H0,56H THE MAXIMUM DRAIN SPACING IS LIMITED BY THE FIELD
     1WIDTH)
  210 FORMAT (1H0,69H THE MAXIMUM DRAIN SPACING IS LIMITED BY THE MAX FE
     1ASIBLE DRAIN DEPTH)
  220 FORMAT (1H0,7H LMAX= ,F10.3)
  230 FORMAT (1H0,21H THE GRADIENT OF Z IS,E20.5)
  240 FORMAT (1H0,24H THE LAST CHANGE IN L IS,E20.5)
  250 FORMAT (1H0,7H DSPCE=,F10.3,10H FOR HMIN=,F10.3)
      END
```

```
      SUBROUTINE GRAD1 (HMIN,DSPCE,DDPTH,D,ALPHA,DE,R,SUMI,VALU,Z,SCM2,S
     1CM3,RMIN)
C
      COMMON /SHAPE/          SFK1          , SFK2          , T
      COMMON /GRAD/           TEXP          , FSUM          , TFSUM         ,
     1         T1             , T2          , PI            , B1MIN         ,
     2         HMAX           , BERM        , HMNM
      COMMON /PLOT/           IJT           , IJJ           , IJP           ,
     1         A1(3000,8)
      COMMON /SOIL/           HYDK          , SMFC          , SMWP          ,
     1         NDFC           , SMBEG       , SYA
      COMMON /LIMIT/          DIMP          , FLNTH         , FWDTH         ,
     1         VMAX           , RN          , FSLPE         , SSLPE         ,
     2         B1             , DMAX
      COMMON /DCOST/          C1(10)        , C2(3)         , RATE          ,
     1         CM(12)         , DPM         , DDEDD         , DEL2          ,
     2         DEL3
      COMMON /MISC/           NDIS          , NGS           , NIRR          ,
     1         NCROPS         , INOUT
      DIMENSION               DEL(5,5)
      DO 110 I = 1,3
         DO 100 J = 1,3
            DEL(I,J) = 0.0
  100    CONTINUE
  110 CONTINUE
      IF (INOUT.EQ.2) WRITE (6,140) DSPCE,DDPTH,D,DE,ALPHA
C
C     ******************************************************************
C     COMPUTE THE MATRIX OF FIRST DERIVATIVES OF THE OBJECTIVE
C     FUNCTION AND CONSTRAINTS
C     ******************************************************************
C
      F1 = D *  * 0.375
      HC = DDPTH - HMIN
      CM(2) = SCM2 * 2.008 * (HYDK * SFK2 * RN/FSLPE *  * 0.5) *  * 0.37
     15/126.24
      CM(3) = SCM3 * 4.032 * (HYDK * SFK2 * RN/FSLPE *  * 0.5) *  * 0.75
     1/15936.5
      TEMP2 = DIMP - DDPTH
      RATIO = TEMP2/DSPCE
      TEMP1 = ALOG(TEMP2/R)
      DDEDL = DE *  * 2 * (8.0 * TEMP1/PI - 3.55 + 3.2 * TEMP2/DSPCE - 6
     1.0 * TEMP2 *  * 2/DSPCE *  * 2)/DSPCE *  * 2
      IF (RATIO.GT.0.3) DDEDL = DE * (1.0 - 8.0 * DE/(DSPCE * PI))/DSPCE
      DDEDD = ( - 1.0 * DE/TEMP2) * (1.0 - DE/DSPCE * (8.0 * TEMP1/PI -
     13.55 + 3.2 * TEMP2/DSPCE - 6.0 * TEMP2 *  * 2/DSPCE *  * 2 + 8.0/P
     2I))
      IF (RATIO.GT.0.3) DDEDD = 0.
      IF (R.EQ.RMIN) GO TO 120
      DEL(1,1) = 0.0 - 1.0 * (CM(1) + CM(4) * DDPTH)/DSPCE *  * 2 - 1.37
     15 * CM(2) * F1 * HC *  * 0.375/DSPCE *  * 2.375 - 1.75 * F1 *  * 2
     2 * HC *  * 0.75 * CM(3)/DSPCE *  * 2.75
      DEL(1,2) = 0.375 * CM(2) * F1/(HC *  * 0.625 * DSPCE *  * 1.375) +
```

```
     1 0.75 * CM(3) * F1 *  * 2/(HC *  * 0.25 * DSPCE *  * 1.75) + CM(4)
     2/DSPCE
      DEL(1,3) = 0.375 * CM(2) * HC *  * 0.375/(DSPCE *  * 1.375 * D *
     1* 0.625) + 0.75 * CM(3) * HC *  * 0.75/(DSPCE *  * 1.75 * D *  * 0
     2.25)
      GO TO 130
  120 DEL(1,1) = ( - 1.0) * (CM(1) + SCM2 * 2.0 * R + SCM3 * 4.0 * R *
     1* 2 + CM(4) * DDPTH)/DSPCE *  * 2
      DEL(1,2) = CM(4)/DSPCE
      DEL(1,3) = 0.0
  130 DEL(2,1) = 0.0 - 2.0 * T1 * ALPHA * PI *  * 2 * (TFSUM + T * TEXP
     1* FSUM/(1.0 - TEXP))/DSPCE *  * 3
      DEL(2,2) = 1.0
      DEL(2,3) = T1 * HYDK * PI *  * 2 * (T * TEXP * FSUM/(1. - TEXP) +
     1TFSUM)/(SYA * DSPCE *  * 2)
      F = DE *  * 2 + SUMI * DSPCE *  * 2/(3.0 * HYDK * T)
      DEL(3,1) = ( - 0.5 * DDEDL) - 0.5 * (DE * DDEDL + SUMI * DSPCE/(3.
     10 * HYDK * T))/F *  * 0.5
      DEL(3,2) = ( - 0.5 * DDEDD) - DDEDD * DE/(2.0 * F *  * 0.5)
      DEL(3,3) = 1.0
C
C     ******************************************************************
C     COMPUTE THE CONSTRAINED DERIVATIVE OF THE OBJECTIVE
C     FUNCTION AND THE VALUE OF Z.
C     ******************************************************************
C
      DELT3 = (DEL(3,2) * DEL(2,1) - DEL(3,1))/(DEL(3,3) - DEL(3,2) * DE
     1L(2,3))
      DELT2 = 0.0 - DEL(2,1) - DEL(2,3) * DELT3
      VALU = (DEL(1,1) + DEL(1,2) * DELT2 + DEL(1,3) * DELT3) * 10000.
      Z = ((CM(1) + SCM2 * 2.0 * R + SCM3 * 4.0 * R *  * 2 + CM(4) * DDP
     1TH)/DSPCE) * 10000.
      DEL2 = DEL(1,2)
      DEL3 = DEL(1,3)
      IJP = IJP + 1
      A1(IJP,7) = DSPCE
      A1(IJP,8) = DDPTH
      RETURN
C
  140 FORMAT (1H0,9H SPACING=,F10.2,3H CM,7H DEPTH=,F10.2,3H CM,3H D=,F6
     1.2,3H CM,4H DE=,F6.2,3H CM,7H ALPHA=,F10.2)
      END
```

```
      SUBROUTINE ALPH1 (J,DSPCE,DDPTH,SUMI,ALPHA,DE,D,Q1,HMIN,R,RMIN)
C
      COMMON /DCOST/        C1(10)       , C2(3)        , RATE         ,
     1        CM(12)       , DPM         , DDEDD        , DEL2         ,
     2        DEL3
      COMMON /SHAPE/        SFK1         , SFK2         , T
      COMMON /GRAD/         TEXP         , FSUM         , TFSUM        ,
     1        T1           , T2          , PI           , B1MIN        ,
     2        HMAX         , BERM        , HMNM
      COMMON /SOIL/         HYDK         , SMFC         , SMWP         ,
     1        NDFC         , SMBEG       , SYA
      COMMON /LIMIT/        DIMP         , FLNTH        , FWDTH        ,
     1        VMAX         , RN          , FSLPE        , SSLPE        ,
     2        B1           , DMAX
C
C     COMPUTE THE RADIUS OF THE PIPE OR BOTTOM WIDTH OF THE OPEN DITCH.
C
      IF (J.EQ.1) GO TO 100
      R = B1/2.0
      GO TO 110
C
C     ******************************************************************
C     THIS SECTION COMPUTES THE DRAIN SIZE AND CAPACITY FOR CLOSED DRAIN
C     SFK2 IS A SHAPE FACTOR WHICH RANGES FROM PI TO 4.0
C     UNITS ARE AS FOLLOWS:
C            HYDK: CM/DAY
C            D: CM
C            HC: CM
C            FLNTH: CM
C            DSPCE: CM
C            RN: SEC/M**.333
C            R: CM
C            Q: M**3/DAY
C            Q1: M**3/DAY
C     ******************************************************************
C
  100 HC = DDPTH - HMIN
      IF (HC.LE.0.0) HC = RMIN
      VAR = (HYDK * SFK2 * D * FLNTH * HC * RN)/(DSPCE)
      R = 1.004 * VAR *  * 0.375/(FSLPE *  * 0.1875 * 126.24)
      Q = 2.0 * SFK2 * HYDK * D * HC * FLNTH/(DSPCE * 1000000.)
      Q1 = (PI * (R/100.) *  * 2.6667 * (FSLPE) *  * 0.5 * 86400.)/(2.0
     1*  * .6667 * RN)
      IF (R.LE.RMIN) R = RMIN
      IF (R.NE.RMIN) GO TO 110
      Q1 = (PI * (R/100.) *  * 2.6667 * (FSLPE) *  * 0.5 * 86400.)/(2.0
     1*  * .6667 * RN)
C
C     ******************************************************************
C     COMPUTE D AND ALPHA USING MOODYS EQUATION TO ACCOUNT FOR FLOW
C     CONVERGENCE.
C     ******************************************************************
C
```

```
  110 RATIO = (DIMP - DDPTH)/DSPCE
      IF (RATIO.LE.0.3) GO TO 130
      TLN = ALOG(DSPCE/R)
      DE = DSPCE * PI/(8.0 * (TLN - 1.15))
  120 F = SUMI * DSPCE *  * 2/(HYDK * 12.0 * T)
      ROOT = SQRT(DE *  * 2 + 4.0 * F)
      D = 0.5 * (DE + ROOT)
      ALPHA = HYDK * D/SYA
      GO TO 140
  130 TLN = ALOG((DIMP - DDPTH)/R)
      TS = (8.0 * TLN)/PI - 3.55 + 1.6 * RATIO - 2.0 * RATIO *  * 2
      DE = (DIMP - DDPTH)/(1.0 + RATIO * TS)
      GO TO 120
  140 RETURN
C
      END
```

```
      SUBROUTINE GRAD2 (HMIN,DSPCE,DDPTH,D,ALPHA,DE,R,SUMI,VALU,Z,H,VEL)
C
      COMMON /SHAPE/        SFK1        , SFK2        , T
      COMMON /GRAD/         TEXP        , FSUM        , TFSUM       ,
     1        T1           , T2         , PI          , B1MIN       ,
     2        HMAX         , BERM       , HMNM
      COMMON /SOIL/         HYDK        , SMFC        , SMWP        ,
     1        NDFC         , SMBEG      , SYA
      COMMON /LIMIT/        DIMP        , FLNTH       , FWDTH       ,
     1        VMAX         , RN         , FSLPE       , SSLPE       ,
     2        B1           , DMAX
      COMMON /DCOST/        C1(10)      , C2(3)       , RATE        ,
     1        CM(12)       , DPM        , DDEDD       , DEL2        ,
     2        DEL3
      COMMON /MISC/         NDIS        , NGS         , NIRR        ,
     1        NCROPS       , INOUT
      DIMENSION             DELT(5,5)   , DEL(5,5)    , D1(5)
C
C     ******************************************************************
C     CONVERT H AND B1 TO CENTIMETERS
C     ******************************************************************
C
      B1 = R * 2.0 * 100.
      H = H * 100.
      C2(1) = C2(1)/10000.
      C2(2) = C2(2)/100.
      DO 110 I = 1,5
         DO 100 J = 1,5
            DEL(I,J) = 0.0
  100    CONTINUE
  110 CONTINUE
C
C     ******************************************************************
C     COMPUTE THE MATRIX OF FIRST DERIVATIVES OF THE OBJECTIVE FUNCTION
C     AND CONSTRAINTS
C     ******************************************************************
C
      DEL(1,1) = (RATE * C2(1) * (B1 * H + H *  * 2 * SSLPE + B1 * DDPTH
     1 + 2.0 * H * SSLPE * DDPTH + DDPTH *  * 2 * SSLPE) + C2(2) * (2.0
     2* BERM + B1 + 2.0 * H * SSLPE + 2.0 * DDPTH * SSLPE) + C2(3))/DSPC
     3E *  * 2 * ( - 1.0)
      DEL(1,2) = 0.0
      DEL(1,3) = (RATE * C2(1) * (2.0 * H * SSLPE + 2.0 * DDPTH * SSLPE)
     1 + 2.0 * SSLPE * C2(2))/DSPCE
      DEL(1,4) = (RATE * C2(1) * (B1 + 2.0 * H * SSLPE + 2.0 * SSLPE * D
     1DPTH) + C2(2) * 2.0 * SSLPE)/DSPCE
      DEL(1,5) = ( - 1.0) * (RATE * C2(1) * (H + DDPTH) + C2(2))/DSPCE
      TEMP2 = DIMP - DDPTH
      RATIO = TEMP2/DSPCE
      TEMP1 = ALOG(TEMP2/R)
      DDEDL = DE *  * 2 * (8.0 * TEMP1/PI - 3.55 + 3.2 * TEMP2/DSPCE - 6
     1.0 * TEMP2 *  * 2/DSPCE *  * 2)/DSPCE *  * 2
      IF (RATIO.GT.0.3) DDEDL = DE * (1.0 - 8.0 * DE/(DSPCE * PI))/DSPCE
```

```
      F = DE *  * 2 + SUMI * DSPCE *  * 2/(3.0 * HYDK * T)
      DEL(2,1) = ( - 0.5 * DDEDL) - 0.5 * (DE * DDEDL + SUMI * DSPCE/(3.
     1* HYDK * T))/F *  * 0.5
      DEL(2,2) = 1.0
      DDEDD = ( - 1.0 * DE/TEMP2) * (1.0 - DE/DSPCE * (8.0 * TEMP1/PI -
     13.55 + 3.2 * TEMP2/DSPCE - 6.0 * TEMP2 *  * 2/DSPCE *  * 2 + 8.0/P
     2I))
      IF (RATIO.GT.0.3) DDEDD = 0.0
      DEL(2,3) = ( - 0.5 * DDEDD) - DDEDD * DE/(2.0 * F *  * 0.5)
      DEL(2,4) = 0.0
      DDEDB = 8.0 * DE *  * 2/(B1 * PI * DSPCE)
      IF (RATIO.GT.0.3) DDEDB = 8.0 * DE *  * 2/(DSPCE * PI * B1)
      DEL(2,5) = ( - 0.5 * DDEDB) - DDEDB * DE/(2.0 * F *  * 0.5)
      DEL(3,1) = 0.0 - 2.0 * T1 * ALPHA * PI *  * 2 * (TFSUM + T * TEXP
     1* FSUM/(1.0 - TEXP))/DSPCE *  * 3
      DEL(3,2) = T1 * HYDK * PI *  * 2 * (T * TEXP * FSUM/(1.0 - TEXP) +
     1 TFSUM)/(SYA * DSPCE *  * 2)
      DEL(3,3) = 1.0
      DEL(3,4) = 0.0
      DEL(3,5) = 0.0
      FUNC = 2.0 * SFK2 * HYDK * D * FLNTH * (DDPTH - HMIN)/(DSPCE * VEL
     1 * 1000000. * 24. * 3600.)
      DEL(4,1) = FUNC/DSPCE
      DEL(4,2) = ( - 1.0) * FUNC/D
      DEL(4,3) = 0.0
      DEL(4,4) = B1 + 2.0 * H * SSLPE
      DEL(4,5) = H
      DEL(5,1) = 0.0
      DEL(5,2) = 0.0
      DEL(5,3) = 0.0
      CONST = (VEL * RN/FSLPE *  * .5) *  * 1.5
      HYP = SQRT(1.0 + SSLPE *  * 2)
      DEL(5,4) = 2.0 * CONST * HYP - B1 - 2.0 * H * SSLPE
      DEL(5,5) = CONST - H
C
C     ******************************************************************
C     COMPUTE THE VALUE OF THE CONSTRAINED DERIVATIVE OF Z WITH RESPECT
C     TO L USING A MODIFIED GAUSS ELIMINATION PROCEDURE.
C     ******************************************************************
C
      DO 120 I1 = 2,5
         DELT(I1) = 0.0
         D1(I1) = 0.0
  120 CONTINUE
      DELT(1) = 1.0
      DO 160 I2 = 1,4
         N2 = I2 + 1
         DO 130 J2 = N2,5
            DEL(I2,J2) = DEL(I2,J2)/DEL(I2,I2)
  130    CONTINUE
         DELT(I2) = DELT(I2)/DEL(I2,I2)
         DO 150 K = N2,5
            DO 140 IK = N2,5
               DEL(K,IK) = DEL(K,IK) - DEL(K,I2) * DEL(I2,IK)
```

```
140         CONTINUE
            DELT(K) = DELT(K) - DELT(I2) * DEL(K,I2)
150      CONTINUE
160 CONTINUE
      D1(5) = DELT(5)/DEL(5,5)
      DO 180 IK = 1,3
         N = 5 - IK
         N2 = N + 1
         DO 170 K = N2,5
            D1(N) = DELT(N) - DEL(N,K) * D1(K)
170      CONTINUE
180 CONTINUE
      IF (H.EQ.HMAX.OR.H.EQ.HMNM) D1(4) = 0.0
      IF (B1.EQ.B1MIN) D1(5) = 0.0
      VALU = 1.0/(1.0/DEL(1,1) - DEL(1,2) * D1(2) - DEL(1,3) * D1(3) - D
     1EL(1,4) * D1(4) - DEL(1,5) * D1(5))
      IF (INOUT.EQ.2) WRITE (6,200) VALU
      IF (INOUT.EQ.2) WRITE (6,190) DSPCE,DDPTH,D,DE,R,H,B1
C
C     ******************************************************************
C     COMPUTE THE DITCH AREA, TOP WIDTH, AND Z, THE COST FUNCTION.
C     ******************************************************************
C
      A = (B1 + H * SSLPE) * H + (B1 + 2.0 * H * SSLPE) * DDPTH + DDPTH
     1*  * 2 * SSLPE
      W = 2.0 * BERM + B1 + 2.0 * SSLPE * (H + DDPTH)
      Z = (RATE * C2(1) * A + C2(2) * W + C2(3)) * 100./DSPCE
      IF (INOUT.EQ.2) WRITE (6,210) Z
      RETURN
C
190 FORMAT (7F13.5)
200 FORMAT (1H0,21H THE GRADIENT OF Z IS,E15.5)
210 FORMAT (1H0,3H Z=,E16.10)
      END
```

```
      SUBROUTINE RTZ (J)
C
C     ******************************************************************
C     RTZ IS THE MAIN SUBROUTINE WHICH COMPUTES WATER AND SALT BALANCES
C     FOR THE SEASON.  SUBROUTINES UPFLOW, ETA, ROOT, AND SMBAL
C     ARE CALLED FROM RTZ.
C     ******************************************************************
C
      COMMON /SOIL/          HYDK          , SMFC          , SMWP          ,
     1       NDFC          , SMBEG         , SYA
      COMMON /GS/            IGSB(30)      , ETP(731)      , CKO(731)      ,
     1       GAMMA(30)     , YK(30)        , YA(5)         , YM(5)         ,
     2       JCROP(5)
      COMMON /IRR/           IRDAY(50)     , QIRR(50)      , DP(50)
      COMMON /MISC/          NDIS          , NGS           , NIRR          ,
     1       NCROPS        , INOUT
      COMMON /EC/            ECMAX(30,3)   , ECRZ(731)     , ECRZI         ,
     1       ECS           , ECIRR
      COMMON /WBAL/          RD(731)       , ET(731)       , INDAY(50)     ,
     1       OPTRD(50)     , DTW(731)      , NRDIN         , FL
      COMMON /SUM/           ETMAX(30)     , ETSUM(30)     , ECSUM(30,3)
      COMMON /MOIS/          AW(731)       , SM(731)       , Z(20)         ,
     1       SMC(20)       , NSMIN         , PHICR         , PHIRR         ,
     2       ICHNG
      COMMON /PLOT/          IJT           , IJJ           , IJP           ,
     1       A1(3000,8)
      COMMON /FLOW/          ZQ(20)        , Q(20)         , NQS           ,
     1       NDRD          , HSAT          , QFLOW(731)    , APEFF(50)     ,
     2       LDS(5)
      INTEGER                DAY
      DO 91 I = 1,NDIS
         RD(I) = 0.0
         ECRZ(I) = 0.0
         SM(I) = 0.0
         ET(I) = 0.0
   91 CONTINUE
      N = 0
      FL = .4
      ECRZS = ECRZI
      DAY = 0
      I = 0
      K = 0
C
C     ******************************************************************
C     THIS SECTION COUNTS THE NO. OF CM-DAYS THE WATER TABLE IS LESS
C     THAN X CM BELOW THE GROUND SURFACE AND THE NO. OF DAYS THE
C     SOIL MOISTURE IS AT WILTING POINT.
C     ******************************************************************
C
      THETA = SMBEG
      CALL ROOT (K,DAY,OLDRD,IKK)
      IJT = 1
      IF (IJJ.GE.2883) IJJ = 2883
```

```
      DO 92 II = 1,NDIS
         A1(IJT,6) = (1658. - RD(II))/100.
         IJT = IJT + 1
   92 CONTINUE
      F1 = 0.0
      F2 = 0.0
C
C     ******************************************************************
C     INCREMENT THE ARGUMENT FOR IRRIGATION MATRICES
C     ******************************************************************
C
   93 I = I + 1
      IF (I.GT.NIRR.AND.ICHNG.EQ.0) GO TO 94
      IF (I.GT.NIRR.AND.J.EQ.0) NIRR = NIRR + 1
      IDAY = IRDAY(I)
C
C     ******************************************************************
C     INCREMENT THE DAY IN THE SEASON
C     ******************************************************************
C
   94 DAY = DAY + 1
      IF (DAY.GT.NDIS) GO TO 118
      IF (DAY.EQ.IDAY.AND.QIRR(I).NE.0.0) GO TO 96
      IF (N.EQ.0) GO TO 106
      N = N + 1
      F2 = F1
      IF (N.GT.NDFC) GO TO 106
C
C     ******************************************************************
C     DAY IS NOT AN IRRIGATION DAY BUT INTERNAL DRAINAGE IS STILL
C     OCCURRING, I.E. DAY < OR = NDFC. ALL ET IS SUPPLIED FROM INPUT
C     IRRIGATION WATER.
C     ******************************************************************
C
      ET(DAY) = CKO(DAY) * ETP(DAY)
      QFLOW(DAY) = ET(DAY)
      F2 = F2 - ET(DAY)
      DEPTH = DTW(DAY) - HSAT
      IF (DEPTH.LT.RD(DAY)) K = K + 1
      IF (DEPTH.LT.RD(DAY)) CALL ROOT (K,DAY,OLDRD,IKK)
      IF (F2.LT.0.0) GO TO 115
      SM(DAY) = SM(DAY - 1)
      IF (N.LT.NDFC) GO TO 94
C
C     ******************************************************************
C     DAY = NDFC
C     ******************************************************************
C
      DP(I - 1) = F2
      APEFF(I - 1) = (QIR - F2)/QIR * 100.0
      GAM = GAMMA(I - 1)
      PICKUP = GAM * ECS - QIR * ECIRR/DP(I - 1)
      QWATER = DP(I - 1) + SMAVG * DTW(DAY)
      LDAY = DAY - NDFC
```

```
      IF (LDAY.LE.0) LDAY = 1
      D1 = RD(LDAY)
      IF (D1.GE.DTW(DAY)) D1 = DTW(DAY)
      D2 = DTW(LDAY) - RD(LDAY)
      IF (DTW(DAY).LE.DTW(LDAY)) D2 = DTW(DAY) - D1
      SALT = QIR * ECIRR + ECRZ(LDAY) * D1 * SM(LDAY) + ECRZB * D2 * (TH
     1ETA * DTW(LDAY) - SM(LDAY) * RD(LDAY))/(DTW(LDAY) - RD(LDAY))
      IF (LDAY.EQ.1) SALT = QIR * ECIRR + DTW(DAY) * ECRZI * THETA
      CHECK = SALT/QWATER - QIR * ECIRR/DP(I - 1)
      IF (CHECK.LE.PICKUP) PICKUP = CHECK
      ECDW = QIR * ECIRR/DP(I - 1) + PICKUP
      ECRZI = (SALT - ECDW * DP(I - 1))/(SMAVG * DTW(DAY))
      ECRZ(DAY) = ECRZI
      IF (ECDW.LE.GAM * ECS) ECDW = GAM * ECS
      DEPTH = RD(DAY)
      CALL SMBAL (DEPTH,SMAVG,1,DAY)
      DO 95 KK = 1,NDFC
         KK1 = DAY - NDFC + 1
         ECRZ(KK1) = ECRZ(DAY)
   95 CONTINUE
      GO TO 94
C
C     ******************************************************************
C     IN THIS SECTION, THE DAY IS CONSIDERED AN IRRIGATION DAY.
C     IF ICHNG=1, THE QUANTITY OF IRRIGATION WATER NEEDED TO FILL
C     THE SM PROFILE AND PROVIDE LEACHING IS COMPUTED.
C     ******************************************************************
C
   96 N = 1
      IP = 0
      F1 = 0.0
      DP(I) = FL * QIRR(I)
      QIR = QIRR(I)
      IF (ICHNG.EQ.1.AND.J.EQ.0) F1 = DP(I)
      ICK = 0
      SDEPTH = DTW(DAY)
      IF (I.EQ.1) GO TO 98
   97 DP(I) = (DP(I) + F1) * 0.5
      ICK = ICK + 1
      IF (ICK.GT.50) GO TO 105
      IF (ICHNG.EQ.1.AND.J.EQ.0) DTW(DAY) = SDEPTH - DP(I)/SYA
      IF (DTW(DAY).LE.0.0) DTW(DAY) = 0.00001
      IF (ICHNG.EQ.1.AND.J.EQ.0) GO TO 99
   98 DEPTH = DTW(DAY) - HSAT
      IF (DEPTH.LT.RD(DAY)) K = K + 1
      IF (K.NE.0) CALL ROOT (K,DAY,OLDRD,IKK)
      ET(DAY) = CKO(DAY) * ETP(DAY)
      QFLOW(DAY) = ET(DAY)
      ECRZB = ECRZI
      IF (IP.EQ.1) GO TO 102
      IF (ICHNG.EQ.1.AND.J.EQ.0) GO TO 100
   99 IF (I.NE.1) THETA = (SMAVG * DTW(DAY) - TET)/DTW(DAY)
  100 IF (DAY.NE.1) ECRZI = ECRZ(DAY - 1)
      DEPTH = DTW(DAY)
```

```
      CALL SMBAL (DEPTH,SMAVG,0,DAY)
      SMSAVE = SMAVG
      IF (I.EQ.1.AND.J.EQ.0) DW = (SMAVG - THETA) * DTW(1)
      IF (I.EQ.1.AND.J.NE.0) THETA = SMAVG - DW/DTW(1)
      DEPTH = RD(DAY)
      CALL SMBAL (DEPTH,SMAVG,1,DAY)
      AW(I) = SM(DAY)
      IF (SMAVG.LT.THETA) GO TO 116
  101 FF1 = (SMAVG - THETA) * DTW(DAY)
      F1 = QIR - FF1
      IF (I.EQ.1) GO TO 105
      IF (ICHNG.EQ.1.AND.J.EQ.0) QIR = (FF1 * 1.25 + QIR) * 0.5
      IF (ICHNG.EQ.1.AND.J.EQ.0) F1 = QIR * FL
      ADP = ABS(F1 - DP(I))
      IF (ICHNG.NE.1.OR.J.NE.0) GO TO 105
      IF (I.EQ.1) GO TO 105
      IF (ADP.GT.0.01 * DP(I)) GO TO 97
      IP = 1
      GO TO 98
  102 DO 103 IK = 1,NDFC
         F1 = F1 + ETP(DAY + IK - 1) * CKO(DAY + IK - 1)
  103 CONTINUE
      DO 104 IK = DAY,NDIS
         DTW(IK) = DTW(DAY)
  104 CONTINUE
  105 DP(I) = F1
      TET = 0.0
      QIRR(I) = QIR
      IF (F1.LE.0.0) GO TO 114
      F1 = F1 - ET(DAY)
      DP(I) = F1
      IF (F1.LE.0.0) GO TO 113
      TET = 0.0
      GO TO 93
C
C     ******************************************************************
C     INTERNAL DRAINAGE HAS CEASED. ET DEMAND MUST BE MET FROM
C     AVAILABLE SOIL MOISTURE OR UPFLOW FROM THE WATER TABLE
C     ******************************************************************
C
  106 Z1 = DTW(DAY) - RD(DAY) - HSAT
      IF (Z1.LE.0.0) GO TO 110
      K = 0
      Z1 = Z1 + HSAT
      QLIM = 0.0
      CALL UPFLOW (Z1,QLIM)
      IF (QLIM.GE.(ETP(DAY) * CKO(DAY))) GO TO 109
      QFLOW(DAY) = QLIM
      CETP = ETP(DAY)
      ETP(DAY) = ETP(DAY) - QLIM/CKO(DAY)
      ECRZ(DAY) = ECRZ(DAY - 1) + QLIM * ECDW/(RD(DAY) * SM(DAY - 1))
      OS = 0.325 * ECRZ(DAY) *  * 1.065
      CALL ETA (DAY,OS,PHI)
      DEPTH = RD(DAY)
```

```
      CALL SMBAL (DEPTH,SMAVG,1,DAY)
      SM(DAY) = SM(DAY) - (TET + ET(DAY))/RD(DAY)
      IF (SM(DAY).LE.SMWP) SM(DAY) = SMWP
      ECRZ(DAY) = ECRZ(DAY - 1) * SM(DAY - 1)/SM(DAY) + QLIM * ECDW/(SM(
     1DAY) * RD(DAY))
      IF (RD(DAY).GE.RD(DAY - 1)) ECRZ(DAY) = (ECRZ(DAY - 1) * RD(DAY -
     11) * SM(DAY - 1) + ECRZB * (RD(DAY) - RD(DAY - 1)) * SMSAVE + QLIM
     2 * ECDW)/(RD(DAY) * SM(DAY))
      TET = TET + ET(DAY)
      IF (ICHNG.NE.1.OR.J.NE.0) GO TO 107
      ICK = 0
      IF (DAY.LE.21) PHIRR = 8.4
      IF (DAY.GT.29) PHIRR = 3.0
      IF (PHI.GT.PHIRR) GO TO 117
  107 ET(DAY) = ET(DAY) + QLIM
      ETP(DAY) = CETP
      LDAY = IDAY - 1
      IF (DAY.GT.IRDAY(NIRR)) LDAY = NDIS
      IF (DAY.EQ.LDAY) DTW(DAY) = DTW(DAY) + QLIM/SYA
      IF (J.NE.0) LDAY = NDIS
      IF (DAY.EQ.LDAY) GO TO 94
      DO 108 L = DAY,LDAY
         DTW(L) = DTW(L) + QLIM/SYA
  108 CONTINUE
      GO TO 94
  109 ET(DAY) = CKO(DAY) * ETP(DAY)
      ECRZ(DAY) = ECRZ(DAY - 1) + ET(DAY) * ECDW/(RD(DAY) * SM(DAY - 1))
      SM(DAY) = SM(DAY - 1)
      GO TO 111
  110 ET(DAY) = CKO(DAY) * ETP(DAY)
      K = K + 1
      CALL ROOT (K,DAY,OLDRD,IKK)
      SM(DAY) = SM(DAY - 1)
      ECRZ(DAY) = ECRZ(DAY - 1) + ET(DAY) * ECDW/(RD(DAY) * SM(DAY))
  111 LDAY = IDAY - 1
      IF (DAY.GT.IRDAY(NIRR)) LDAY = NDIS
      IF (J.NE.0) LDAY = NDIS
      DO 112 L = DAY,LDAY
         DTW(L) = DTW(L) + ET(DAY)/SYA
  112 CONTINUE
      DEPTH = RD(DAY)
      IF (SM(DAY).GT.SMFC) CALL SMBAL (DEPTH,SMAVG,1,DAY)
      IF (SM(DAY).GT.SMFC) SM(DAY) = SM(DAY) - TET/RD(DAY)
      QFLOW(DAY) = ET(DAY)
      GO TO 94
C
C     ******************************************************************
C     THE FOLLOWING SECTIONS MODIFY THE ABOVE IF NEEDED
C     ******************************************************************
C
  113 IF (INOUT.EQ.2) WRITE (6,125) I
      ET(DAY) = CKO(DAY) * ETP(DAY)
      APEFF(I) = 100.0
      SMAVG = SMAVG - (ET(DAY) + DP(I))/DTW(DAY)
```

```
      DEPTH = RD(DAY)
      IF (DP(I).NE.0.0) CALL SMBAL (DEPTH,SMAVG,1,DAY)
      SM(DAY) = SM(DAY) + F1/RD(DAY)
      IF (SM(DAY).LE.SMWP) SM(DAY) = SMWP
      SMSAVE = SMAVG
      IF (DP(I).EQ.0.0) SM(DAY) = SM(DAY - 1) - F1/RD(DAY)
      DP(I) = 0.0
      IF (SM(DAY).LE.SMWP) SM(DAY) = SMWP
      GO TO 93
  114 IF (INOUT.EQ.2) WRITE (6,126) I
      SMAVG = SMAVG + F1/DTW(DAY)
      IF (I.EQ.1) SMAVG = SMFC
      SM(DAY) = SMAVG
      SMSAVE = SMAVG
      IF (I.EQ.1) SM(DAY) = SMFC
      DP(I) = 0.0
      APEFF(I) = 100.0
      TET = ET(DAY)
      F1 = 0.0
      GO TO 93
  115 IL = I - 1
      IF (INOUT.EQ.2) WRITE (6,127) IL,DAY
      APEFF(I - 1) = 100.0
      DEPTH = RD(DAY)
      CALL SMBAL (DEPTH,SMAVG,1,DAY)
      TET = TET - F2
      SM(DAY) = SM(DAY) - TET/RD(DAY)
      IF (SM(DAY).LE.SMWP) SM(DAY) = SMWP
      SMAVG = SMAVG - (ET(DAY) + F2)/DTW(DAY)
      ECDW = GAM * ECS
      SMSAVE = SMAVG
      DP(I - 1) = 0.0
      IF (N.LT.NDFC) GO TO 94
      LDAY = IRDAY(I - 1) - 1
      IF (I.EQ.2) LDAY = 1
      D1 = RD(LDAY)
      IF (D1.GE.DTW(DAY)) D1 = DTW(DAY)
      D2 = DTW(LDAY) - RD(LDAY)
      IF (DTW(DAY).LE.DTW(LDAY)) D2 = DTW(DAY) - D1
      SALT = QIR * ECIRR + ECRZI * D1 * SM(LDAY) + ECRZB * D2 * (THETA *
     1 DTW(LDAY) - SM(LDAY) * RD(LDAY))/(DTW(LDAY) - RD(LDAY))
      ECRZI = (SALT)/(SMAVG * DTW(DAY))
      ECRZ(DAY) = ECRZI
      GO TO 94
  116 IF (INOUT.EQ.2) WRITE (6,128)
      IF (INOUT.EQ.2) WRITE (6,129) DTW(DAY),SMAVG,THETA
      THETA = SMAVG
      DP(I) = 0.0
      GO TO 101
C
C     ******************************************************************
C     THIS SECTION IS CALLED WHEN PHI > OR = PHIRR AND ICHNG=1.
C     ******************************************************************
C
```

```
  117 DEPTH = DTW(DAY)
      LDAY = IRDAY(I - 1)
      IF (ICK.EQ.0) THETA = SMAVG
      IF (ICK.EQ.0) SDTW = DEPTH
      ICK = ICK + 1
      IF (ICK.GT.50) STOP
      CALL SMBAL (DEPTH,SMAVG,0,DAY)
      FL = .4
      SMDEF = SMAVG * DTW(DAY) + TET - THETA * DTW(DAY)
      IF (DTW(LDAY).LT.DTW(DAY)) SMDEF = SMAVG * DTW(DAY) + TET - THETA
     1* DTW(LDAY)
      IF (SMDEF.LE.0.0) SMDEF = 0.0
      TQIR = QIR
      QIR = (SMDEF + SMDEF * FL)
      DTW(DAY) = SDTW - (FL * SMDEF)
      AQIR = ABS(TQIR - QIR)
      IF (AQIR.GE.0.05 * QIR) GO TO 117
      QIRR(I) = (QIR + TQIR) * 0.5
      DTW(DAY) = SDTW
      IRDAY(I) = DAY + 1
      IDAY = DAY + 1
      SMAVG = THETA
      GO TO 107
C     ******************************************************************
C     OUTPUT AND MATRIX MANIPULATION FOR OUTPUT
C     ******************************************************************
  118 SUM = 0.0
      SUM1 = 0.0
      SUM2 = 0.0
      SUM3 = 0.0
      ECM = 0.0
      SMMIN = SMC(1)
      IK = 1
      IKK = 0
      DO 121 I = 1,NDIS
         IF (ET(I).EQ.0.0) ET(I) = 0.00001
         IF (I.GE.IRDAY(IK).AND.I.LE.(IRDAY(IK) + NDFC - 1)) IKK = 1
         IF (IKK.EQ.1) GO TO 119
         SUM = SUM + QFLOW(I)
         GO TO 120
  119    CONTINUE
         IKK = 0
         IF (I.EQ.(IRDAY(IK) + NDFC - 1)) IK = IK + 1
         IF (IK.GT.NIRR) IK = NIRR
  120    SUM1 = SUM1 + ET(I)
         IF (ECRZ(I).GE.ECM) ECM = ECRZ(I)
         IF (SM(I).LE.SMMIN) SMMIN = SM(I)
  121 CONTINUE
      IF (INOUT.EQ.2.OR.J.EQ.0) WRITE (6,132) SUM1,SUM
      SUM2 = 0.0
      DO 122 I = 1,NIRR
         IF (INOUT.EQ.2.OR.J.EQ.0) WRITE (6,133) I,IRDAY(I),QIRR(I),DP(I
     1   ),APEFF(I)
         SUM2 = SUM2 + QIRR(I)
```

```
      SUM3 = SUM3 + DP(I)
 122 CONTINUE
     IF (INOUT.EQ.2.OR.J.EQ.0) WRITE (6,134) SUM2,SUM3
     IF (INOUT.EQ.2.OR.J.EQ.0) WRITE (6,135) ECM,SMMIN
     IF (INOUT.EQ.2.OR.J.EQ.0) WRITE (6,130)
     IF (INOUT.EQ.2.OR.J.EQ.0) WRITE (6,131)
     IF (INOUT.EQ.2.OR.J.EQ.0) WRITE (6,136)
     DO 123 I = 1,NDIS
        WTCONT = (QFLOW(I)/ET(I)) * 100.
        IF (INOUT.EQ.2.OR.J.EQ.0) WRITE (6,137) I,SM(I),ET(I),ECRZ(I),R
    1   D(I),DTW(I),QFLOW(I),WTCONT
 123 CONTINUE
     IJT = 1
     IP = 1
     DO 124 I = 1,NDIS
        A1(IJT,1) = FLOAT(I)
        IDAY = IRDAY(IP)
        ITEMP = IDAY + NDFC - 1
        IF (I.GE.IDAY.AND.I.LE.ITEMP) SM(I) = SM(ITEMP)
        A1(IJT,2) = SM(I)/AW(IP)
        IF (A1(IJT,2).GT.1.0) A1(IJT,2) = 1.0
        IF (ECRZ(I).EQ.0.00) ECRZ(I) = ECRZ(ITEMP)
        A1(IJT,3) = ECRZ(I)
        A1(IJT,4) = (1658. - RD(I))/100.0
        A1(IJT,5) = (1658. - DTW(I))/100.0
        IJT = IJT + 1
        IF (IP.EQ.NIRR) GO TO 124
        IF (I.EQ.ITEMP) IP = IP + 1
 124 CONTINUE
     IF (ECRZ(DAY).GT.ECRZS) ECRZI = ECRZS
     RETURN
 125 FORMAT (1H0,11H IRRIGATION,I5,44H IS NOT SUFFICIENT TO PROVIDE ET
    1FOR IRR DAY)
 126 FORMAT (1H0,11H IRRIGATION,I5,50H IS NOT SUFFICIENT TO FILL SOIL M
    1OISTURE RESERVOIR)
 127 FORMAT (1H0,11H IRRIGATION,I5,40H IS NOT SUFFICIENT TO PROVIDE ET
    1FOR DAY,I5)
 128 FORMAT (1H0,45H SMBEG INPUT IS TOO LARGE, RECHECK INPUT DATA)
 129 FORMAT (1H0,5H DTW=,F10.4,7H SMAVG=,F6.4,7H SMBEG=,F6.4)
 130 FORMAT (1H0,32H SUMMARY OF ROOT ZONE CONDITIONS)
 131 FORMAT (1H0,17H  DAY   AVG SMRZ ,3X,3HETA,6X,6HECRZ  ,10HROOT DEPT
    1H,5X,3HDTW,5X,18H W.T. CONTRIBUTION)
 132    FORMAT (1H0,21H TOTAL ET FOR SEASON=,F8.3,25H TOTAL W.T. CONTRI
    1   BUTION=,F8.3)
 133 FORMAT (1H0,5H IRR=,I2,5H DAY=,I3,9H APPLIED=,F8.4,12H PERCOLATED=
    1,,F8.4,17H APPLICATION EFF=,F8.4)
 134 FORMAT (1H0,21H TOTAL WATER APPLIED=,F8.2,3H CM,24H TOTAL WATER PE
    1RCOLATED=,F8.2,3H CM)
 135 FORMAT (1H0,21H MAX EC IN ROOT ZONE=,F9.2,9H MMHOS/CM,7X,8H MIN SM
    1=,F5.4)
 136 FORMAT (1H ,20X,  2HCM,6X,  5HMMHOS,6X,  2HCM,8X,  2HCM,9X,  2HCM,
    17X,  7HPERCENT)
 137 FORMAT (I5,6F10.4,F12.2)
     END
```

```
      SUBROUTINE ROOT (K,DAY,OLDRD,IKK)
C
      COMMON /WBAL/          RD(731)      , ET(731)      , INDAY(50)    ,
     1        OPTRD(50)    , DTW(731)     , NRDIN        , FL
      COMMON /MISC/          NDIS         , NGS          , NIRR         ,
     1        NCROPS       , INOUT
      COMMON /MOIS/          AW(731)      , SM(731)      , Z(20)        ,
     1        SMC(20)      , NSMIN        , PHICR        , PHIRR        ,
     2        ICHNG
      COMMON /FLOW/          ZQ(20)       , Q(20)        , NQS          ,
     1        NDRD         , HSAT         , QFLOW(731)   , APEFF(50)    ,
     2        LDS(5)
      INTEGER                DAY
      SNDIS = NDIS
      IF (DAY.NE.0) GO TO 92
C
C     ******************************************************************
C     THE ROOT DEPTH MATRIX IS FILLED WITH UNSTRESSED ROOT DEPTHS
C     ******************************************************************
C
      RD(1) = OPTRD(1)
      J = 2
      DO 91 I = 2,NDIS
         IF (I.EQ.INDAY(J)) J = J + 1
         A = I - INDAY(J - 1)
         B = INDAY(J) - INDAY(J - 1)
         SUM = A/B * (OPTRD(J) - OPTRD(J - 1))
         RD(I) = OPTRD(J - 1) + SUM
   91 CONTINUE
      RETURN
C
C     ******************************************************************
C     ROOT GROWTH IS RETARDED OR ROOTS TRUNCATED IS AN AREA OF THE
C     ROOT ZONE IS SATURATED.
C     ******************************************************************
C
   92 IF (DAY.LE.LDS(1)) NDIS = LDS(1)
      IF (NCROPS.EQ.1) GO TO 94
      DO 93 I = 2,NCROPS
         IF (DAY.GT.LDS(I - 1)) NDIS = LDS(I)
   93 CONTINUE
   94 IF (K.GE.NDRD) GO TO 96
      IF (K.EQ.1) OLDRD = RD(DAY)
      IF (K.EQ.1) IKK = DAY
      IDP1 = DAY + 1
      DO 95 I = IDP1,NDIS
         J = NDIS + IDP1 - I
         RD(J) = RD(J - 1)
   95 CONTINUE
      IF (INOUT.EQ.2) WRITE (6,104) DAY
      RD(DAY) = DTW(DAY) - HSAT
      GO TO 99
```

```
   96 DISP = OLDRD - RD(IKK)
      IP = 0
      DO 97 I = DAY,NDIS
         RD(I) = RD(I) - DISP
         IF (RD(I).LE.0.0) IP = IP + 1
         IF (RD(I).GT.0.0) IP = 0
         IF (RD(I).LE.0.0) RD(I) = 0.0001
         IF (IP.EQ.NDRD) GO TO 101
   97 CONTINUE
      K = 0
      DO 98 I = 1,NDRD
         J = DAY - I + 1
         TRD = DTW(J) - HSAT
         IF (TRD.LE.RD(J)) K = K + 1
         IF (K.EQ.1) OLDRD = RD(DAY)
   98 CONTINUE
      NDIS = SNDIS
      RETURN
   99 CONTINUE
      DO 100 I = DAY,NDIS
  100 CONTINUE
      NDIS = SNDIS
      RETURN
  101 IF (INOUT.EQ.2) WRITE (6,102) NDRD
      WRITE (6,103)
      NDIS = SNDIS
      RETURN
C
  102 FORMAT (1H0,35H ROOTS ARE COMPLETELY SATURATED FOR,I5,5H DAYS)
  103 FORMAT (1H0,47H ROOTS ARE DESTROYED, NO CROP YIELD IS REALIZED)
  104 FORMAT (1H0,35H ROOT ELONGATION IS RETARDED AT DAY,I5)
      END
```

```
      SUBROUTINE SMBAL (DEPTH,SMAVG,K,DAY)
C
C     ******************************************************************
C     SUBROUTINE SMBAL COMPUTES THE AVERAGE SOIL MOISTURE IN THE ENTIRE
C     PROFILE TO THE WATER TABLE AND THE AVERAGE IN THE ROOT ZONE BASED
C     ON THE INPUT EQUILIBRIUM PROFILE
C     ******************************************************************
C
      COMMON /WBAL/          RD(731)      , ET(731)      , INDAY(50)    ,
     1        OPTRD(50)    , DTW(731)     , NRDIN        , FL
      COMMON /SOIL/          HYDK         , SMFC         , SMWP         ,
     1        NDFC         , SMBEG        , SYA
      COMMON /MOIS/          AW(731)      , SM(731)      , Z(20)        ,
     1        SMC(20)      , NSMIN        , PHICR        , PHIRR        ,
     2        ICHNG
      INTEGER                DAY
      IF (K.EQ.1) GO TO 94
      SMFC = SMC(NSMIN)
      SMSAT = SMC(1)
      D1 = DEPTH - Z(1)
      IF (D1.LE.0.0) GO TO 93
      D2 = DEPTH - Z(NSMIN)
      IF (D2.LE.0.0) D2 = 0.0
      SMAVG = Z(1) * SMSAT + D2 * SMFC
      DO 91 I = 2,NSMIN
         D2 = DEPTH - Z(I)
         IF (D2.LE.0.0) GO TO 92
         SMAVG = SMAVG + (Z(I) - Z(I - 1)) * (SMC(I) + SMC(I - 1)) * 0.5
   91 CONTINUE
      SMAVG = SMAVG/DEPTH
      RETURN
   92 DIST = DEPTH - Z(I - 1)
      RATIO = (DEPTH - Z(I - 1))/(Z(I) - Z(I - 1))
      SMAVG = SMAVG + DIST * ((SMC(I - 1) - RATIO * (SMC(I - 1) - SMC(I)
     1)) + SMC(I - 1)) * 0.5
      SMAVG = SMAVG/DEPTH
      RETURN
   93 SMAVG = SMC(1)
      RETURN
   94 SMMAX = 0.0
      SMMIN = 0.0
      SM(DAY) = 0.0
      DMIN = DTW(DAY) - DEPTH
      DMAX = DTW(DAY)
      IF (DMAX.LE.Z(1)) GO TO 101
      IF (DMAX.GE.Z(NSMIN)) GO TO 102
      DO 96 I = 1,NSMIN
         IF (SMMAX.NE.0.0) GO TO 95
         IF (DMIN.LE.Z(I)) SMMAX = SMC(I - 1) - (DMIN - Z(I - 1))/(Z(I)
     1   - Z(I - 1)) * (SMC(I - 1) - SMC(I))
   95    IF (DMAX.LE.Z(I)) SMMIN = SMC(I - 1) - (DMAX - Z(I - 1))/(Z(I)
     1   - Z(I - 1)) * (SMC(I - 1) - SMC(I))
         IF (SMMIN.NE.0.0) GO TO 97
```

```
 96 CONTINUE
 97 IF (DMIN.GE.Z(I - 1)) GO TO 100
    SM(DAY) = (DMAX - Z(I - 1)) * (SMMIN + SMC(I - 1))/2.0
 98 I = I - 1
    IF (DMIN.GE.Z(I)) GO TO 99
    SM(DAY) = SM(DAY) + (Z(I + 1) - Z(I)) * (SMC(I + 1) + SMC(I))/2.0
    GO TO 98
 99 SM(DAY) = SM(DAY) + (Z(I + 1) - DMIN) * (SMC(I + 1) + SMMAX)/2.0
    SM(DAY) = SM(DAY)/DEPTH
    RETURN
100 SM(DAY) = 0.5 * (SMMAX + SMMIN)
    RETURN
101 SM(DAY) = SMC(1)
    RETURN
102 SM(DAY) = SMC(NSMIN)
    RETURN
    END
```

```
      SUBROUTINE ETA (DAY,OS,PHI)
C
C     ******************************************************************
C     ETA COMPUTES THE ACTUAL ET FROM INPUT ETA/ETM VS. SUCTION CURVES
C     ******************************************************************
C
      COMMON /SOIL/          HYDK        , SMFC        , SMWP        ,
     1        NDFC        , SMBEG       , SYA
      COMMON /GS/            IGSB(30)    , ETP(731)    , CKO(731)    ,
     1        GAMMA(30)   , YK(30)      , YA(5)       , YM(5)       ,
     2        JCROP(5)
      COMMON /WBAL/          RD(731)     , ET(731)     , INDAY(50)   ,
     1        OPTRD(50)   , DTW(731)    , NRDIN       , FL
      COMMON /MOIS/          AW(731)     , SM(731)     , Z(20)       ,
     1        SMC(20)     , NSMIN       , PHICR       , PHIRR       ,
     2        ICHNG
      INTEGER                DAY
      IF (SM(DAY - 1).GT.SMFC) GO TO 92
      IF (SM(DAY - 1).LE.SMWP) GO TO 91
      PHI = 15.0 - (SM(DAY - 1) - SMWP)/(SMFC - SMWP) * 14.67
      GO TO 95
   91 ET(DAY) = 0.0
      RETURN
   92 DO 93 I = 1,NSMIN
         J = NSMIN - I + 1
         IF (SM(DAY - 1).LE.SMC(J)) GO TO 94
   93 CONTINUE
   94 PHI = (Z(J) + (SMC(J) - SM(DAY - 1))/(SMC(J) - SMC(J + 1)) * (Z(J
     1+ 1) - Z(J)))/1020.0
   95 PHI = PHI + OS
      IF (PHI.GE.15.0) PHI = 15.0
      IF (PHI.LE.PHICR) GO TO 96
      ET(DAY) = ETP(DAY) * CKO(DAY) * (1.0 - (PHI - PHICR)/(15.0 - PHICR
     1))
      RETURN
   96 ET(DAY) = CKO(DAY) * ETP(DAY)
      RETURN
      END
```

```
      SUBROUTINE UPFLOW (DEPTH,QLIM)
C
C     ******************************************************************
C     UPFLOW COMPUTES THE ACTUAL LIMITING UPFLOW FROM THE WATER TABLE
C     ******************************************************************
C
      COMMON /FLOW/          ZQ(20)       , Q(20)        , NQS          ,
     1        NDRD          , HSAT        , QFLOW(731)   , APEFF(50)    ,
     2        LDS(5)
      IF (DEPTH.LT.ZQ(1)) QLIM = 10000.
      IF (DEPTH.GT.(ZQ(NQS))) QLIM = 0.0
      IF (QLIM.EQ.0.0) GO TO 91
      RETURN
   91 DO 92 J = 1,NQS
         IF (DEPTH.GT.ZQ(J)) GO TO 92
         QLIM = Q(J) + (Q(J - 1) - Q(J)) * (DEPTH - ZQ(J))/(ZQ(J - 1) -
     1   ZQ(J))
         GO TO 93
   92 CONTINUE
   93 RETURN
      END


      SUBROUTINE YIELD
C
C     ******************************************************************
C     SUBROUTINE YIELD COMPUTES THE ACTUAL YIELD FROM AN INPUT LINEAR
C     PRODUCTION FUNCTION.  FOR OTHER FORMS, REPLACE OR MODIFY THIS
C     SUBROUTINE.
C     ******************************************************************
C
      COMMON /MISC/          NDIS         , NGS          , NIRR         ,
     1        NCROPS        , INOUT
      COMMON /GS/            IGSB(30)     , ETP(731)     , CKO(731)     ,
     1        GAMMA(30)     , YK(30)       , YA(5)        , YM(5)        ,
     2        JCROP(5)
      COMMON /SUM/           ETMAX(30)    , ETSUM(30)    , ECSUM(30,3)
      DIMENSION              DEF(5)
      J = 1
      DEF(1) = 0.0
      DO 91 I = 1,NGS
         IF (ETMAX(I).EQ.0.0) GO TO 91
         DEF(J) = YK(I) * (1.0 - ETSUM(I)/ETMAX(I)) + DEF(J)
         IF (J.EQ.NCROPS) GO TO 91
         IF (IGSB(I).EQ.JCROP(J)) DEF(J + 1) = 0.0
         IF (IGSB(I).EQ.JCROP(J + 1)) J = J + 1
   91 CONTINUE
      DO 92 I = 1,NCROPS
         YA(I) = (1.0 - DEF(I)) * YM(I)
   92 CONTINUE
      RETURN
      END
```

```
      SUBROUTINE DERIV (J,DDPTH,DSPCE,SUMI,ALPHA,D,DE,R,HMIN)
C
C     ******************************************************************
C     SUBROUTINE DERIV COMPUTES DZ/DK AND DZ/DSYA FOR CLOSED DRAINS.
C     ******************************************************************
C
      COMMON /GRAD/          TEXP        , FSUM        , TFSUM       ,
     1        T1           , T2          , PI          , B1MIN       ,
     2        HMAX         , BERM        , HMNM
      COMMON /SOIL/          HYDK        , SMFC        , SMWP        ,
     1        NDFC         , SMBEG       , SYA
      COMMON /LIMIT/         DIMP        , FLNTH       , FWDTH       ,
     1        VMAX         , RN          , FSLPE       , SSLPE       .
     2        B1           , DMAX
      COMMON /SHAPE/         SFK1        , SFK2        , T
      COMMON /DCOST/         C1(10)      , C2(3)       , RATE        ,
     1        CM(12)       , DPM         , DDEDD       , DEL2        ,
     2        DEL3
      IF (J.EQ.2) RETURN
C
C     ******************************************************************
C     J=1,0.LE.L/D.LE.0.3,  DZDK
C     ******************************************************************
C
      HC = DDPTH - HMIN
      DDDK = (T1 * PI *  * 2 * ( - 1.0)) * (ALPHA * T * FSUM * TEXP/(1.0
     1 - TEXP) + TFSUM)/(DSPCE *  * 2 * SYA)
      DDEDR = ( - 1.0) * (DE + 4.0 * (DIMP - DDPTH) *  * 2/(PI * DSPCE *
     1 R * DE))
      DCDDK = DDEDD * DDDK + 0.375 * R * DDEDR * (1.0/HYDK + 1.0/HC)/(1.
     10 - HYDK * HC * DDEDR)
      DRDK = 0.375 * R * (HC * D + HYDK * D * DDDK + HYDK * HC * DCDDK)/
     1(HYDK * D * HC)
      DDEDK = DDEDD * DDDK + DDEDR * DRDK
      DZDK = DEL3 * DCDDK + DEL2 * DDDK
      WRITE (6,91)
      WRITE (6,92) DZDK
C
C     ******************************************************************
C     DZ/DSYA: J=1
C     ******************************************************************
C
      F1 = (SUMI * DSPCE *  * 2)/(12.0 * HYDK * T * D *  * 2)
      F2 = DE/(DIMP - DDPTH)
      F3 = (TFSUM - T * FSUM * TEXP * ALPHA)/(1.0 - TEXP)
      F4 = DE * (8.0 * F2 + 3.0 * DE/HC)/(PI * DSPCE)
      DENOM = F1 - 3.0 * DE *  * 2/(PI * DSPCE * D) + T1 * PI *  * 2 * F
     13 * F4/(DSPCE *  * 2 * D)
      DCDDS = (F2 - F2 *  * 2 + F4 * (T1 * PI *  * 2 * F3/(DSPCE *  * 2
     1* SYA) - T1 * FSUM/SYA))/DENOM
      DADS = ALPHA * (DCDDS/D - 1.0/SYA)
      DDDS = ( - 1.0) * T1 * (FSUM/SYA + DADS * PI *  * 2 * (TFSUM - T *
     1 FSUM * TEXP/(1.0 - TEXP))/DSPCE *  * 2)
```

```
      DZDS = DEL3 * DCDDS + DEL2 * DDDS
      WRITE (6,93) DZDS
      RETURN
C
   91 FORMAT (1H0,21H SENSITIVITY ANALYSIS)
   92 FORMAT (1H0,5X,7H DZ/DK=,E10.3)
   93 FORMAT (1H0,5X,9H DZ/DSYA=,E10.3)
      END
```

```
      SUBROUTINE ALPH2 (J,DSPCE,DDPTH,H,SUMI,ALPHA,DE,D,Q1,HMIN,R,RMIN,V
     1EL)
C
C     ******************************************************************
C     COMPUTES THE FLOW VELOCITY AND DISCHARGE, DE, AND ALPHA FOR
C     OPEN DITCHES.
C     ******************************************************************
C
      COMMON /SHAPE/        SFK1        , SFK2        , T
      COMMON /GRAD/         TEXP        , FSUM        , TFSUM       ,
     1        T1          , T2          , PI          , B1MIN       ,
     2        HMAX        , BERM        , HMNM
      COMMON /SOIL/         HYDK        , SMFC        , SMWP        ,
     1        NDFC        , SMBEG       , SYA
      COMMON /LIMIT/        DIMP        , FLNTH       , FWDTH       ,
     1        VMAX        , RN          , FSLPE       , SSLPE       ,
     2        B1          , DMAX
      R = 0.0
      HYP = SQRT(1.0 + SSLPE *  * 2)
      VMAX = .25
      HCMAX = 0.
      HMNM = .2
      B1MIN = .5
      IF (HCMAX.EQ.0.0) HCMAX = DDPTH - HMIN
C
C     ******************************************************************
C     Q1 IS THE FLOW CAPACITY REQUIRED IN THE DITCH IN M**3/SEC.
C     ******************************************************************
C
   91 Q1 = (2.0 * HYDK * SFK2 * D * FLNTH * HCMAX)/(DSPCE * 1000000. * 2
     14. * 3600.)
      VEL = VMAX
      IC = 0
      ICK = 0
   92 IC = IC + 1
C
C     ******************************************************************
C     COMPUTE THE REQUIRED AREA AND PERIMETER FOR THE CURRENT VALUE OF
C     VELOCITY.
C     ******************************************************************
C
      AREA = Q1/VEL
      RADIUS = (VEL * RN/FSLPE *  * 0.5) *  * 1.5
      PER = AREA/RADIUS
C
C     ******************************************************************
C     CHECK IF ROOTS FOR H ARE REAL
C     ******************************************************************
C
      B = PER/(2.0 * HYP - SSLPE)
      C = AREA/(2.0 * HYP - SSLPE)
      TROOT = B *  * 2 - 4.0 * C
      IF (TROOT.LE.0.0) GO TO 93
```

```
      ROOT = SQRT(TROOT)
C
C     ******************************************************************
C     DETERMINE THE DEPTH AND BOTTOM WIDTH OF THE FLOW AREA
C     ******************************************************************
C
      H1 = (B + ROOT)/2.0
      H2 = (B - ROOT)/2.0
      B11 = PER - 2.0 * HYP * H1
      B12 = PER - 2.0 * HYP * H2
      B1 = 0.0
      IF (H2.LE.0.0) B1 = B11
      IF (B11.LE.0.0) B1 = B12
      IF (H2.GE.0.0) B1 = B12
      IF (B12.LE.0.0) B1 = B11
      IF (B1.LE.B1MIN) B1 = B1MIN
      H = ( - B1)/(SSLPE * 2.0) + SQRT(B1 *  * 2 + 4.0 * AREA)/2.0
      IF (H.LE.HMNM) H = HMNM
      IF (H.GT.HMAX) H = HMAX
      IF (H.EQ.HMAX) B1 = AREA/H - H * SSLPE
      IF (B1.LE.B1MIN) B1 = B1MIN
      AREA = (B1 + H * SSLPE) * H
      PER = B1 + 2.0 * HYP * H
      RADIUS = AREA/PER
      VEL = Q1/AREA
      GO TO 94
   93 VEL = VMAX - IC * .1 * VMAX
      IF (IC.GE.10) VEL = .1 * VMAX - .005 * IC * VMAX
      IF (VEL.LE.0.0) VEL = .001 * VMAX
      IF (IC.GE.19) GO TO 94
      GO TO 92
   94 IF (B1.LE.0.0) B1 = B1MIN
      IF (H.LE.0.0) H = HMNM
      R = B1/2.0
      RATIO = (DIMP - DDPTH)/DSPCE
      IF (RATIO.LE.0.3) GO TO 96
      TLN = ALOG(DSPCE/R)
      DE = DSPCE * PI/(8.0 * (TLN - 1.15))
   95 F = SUMI * DSPCE *  * 2/(HYDK * 12.0 * T)
      ROOT = SQRT(DE *  * 2 + 4.0 * F)
      DSTORE = D
      D = 0.5 * (DE + ROOT)
      ALPHA = HYDK * D/SYA
      IF (J.EQ.2) DELTA = ABS(D - DSTORE)
      ICK = ICK + 1
      IF (ICK.GT.20) STOP
      IF (DELTA.GT.0.05 * D) GO TO 91
      GO TO 97
   96 TLN = ALOG((DIMP - DDPTH)/R)
      TS = (8.0 * TLN)/PI - 3.55 + 1.6 * RATIO - 2.0 * RATIO *  * 2
      DE = (DIMP - DDPTH)/(1.0 + RATIO * TS)
      GO TO 95
   97 RETURN
      END
```

```
      SUBROUTINE LSQR (NPHIS,PHI,COST)
C
      COMMON /DCOST/          C1(10)        , C2(3)         , RATE
     1         CM(12)       , DPM           , DDEDD         , DEL2
     2         DEL3
      DIMENSION               A(3,3)        , B(3,3)        , PHI(20)
     1         COST(20)     , X(3)
      DO 92 I = 1,3
         DO 91 J = 1,3
            A(I,J) = 0.0
   91    CONTINUE
   92 CONTINUE
      C11 = 0.0
      C22 = 0.0
      C33 = 0.0
      COST2 = 0.0
      DO 93 J = 1,NPHIS
         A(1,2) = A(1,2) + 2.0 * PHI(J)
         A(1,3) = A(1,3) + 2.0 * PHI(J) *  * 2
         A(2,3) = A(2,3) + 2.0 * PHI(J) *  * 3
         A(3,3) = A(3,3) + 2.0 * PHI(J) *  * 4
         C11 = C11 + 2.0 * COST(J)
         C22 = C22 + 2.0 * PHI(J) * COST(J)
         C33 = C33 + 2.0 * PHI(J) *  * 2 * COST(J)
         COST2 = COST2 + COST(J) *  * 2
   93 CONTINUE
      A(1,1) = 2.0 * NPHIS
      A(2,1) = A(1,2)
      A(2,2) = A(1,3)
      A(3,1) = A(1,3)
      A(3,2) = A(2,3)
      D1 = C11
      D2 = C22
      D3 = C33
      DO 95 I = 1,3
         DO 94 J = 1,3
            B(I,J) = A(I,J)
   94    CONTINUE
   95 CONTINUE
      DO 96 J = 2,3
         A(1,J) = A(1,J)/A(1,1)
   96 CONTINUE
      C11 = C11/A(1,1)
      DO 98 I = 2,3
         DO 97 J = I,3
            A(I,J) = A(I,J) - A(I,1) * A(1,J)
            IF (J.EQ.I) GO TO 97
            A(I,J) = A(I,J)/A(I,I)
   97    CONTINUE
   98 CONTINUE
      C22 = (C22 - C11 * A(2,1))/A(2,2)
      A(3,2) = A(3,2) - A(3,1) * A(1,2)
```

```
      A(3,3) = (A(3,3) - A(3,2) * A(2,3))
      C33 = ((C33 - C11 * A(3,1) - C22 * A(3,2))/A(3,3))
      X(3) = C33
      X(2) = C22 - A(2,3) * X(3)
      X(1) = C11 - A(1,3) * X(3) - A(1,2) * X(2)
      VALU = B(1,2) * X(1) * X(2) + B(1,3) * X(1) * X(3) + B(2,3) * X(2)
     1 * X(3) - D1 * X(1) - D2 * X(2) - D3 * X(3) + B(2,2) * X(2)/2.0 +
     2B(3,3) * X(3)/2.0 + B(1,1) * X(1)/2.0 + COST2
      C1(1) = X(1)
      C1(2) = X(2)
      C1(3) = X(3)
      RETURN
C
      END
```

A.2 INPUT DATA REQUIREMENTS

This section summarizes the input requirements of the program. For more information, the reader is referred to Chapter 3 and Table A.1.

SET 1: Control Cards

Card 1:

AREA: An 80 character alphanumeric specification of the study area.

Card 2:

SITE: An 80 character alphanumeric specification of the site.

Card 3:

NDIS: Number of days in the crop season. For more than one crop, this is the number of days from the planting of the first crop to the harvesting of the last crop considered. Days are numbered consecutively from 1 to NDIS.

NGS: Number of growth stages for more than one crop, this is the total number of growth stages.

NIRR: Number of irrigations

NCROPS: Number of crops

INOUT: A control variable which specifies the type of output desired.

If INOUT=0, only final results are printed

If INOUT = 1, the input data and final results are printed.

If INOUT = 2, the input data, intermediate results and final results are printed.

Card 4:

HMINI (cm): The initial trial for HMIN. HMIN is the minimum allowable midspan water table height for the season.

DELH (cm): the increment for HMIN.

J: J controls the main loop of the program.

If J=0, only the existing field case without drains is evaluated.

If J=1, closed drains only are considered.

If J=2, open drains only are considered.

If J=3, both open and closed drains are evaluated.

The existing field case is considered for any J.

Card 5:

IT: The number of days in the period considered. The period is the length of the cycle that is required for the cropping pattern, irrigation pattern and dynamic equilibrium water table hydograph to repeat.

DSPCE (m): An initial trial value for the drain spacing.

DDPTH (m): An initial trial value for the drain depth. The value entered must be less than DMAX.

SFK1: A shape factor used in the simplified spacing depth equation which varies from π to 2/3.

SFK2: A shape factor used in the approximation of the drain discharge which varies from π to 4.

X (cm): The value of the depth to water below which crop damage will occur. This is the criteria used in the sum of excess water days proposed by Sieber (Bouwer, 1974).

SET 2: <u>Field Properties and Initial Conditions</u>

Card 1:

HYDK (cm/day): the saturated hydraulic conductivity.

SMFC: Volumetric soil moisture content at field capacity (.34 bars).

SMWP: Volumetric soil moisture content at wilting point (15 bars).

NDFC: Number of days until internal drainage ceases and field capacity is reached.

SMBEG: Volumetric soil moisture content at the beginning of the period considered, i.e. before the first irrigation.

SYA: Apparent specific yield.

Card 2:

ECRZI (mmhos/cm): The initial salinity of the root zone, i.e. before the first irrigation.

ECS (mmhos/cm): The salinity of the soil water saturated with indigenous root zone salts.

ECIRR (mmhos/cm): The salinity of the irrigation water.

A: (mmhos/cm): The salinity at initial yield decline.

B: Yield decrease per unit increase in salinity beyond the threshold value given by A. See Maas and Hoffman (1977).

Card 3:

FSLPE: The field slope. Also the bottom slope of the drains.

FLNTH (m): The length of the field. Also the length of the drains.

FWDTH (m): The field width measured perpendicular to the drain lines.

DIMP (m): The depth of soil to a lower impermeable layer.

DMAX (m): The maximum allowable drain depth. This is less than or equal to DIMP.

EPS (cm): An epsilon which specifies the allowable error in the drain spacing.

Card 4:

HSAT (cm): The height above the water table below which root respiration is assumed to cease.

PHICR (bars): The soil moisture suction above which soil moisture is assumed to be decreasingly available for plant use.

NDRD (days): The number of days that the roots can be below HSAT before root death occurs.

PHIRR (bars): The soil moisture suction above which an irrigation event is required. This is only used if ICHNG=1.

FL: The leaching fraction required if ICHNG=1.

ICHNG: If ICHNG=1, the program will determine an irrigation pattern internally. An irrigation event occurs if the soil moisture suction becomes equal to or greater than PHIRR. The quantity of irrigation water is determined to fill the soil moisture profile and provide the required leaching, as specified by FL. If ICHNG=0, the program will not change the irrigation pattern.

SET 3: Irrigation Data: One card for each irrigation event is required with the following information:

IRDAY (I): The day the irrigation event occurs.

QIRR (I): The depth of irrigation in cm.

GAMMA (I): A coefficient between 0 and 1 which specifies the efficiency of the irrigation. For example, large deep cracks in the soil layer may suggest a value for GAMMA which is less than 1.

SET 4: Crop Data

Card 1:

IGSB (I), I=1, NGS: The array IGSB gives the first day of each growth stage. For more than one crop, the period between harvesting one crop and planting the next is considered a growth stage. The coefficient YK for this growth stage is zero.

Card 2:

JCROP (I), LDS (I): For each crop, specify the planting and harvesting day for the crop. One card is required for each crop.

Card (NCROPS + 2) - YK (I), I = 1, NGS: The YK matrix is the matrix of coefficients used in the production function.

Card (NCROPS + 3) - YM (I), I = 1, NCROPS: The maximum yield for each crop.

SET 5: <u>Evapotranspiration Data</u>

Card 1:

NETIN: The number of daily values for the potential ET and coefficients that are going to be read in. NETIN could be equal to NDIS which means values for each day will be read. If the ET values remain the same for several days, only the first day and the values need to be entered.

Card 2 through (NETIN + 1):

NETIN cards are required. If NETIN equals NDIS, the ET rate and coefficient for each day are read. If the ET rate and coefficient remain the same for several days, only the data for the first of these days is required. Each card requires the following data:

NET (I): The day for which the ET and coefficient are valid.

CETP (I): The potential ET for day NET (I).

CCKO (I): The growth coefficient for NET (I).

SET 6: <u>Soil Moisture Data</u>

Card 1:

NSMIN: The number of soil moisture points which follow.

Card 2 to (NSMIN + 1):

These cards define the equilibrium volumetric soil moisture profile. NSMIN cards are required, each with the following data:

Z (I): Capillary pressure head in bars.

SMC (I): Volumetric water content.

SET 7: <u>Upflow Data</u>

Card 1:

NQS: Number of points which follow.

Card 2 to (NQS + 1):

The daily upflow of water from the water table is specified by the following input data. NQS cards are required, each with the following information.

Q (I): Groundwater depth below the bottom of the root zone in centimeters.

Q (I): The limiting steady upward flow rate in cm/day.

SET 8: Root Growth Data

Card 1:

NRDIN: The number of unstressed root depths read in.

Card 2 to (NRDIN + 1):

NRDIN cards each containing the following information:

INDAY (I): The day which corresponds to the root depth given.

OPTRD (I): The unstressed root depth on the day given

SET 9: Water Table Depths

Card 1:

NWDIN: Number of values of depth to water following.

Card 2 to (NWDIN + 1):

NWDIN cards are required, each containing the following:

INDTW (I): The day in the period when the depth to water was measured.

CDTW (I): The measured depth to the water table from ground surface in cm.

SET 10: Closed Drain Data. If open drains only or the existing field case only are to be analyzed, this data is not required.

Card 1:

C1 (I), I = 1, 10: Cost coefficients for closed drains. If C1, C2 and C3 are to be determined by subroutine LSQR, enter zeroes for these coefficients.

Card 2:

NPHIS: The number of drain diameters with corresponding material costs to be read in.

Card 3 to (NPHIS + 3):

If NPHIS = 0, no data is required. If NPHIS $\neq$ 0, enter NPHISM cards, each with the following data:

DIAM (I): Drain diameter in cm.

CDR (I): The cost of the drain in dollars per meter of length.

Card (NPHIS + 4):

RMIN (cm): The minimum allowable drain radius.

RN1: Manning's roughness coefficient.

RATE1: The rate used to convert present costs to uniform annual costs for closed drains.

DPM (m): The maximum allowable length of drain between manholes.

SET 11: <u>Open Ditch Data</u>. If only closed drains or the existing field case are to be analyzed, this data is not required.

Card 1:

C2 (I), I = 1,3: Cost coefficients for open ditches.

Card 2:

B1MIN (cm): The minimum bottom width of the ditch.

HMAX (cm): The maximum flow depth.

HMNM (cm): The minimum flow depth.

BERM (cm): The berm and spoil width on one side of the ditch.

RN2: Mannings roughness coefficient.

VMAX (m/s): The maximum allowable flow velocity.

SSLPE: The side slope of the ditch given as horizontal divided by vertical.

RATE2: The rate to be used to convert present costs to uniform annual costs for open ditches.

Table A1: Summary of Input Requirements

Set	Description	Number of Cards Required	Input Data	Format
1	Control Cards	1	Area	10A8
		1	Site	10A8
		1	NDIS, NGS, NIRR, NCROPS, INOUT	*
		1	HMINI, DELH, J	*
		1	IT, DSPCE, DDPTH, SFK1, SFK2, X	*
2	Field properties and initial conditions	1	HYDK, SMFC, SMWP, NDFC, SMBEG, SYA	*
		1	ECRZI, ECS, ECIRR, A, B	*
		1	FSLPE, FLNTH, FWDTH, DIMP, DMAX, EPS	*
		1	HSAT, PHICR, NDRD, PHIRR, FL, ICHNG	*
3	Irrigation Schedule	NIRR (1 card for each irrigation event)	IRDAY(I), QIRR(J), GAMMA(J)	*
4	Crop Data	1	IGSB(I), I = 1, NGS	*
		NCROPS (1 card for each crop season)	JCROP(I), LDS(I)	2I5
		1	YK(I), I = 1, NGS	*
		1	YM(I), I = 1, NCROPS	*
5	Evapotranspiration data	1	NETIN	I5
		Netin	NET(I), CETP(I), CCKO(I)	*

Table A1: Summary of Input Requirements (Continued)

Set	Description	Number of Cards Required	Input Data	Format
6	Soil moisture data	1	NSMIN	I5
		NSMIN	Z(I), SMC(I)	2F10.4
7	Upflow data	1	NQS	I5
		NQS	ZQ(I), Q(I)	2F10.4
8	Root growth data	1	NRDIN	I5
		NRDIN	INDAY(I), OPTRD(I)	I5,F10.3
9	Water table depths	1	NWDIN	I5
		NWTIN	INDTW(I), CDTW(I)	*
10	Closed drain data	1	C1(I), I=1,10	*
	(If J=2 or J=0, this	1	NPHIS	*
	set is not required)	NPHIS (if NPHIS = 0, this data is not required)	PHI(I), CPHI(I)	2F10.4
		1	RMIN, RN1, RATE1, DPM	*
11	Open ditch data	1	C2(I), I=1,3	*
	(if J=1 or J=0,	1	B1MIN, HMAX, HMNM, BERM, RN2,	*
	this set is not		VMAX, SSLPE, RATE2	
	required			

A.3 MAJOR VARIABLES USED IN DRAINS

ALPHA: An aquifer response coefficient equal to KD/Sya.

APEFF: An array containing the application efficiency for each irrigation.

AREA: Cross sectional area of the open ditch.

AW: Total available water in the soil profile.

BERM: The berm and spoil width on one side of an open ditch.

B1: Bottom width of an open ditch.

B1MIN: Minimum allowable bottom width of an open ditch.

CDR: An input array of drain costs in dollars per meter for various drain diameters in cm. Used in subroutine LSQR to determine material costs of closed drains as a quadratic function of the diameter.

CKO: An array of crop coefficients that relates a reference evapotranspiration to the maximum crop evapotranspiration.

CONST: A constant used in the optimization routine for open drains, defined in GRAD2.

C1: An array of cost coefficients for closed drains.

C2: An array of cost coefficients for open drains.

DAY: An integer which increments the day in the season.

DDEDB: The partial derivative of the equivalent drain depth, de, with respect to the bottom width of an open drain.

DDEDD: The partial derivative of the equivalent drain depth, de, with respect to the bottom width of an open drain.

DDEDK: The partial derivative of the equivalent drain depth, de, with respect to the hydraulic conductivity.

DDEDL: The partial derivative of the equivalent drain depth, de, with respect to the drain spacing.

DDPTH: The drain depth, i.e. the distance from the ground surface to the center line of a closed drain or the distance from ground surface to the water surface in an open drain.

DE: An equivalent drain depth, corrected for convergence at the drain.

DELH: The increment used for increasing HMIN.

DIAM: An array of drain diameters input with corresponding drain costs.

DIMP: Depth to the impermeable lower barrier in the soil profile.

DMAX: The maximum allowable drain depth.

DP: An array of deep percolation values.

DPM: Distance per manhole, i.e. the maximum length of closed drain which must have a manhole for access.

DSPCE: The drain spacing.

DTW: An array containing depths to water, i.e. the distance from ground surface to the water table.

ECIRR: The electrical conductivity of the irrigation water in mmhos/cm.

ECRZ: An array containing the average daily electrical conductivity of the root zone.

ECRZI: The initial electrical conductivity of the root zone just before the first irrigation.

ECS: The electrical conductivity of water saturated with indigeneous soil salts.

EPS: An input epsilon in cm which specifies the accuracy of the drain spacing determination.

ET: An array containing daily values of crop evapotranspiration demand.

ETP: An array of maximum daily evapotranspiration rates. The product of maximum daily evapotranspiration and a crop coefficient is the crop evapotranspiration demand.

FL: Leaching fraction.

FLNTH: Field length or drain length.

FSLPE: Field slope or bottom slope of the drain.

FWDTH: Field width.

GAMMA: An array of coefficients which range from zero to one and are used to specify leaching efficiency.

HMAX: The maximum allowable depth of flow in an open drain.

HMIN: The minimum allowable depth to water midway between the drains.

HMINI: The initial i.e. smallest value of HMIN considered. The program increments HMIN by DELH from HMINI.

HMNM: The minimum allowable depth of flow in an open drain.

HSAT: The height above the water table below which root respiration is assumed to cease.

HYDK: The saturated hydraulic conductivity of the soil.

ICHNG: An input control variable. If ICHNG = 1, the program will determine an irrigation regime internally. If ICHNG = 0, the input irrigation regime will not be modified.

IGSB: An array of input values which specify the first day of each crop growth stage.

IJ: A control variable used to store the input value of J.

INDAY: An array of values giving the day of an input unstressed root depth.

INDIAM: The number of drain diameters and corresponding drain costs that will input.

IRDAY: An array containing each day that an irrigation event occurs.

IT: The time interval for a complete cycle of irrigation events.

J: An input control variable. If J=0, only the existing field case is evaluated. If J=1, the existing field case and closed drains are considered. If J=2, the existing field case and open drain systems are considered. If J=3, closed drains, open drains and the existing field case are evaluated.

JCROP: An array containing the first days of each crop season.

LMAX: The maximum allowable drain spacing. This is assumed to be the smaller of the field width and a spacing which requires a drain on the impermeable lower barrier or at DMAX.

NCROPS: The number of crops.

NDIS: The number of days from the planting date of the first crop to the harvest date of the last crop in the irrigation cycle.

NDRD: The number of days that roots can be subjected to anaerobic conditions without root death.

NGS: The total number of growth stages for all crops.

NIRR: The total number of irrigation events in one complete irrigation cycle.

NQS: The number of values input which specify upflow rates from the water table.

NRDIN: The number of unstressed root depths input.

NSMIN: The number of volumetric soil moisture contents input.

OPTRD: An array containing unstressed root depths.

OS: Average osmotic suction in the root zone in bars.

PHICR: An input suction in bars between field capacity and wilting point. If the average root zone soil moisture suction is less than or equal to PHICR, the soil moisture is readily available for plant uptake and use. Soil moisture is decreasingly available for plant use from PHICR to a suction of 15 bars (wilting point).

PHIRR: An input suction in bars. When ICHNG = 1, the program will schedule an irrigation event when the average root zone suction is greater than or equal to PHIRR.

Q: An array containing maximum daily upflow rates from the water table. The value of the entries in array Q are input for different distances between the water table and the bottom of the root zone. Q is also used as a variable in ALPH1 to store the discharge of the drains.

QFLOW: An array containing the quantity of water supplied from the water table for plant evapotranspiration.

QLIM: The limiting upflow rate from the water table to the root zone depending on the distance between the root zone and the water table.

Q1: The discharge of open or closed drains determined from Manning's equation.

R: The drain radius

RATE1: The rate used in the cost analysis of closed drains, usually an interest rate, discount rate or opportunity cost.

RATE2: The rate used in the cost analysis of open drains.

RD: An array containing daily values for root depths.

RMIN: The minimum allowable drain radius.

RN1: Manning's roughness coefficient for closed drains.

RN2: Manning's roughness coefficient for open drains.

SFK1: A shape factor which ranges from $\pi/2$ to 2 used in the approximation for the drain depth in the optimization routine.

SFK2: A shape factor which ranges from π to 4 used in the approximation for drain capacity.

SM: An array containing daily average root zone soil moisture suctions.

SMAVG: The average suction in the soil moisture profile from the water table to the ground surface.

SMBEG: The initial average suction of the soil moisture prior to the first irrigation.

SMC: An array of soil moisture suctions in bars input with the Z array which define an equilibrium volumetric soil moisture profile.

SMFC: Soil moisture suction in bars at field capacity.

SMWP: Soil moisture suction in bars at wilting point.

SLPE: Side slope of the open ditch.

SYA: Apparent specific yield.

T: The time interval for a complete cycle of irrigation events.

VEL: The flow velocity in an open ditch.

VMAX: The maximum allowable flow velocity in an open ditch.

WTCONT: The percent of the total daily evapotranspiration supplied from the water table.

WTH: An array containing midspan water table heights above drain level.

WTMAX: The maximum midspan water table height for the period.

X: The limit in the SEW_x procedure above which the water table will cause crop damage.

YA: An array containing the computed yield of each crop.

YK: An array containing crop response factors for each crop growth stage, used in the production function for determining crop yield.

YM: An array of maximum crop yields.

Z: An array of capillary pressures in cm input with the SMC array to define the equilibrium soil moisture retention curve. Z is also used for the objective function in the cost optimization.

Z1: The distance in cm between the water table and the bottom of the root zone.

ZQ: An array of distances input with the Q matrix to specify uptake rates from the water table.

APPENDIX B

EXAMPLE PROGRAM INPUT AND OUTPUT

B.1 EXAMPLE INPUT

```
EXAMPLE
FARM 5, FIELD 2
116,5,10,1,1
100.,725.,1
365,2000.,300.,.6366,3.14156,100.
3.5,.48,.125,2,.47,.06
3.64,6.5,.32,1.7,12.
30.,.340,3,8.4,.4,0
1,16.6,1.0
29,8.1,1.0
45,5.0,1.0
54,6.0,1.0
62,6.2,1.0
69,7.0,1.0
76,6.0,1.0
83,5.0,1.0
93,8.0,1.0
102,7.0,1.0
1,21,54,69,102
1,116
0.0,.4,1.5,.5,.2
14.25
   10
1,.582,.513
29,.826,.73
45,.684,.92
54,.823,1.04
62,.857,1.08
69,.794,1.11
76,.773,1.12
83,.74,1.1
93,.69,1.02
102,.624,.805
    2
  30.        .54
  340.       .48
    7
  40.       .40
  50.       .15
  69.       .128
  78.       .087
  80.       .0869
 100.       .05
 130.        .01
```

```
     4
     1   .1
    21  30.
    69  100.
   116  100.
    10
 1,78.
 29,66.
 45,77.
 54,90.
 62,56.
 69,50.
 76,62.
 83,71.
 93,64.
102,55.
0.,0.,0.,.1,.01,0.0,0.,.3,.3,0.
5
8.,.74
10.,.90
15.,2.66
20.,4.92
25.,8.2
4.,.0015,.202,200.
```

B.2 EXAMPLE OUTPUT

EXAMPLE

SITE=FARM 5, FIELD 2

INPUT DATA

J = 1 INITIAL HMIN =100.00 CM
NO. OF DAYS IN SEASON = 116
NO. OF IRRIGATIONS = 10
NO. OF DAYS TO FIELD CAPACITY = 2
PERIOD = 365
EC OF THE IRRIGATION WATER = .32
SHAPE FACTORS: K1 = .64 K2 = 3.14
PHI CRITICAL = .34

HMIN INTERVAL =725.00 CM
NO. OF GROWTH STAGES = 5
NO. OF CROPS = 1
NO. OF DAYS UNTIL ROOT DEATH = 3
SATURATED HT. ABOVE W.T. = 30.0 CM
ECS = 6.50 MMHOS PER CM
SEWX: X = 100.00

IRRIGATION SCHEDULE

DAY	QUANTITY(CM)	GAMMA
1	16.60	1.000
29	8.10	1.000
45	5.00	1.000
54	6.00	1.000
62	6.20	1.000
69	7.00	1.000
76	6.00	1.000
83	5.00	1.000
93	8.00	1.000
102	7.00	1.000

NOTE:ICHNG=0

FIELD GEOMETRY AND SOIL PROPERTIES

FIELD LENGTH = 100.00 METERS
FIELD SLOPE = .00160
APPARENT SPECIFIC YIELD = .060
INITIAL SOIL MOISTURE = .470

FIELD WIDTH = 100.00 METERS
DEPTH TO IMPERMEABLE LAYER = 700.00 CMS
HYDRAULIC CONDUCTIVITY = 3.50 CM PER DAY
INITIAL SALINITY = 3.640 MMHOS PER CM

SOIL MOISTURE PROFILE:

Z	SMC
30.000	.54000
340.000	.48000

UPFLOW:

Z	QLIM
40.000	.40000
50.000	.15000
69.000	.12800
78.000	.08700
80.000	.08690
100.000	.05000
130.000	.01000

CROP DATA

CROP 1 PLANTED ON DAY 1 ,MAXIMUM YIELD IS 14.25

GROWTH STAGE	FIRST DAY	YK
1	1	0.00
2	21	.40
3	54	1.50
4	69	.50
5	102	.20

ROOT DEPTHS(CM):

DAY	ROOT DEPTH
1	.10
21	30.00
69	100.00
116	100.00

CLOSED DRAIN DATA

COSTS:

C1 = .5263 DOLLARS PER METER
C2 = -.1195 DOLLARS PER METER PER CM
C3 = .0170 DOLLARS PER METER PER CM SQUARED
C4 = .1000 DOLLARS PER METER
C5 = .0100 DOLLARS PER METER PER YEAR
C6 = 0.0000 DOLLARS
C7 = 0.0000 DOLLARS
C8 = .3000 DOLLARS PER METER
C9 = .3000 DOLLARS PER METER SQUARED
C10= 0.0000 DOLLARS

RMIN = 4.0000 CM
ROUGHNESS COEFFICIENT = .0015
RATE = .2020
DISTANCE PER MANHOLE = 200.00 METERS

ANALYSIS OF EXISTING FIELD

TOTAL ET FOR SEASON= 65.499 TOTAL W.T. CONTRIBUTION= 20.140

IRR= 1 DAY= 1 APPLIED=16.6000 PERCOLATED=10.7658 APPLICATION EFF= 35.1456
IRR= 2 DAY= 29 APPLIED= 8.1000 PERCOLATED= 2.8471 APPLICATION EFF= 64.8503
IRR= 3 DAY= 45 APPLIED= 5.0000 PERCOLATED= 0.0000 APPLICATION EFF=100.0000
IRR= 4 DAY= 54 APPLIED= 6.0000 PERCOLATED= 1.2981 APPLICATION EFF= 78.3650
IRR= 5 DAY= 62 APPLIED= 6.2000 PERCOLATED= 1.1835 APPLICATION EFF= 80.9111
IRR= 6 DAY= 69 APPLIED= 7.0000 PERCOLATED= 2.6787 APPLICATION EFF= 61.7325
IRR= 7 DAY= 76 APPLIED= 6.0000 PERCOLATED= 2.0034 APPLICATION EFF= 66.6102
IRR= 8 DAY= 83 APPLIED= 5.0000 PERCOLATED= .9692 APPLICATION EFF= 80.6158
IRR= 9 DAY= 93 APPLIED= 8.0000 PERCOLATED= 2.4732 APPLICATION EFF= 69.0855
IRR=10 DAY=102 APPLIED= 7.0000 PERCOLATED= 3.1634 APPLICATION EFF= 54.8092

TOTAL WATER APPLIED= 74.90 CM TOTAL WATER PERCOLATED= 27.38 CM

MAX EC IN ROOT ZONE= 7.02 MMHOS/CM MIN SM=.3955

SUMMARY OF ROOT ZONE CONDITIONS

DAY	AVG SMRZ	ETA CM	ECRZ MMHOS	ROOT DEPTH CM	DTW CM	W.T. CM	CONTRIBUTION PERCENT
1	.5307	.2986	2.6348	.1000	78.0000	.2986	100.00
2	.5309	.2986	2.6348	1.5950	78.0000	.2986	100.00
3	.4706	.2878	3.9964	3.0900	79.6846	.1011	35.12
4	.4525	.2726	4.5238	4.5850	81.3548	.1002	36.76
5	.4452	.2600	4.7864	6.0800	83.0117	.0994	38.24
6	.4413	.2546	4.9419	7.5750	84.6564	.0987	38.76
7	.4389	.2516	5.0443	9.0700	86.2896	.0980	38.95
8	.4372	.2497	5.1166	10.5650	87.9124	.0974	39.00
9	.4360	.2483	5.1704	12.0600	89.5254	.0968	38.98
10	.4351	.2472	5.2119	13.5550	91.1295	.0962	38.93
11	.4343	.2464	5.2449	15.0500	92.7253	.0957	38.86
12	.4336	.2457	5.2717	16.5450	94.3135	.0953	38.78
13	.4331	.2451	5.2941	18.0400	95.8946	.0949	38.70
14	.4326	.2446	5.3130	19.5350	97.4691	.0945	38.62
15	.4322	.2442	5.3292	21.0300	99.0376	.0941	38.54
16	.4318	.2438	5.3432	22.5250	100.6006	.0938	38.47
17	.4314	.2434	5.3555	24.0200	102.1583	.0935	38.40
18	.4311	.2431	5.3665	25.5150	103.7114	.0932	38.33
19	.4308	.2428	5.3762	27.0100	105.2600	.0929	38.27
20	.4305	.2425	5.3850	28.5050	106.8045	.0927	38.22
21	.4302	.2422	5.3930	30.0000	108.3453	.0924	38.16
22	.4298	.2419	5.4028	31.4583	109.8798	.0921	38.06
23	.4295	.2416	5.4117	32.9167	111.4085	.0917	37.97
24	.4291	.2412	5.4198	34.3750	112.9319	.0914	37.89
25	.4288	.2409	5.4273	35.8333	114.4503	.0911	37.82
26	.4285	.2406	5.4343	37.2917	115.9642	.0908	37.75
27	.4282	.2403	5.4408	38.7500	117.4739	.0906	37.69

28	.4279	.2401	5.4468	40.2083	118.9796	.0903	37.63
29	.5365	.6030	3.3992	36.0000	66.0000	.6030	100.00
30	.5365	.6030	3.3992	36.0000	66.0000	.6030	100.00
31	.5346	.6030	3.6021	36.0000	76.0497	.6030	100.00
32	.5328	.6030	3.7978	37.4583	86.0993	.6030	100.00
33	.5238	.5743	3.8897	38.9167	89.7732	.2204	38.38
34	.5136	.5680	3.9752	40.3750	92.5240	.1650	29.06
35	.5039	.5642	4.0543	41.8333	95.0106	.1492	26.45
36	.4950	.5616	4.1299	43.2917	97.4775	.1480	26.35
37	.4866	.5592	4.2027	44.7500	99.9248	.1468	26.26
38	.4788	.5570	4.2729	46.2083	102.3531	.1457	26.16
39	.4715	.5535	4.3402	47.6667	104.7627	.1446	26.12
40	.4648	.5431	4.4035	49.1250	107.1539	.1435	26.41
41	.4586	.5336	4.4631	50.5833	109.5271	.1424	26.69
42	.4529	.5247	4.5192	52.0417	111.8826	.1413	26.94
43	.4477	.5164	4.5720	53.5000	114.2208	.1403	27.17
44	.4428	.5087	4.6217	54.9583	116.5421	.1393	27.38
45	.5291	.6293	0.0000	47.0000	77.0000	.6293	100.00
46	.5157	.6293	3.6781	47.0000	77.0000	.6293	100.00
47	.5137	.6293	3.8468	47.0000	87.4880	.6293	100.00
48	.5124	.6293	4.0112	48.4583	97.9760	.6293	100.00
49	.5052	.5918	4.1060	49.9167	101.2846	.1985	33.54
50	.4970	.5856	4.1981	51.3750	103.8223	.1523	26.00
51	.4894	.5828	4.2861	52.8333	106.3032	.1489	25.54
52	.4822	.5803	4.3716	54.2917	108.7644	.1477	25.45
53	.4754	.5779	4.4545	55.7500	111.2062	.1465	25.35
54	.5339	.8559	3.7703	57.2083	90.0000	.8559	100.00
55	.5341	.8559	3.7703	58.6667	90.0000	.8559	100.00
56	.5314	.8559	3.9439	60.0000	104.2653	.3559	100.00
57	.5229	.8118	4.0692	60.1250	109.2069	.2965	36.52
58	.5127	.8012	4.1863	61.5833	112.6971	.2094	26.14
59	.5025	.7925	4.2956	63.0417	115.3406	.1586	20.01
60	.4928	.7872	4.4015	64.5000	117.8244	.1490	18.93
61	.4837	.7828	4.5059	65.9583	120.2884	.1478	18.89
62	.5375	.9256	3.9554	26.0000	56.0000	.9256	100.00
63	.5375	.9256	3.9554	26.0000	56.0000	.9256	100.00
64	.5345	.9256	4.3859	26.0000	[illegible]	.9256	100.00
65	.5140	.8686	4.6674	27.4583	[illegible]	.3008	34.63
66	.4921	.8509	4.9341	28.9167	[illegible]	.2119	24.91
67	.4713	.8348	5.1837	30.3750	[illegible]	.1601	19.18
68	.4531	.8065	5.4173	31.8333	85.1241	.1491	18.48
69	.5381	.8813	3.9457	20.0000	50.0000	.8813	100.00
70	.5381	.8813	3.9457	20.0000	50.0000	.8813	100.00
71	.5352	.8813	4.4781	20.0000	64.6890	.8813	100.00
72	.5116	.8282	4.8384	21.4583	70.0096	.3192	38.55
73	.4867	.8084	5.1713	22.9167	73.7209	.2227	27.54
74	.4634	.7904	5.4777	24.3750	76.4934	.1664	21.05
75	.4438	.7467	5.7519	25.8333	78.9807	.1492	19.99
76	.5364	.8658	4.0559	27.2917	62.0000	.8658	100.00
77	.5366	.8658	4.0559	28.7500	62.0000	.8658	100.00
78	.5339	.8658	4.4030	30.2083	76.4293	.8658	100.00
79	.5152	.8092	4.6649	30.2083	80.5039	.2445	30.21
80	.4932	.7918	4.9387	30.2083	82.9982	.1497	18.90
81	.4717	.7808	5.2305	30.2083	85.4444	.1468	18.80

82	.4510	.7550	5.5392	30.2083	87.8433	.1439	19.07
83	.5350	.8140	4.2153	30.2083	71.0000	.8140	100.00
84	.5350	.8140	4.2153	30.2083	71.0000	.8140	100.00
85	.5219	.7762	4.4780	30.2083	77.3368	.3802	48.98
86	.5029	.7566	4.7414	30.2083	81.0333	.2218	29.31
87	.4826	.7411	5.0074	30.2083	83.5174	.1490	2[illegible].11
88	.4628	.7314	5.2902	30.2083	85.9535	.1462	19.98
89	.4441	.6931	5.5821	30.2083	88.3426	.1433	20.68
90	.4267	.6519	5.8804	30.2083	90.6856	.1406	21.56
91	.4105	.6128	6.1844	30.2083	92.9835	.1379	22.50
92	.3955	.5755	6.4928	30.2083	95.2369	.1352	23.49
93	.5363	.7038	4.1392	30.2083	64.0000	.7038	100.00
94	.5363	.7038	4.1392	30.2083	64.0000	.7038	100.00
95	.5341	.7038	4.42[illegible]5	30.2083	75.7300	.7038	100.00
96	.5208	.6633	4.6426	30.2083	80.0960	.2620	39.49
97	.5035	.6482	4.8669	30.2083	82.6428	.1528	23.57
98	.4867	.6411	5.1004	30.2083	85.0958	.1472	22.96
99	.4700	.6341	5.3475	30.2083	87.5015	.1443	22.76
100	.4539	.6131	5.6040	30.2083	89.8607	.1416	23.09
101	.4388	.5832	5.8658	30.2083	92.1745	.1388	23.80
102	.5376	.5023	4.0374	25.0000	55.0000	.5023	100.00
103	.5376	.5023	4.0374	25.0000	55.0000	.5023	100.00
104	.5360	.5023	4.2803	25.0000	63.3720	.5023	100.00
105	.5343	.5023	4.5240	25.0000	71.7440	.5023	100.00
106	.5245	.4768	4.7234	25.0000	75.6007	.2314	48.54
107	.5111	.4663	4.9234	25.0000	78.0891	.1493	32.02
108	.4980	.4625	5.1296	25.0000	80.5295	.1464	31.66
109	.4849	.4586	5.3449	25.0000	82.9228	.1436	31.31
110	.4719	.4546	5.5699	25.0000	85.2699	.1408	30.98
111	.4592	.4432	5.8017	25.0000	87.5717	.1381	31.16
112	.4471	.4274	6.0378	25.0000	89.8291	.1354	31.69
113	.4355	.4120	6.2779	25.0000	92.0429	.1328	32.24
114	.4244	.3968	6.5218	25.0000	94.2140	.1303	32.83
115	.4138	.3817	6.7687	25.0000	96.3311	.12[illegible]0	33.28
116	.4035	.3646	7.0171	25.0000	98.2874	.1174	32.20

THE SUM OF EXCESS WATER DAYS ABOVE 100.00 IS 85
THE SOIL MOISTURE CONTENT IS AT WILTING POINT 0 DAYS
YIELD REDUCTION DUE TO SALINITY, PER MAAS,ET.AL.,1977 IS 36.2 PERCENT
ET IS LESS THAN POTENTIAL 85 DAYS

YIELD DATA, CROP 1

ACTUAL YIELD= 11.92 MAXIMUM YIELD= 14.25

ANALYSIS FOR HMIN= 100.00000

THE APPROX FOR HCMAX IS 11.6534 TOO HIGH
CHANGE SFK1 IF BETTER ACCURACY IS DESIRED
APPROX HCMAX= 243.9919 ACTUAL HCMAX= 232.3385
THE APPROX FOR HCMAX IS 5.4082 TOO HIGH
CHANGE SFK1 IF BETTER ACCURACY IS DESIRED
APPROX HCMAX= 403.5229 ACTUAL HCMAX= 398.1147
THE SUM OF EXCESS WATER DAYS ABOVE 100.00 IS 0
THE SOIL MOISTURE CONTENT IS AT WILTING POINT 0 DAYS
YIELD REDUCTION DUE TO SALINITY, PER MAAS,ET.AL.,1977 IS 23.3 PERCENT
ET IS LESS THAN POTENTIAL 96 DAYS

SUMMARY OF ROOT ZONE CONDITIONS

DAY	AVG SMRZ	ETA CM	ECRZ MMHOS	ROOT DEPTH CM	DTW CM	W.T. CM	CONTRIBUTION PERCENT
1	.5189	.2986	2.7990	.1000	137.0241	.2986	100.00
2	.5189	.2986	2.7990	1.5950	139.7639	.2986	100.00
3	.4271	.2829	3.7896	3.0900	142.0339	0.0000	0.00
4	.4072	.2269	4.1161	4.5850	143.9247	0.0000	0.00
5	.4002	.2076	4.2611	6.0800	145.5103	0.0000	0.00
6	.3969	.2006	4.3414	7.5750	146.8506	0.0000	0.00
7	.3951	.1972	4.3919	9.0700	147.9941	0.0000	0.00
8	.3939	.1953	4.4261	10.5650	148.9801	0.0000	0.00
9	.3932	.1941	4.4508	12.0600	149.8403	0.0000	0.00
10	.3927	.1933	4.4692	13.5550	150.6002	0.0000	0.00
11	.3924	.1927	4.4833	15.0500	151.2802	0.0000	0.00
12	.3921	.1923	4.4945	16.5450	151.8969	0.0000	0.00
13	.3919	.1920	4.5035	18.0400	152.4633	0.0000	0.00
14	.3918	.1918	4.5109	19.5350	152.9899	0.0000	0.00
15	.3917	.1916	4.5170	21.0300	153.4851	0.0000	0.00
16	.3917	.1915	4.5220	22.5250	153.9555	0.0000	0.00
17	.3916	.1914	4.5263	24.0200	154.4062	0.0000	0.00
18	.3919	.1952	4.5339	25.5150	155.0231	.0109	5.58
19	.3921	.1958	4.5413	27.0100	155.6476	.0121	6.17
20	.3923	.1963	4.5484	28.5050	156.2819	.0133	6.75
21	.3926	.1969	4.5552	30.0000	156.9279	.0144	7.32
22	.3926	.1974	4.5634	31.4583	157.5859	.0155	7.86
23	.3927	.1978	4.5712	32.9167	158.2568	.0166	8.38
24	.3928	.1981	4.5786	34.3750	158.9415	.0176	8.90
25	.3929	.1985	4.5857	35.8333	159.6402	.0187	9.41
26	.3930	.1989	4.5926	37.2917	160.3533	.0197	9.90
27	.3931	.1993	4.5992	38.7500	161.0809	.0207	10.38
28	.3932	.1997	4.6055	40.2083	162.1842	.0217	10.85
29	.5293	.6030	2.9198	41.6667	105.9210	.6030	100.00
30	.5293	.6030	2.9198	43.1250	106.7210	.6030	100.00
31	.5194	.5783	3.0106	44.5833	109.6997	.1351	23.36
32	.5097	.5755	3.1007	46.0417	112.5912	.1334	23.18
33	.5006	.5727	3.1880	47.5000	115.4088	.1318	23.01

34	.4920	.5701	3.2725	48.9583	118.1629	.1303	22.85
35	.4840	.5676	3.3545	50.4167	120.8623	.1288	22.69
36	.4764	.5651	3.4337	51.8750	123.4850	.1257	22.24
37	.4692	.5582	3.5094	53.3333	126.0017	.1204	21.58
38	.4625	.5470	3.5811	54.7917	128.4243	.1157	21.15
39	.4563	.5363	3.6490	56.2500	130.7630	.1113	20.76
40	.4505	.5262	3.7134	57.7083	133.0266	.1074	20.40
41	.4451	.5167	3.7744	59.1667	135.2228	.1037	20.08
42	.4400	.5077	3.8323	60.6250	137.3585	.1004	19.77
43	.4353	.4991	3.8872	62.0833	139.4395	.0973	19.50
44	.4308	.4911	3.9393	63.5417	143.0460	.0945	19.24
45	.5057	.6293	3.1163	65.0000	141.9263	.6293	100.00
46	.5057	.6293	3.1163	66.4583	142.3809	.6293	100.00
47	.4989	.5947	3.1767	67.9167	144.5195	.1010	16.99
48	.4921	.5924	3.2378	69.3750	146.6069	.0979	16.53
49	.4855	.5901	3.2975	70.8333	148.6475	.0951	16.11
50	.4792	.5879	3.3558	72.2917	150.6451	.0924	15.72
51	.4731	.5847	3.4128	73.7500	152.6033	.0899	15.38
52	.4674	.5745	3.4679	75.2083	154.5253	.0877	15.26
53	.4620	.5649	3.5211	76.6667	157.8879	.0870	15.40
54	.5136	.8559	3.1253	78.1250	156.9037	.8559	100.00
55	.5136	.8559	3.1253	79.5833	157.3716	.8559	100.00
56	.5050	.8079	3.1949	81.0417	159.3832	.0925	11.45
57	.4964	.8041	3.2657	82.5000	161.3554	.0899	11.18
58	.4881	.8003	3.3360	83.9583	163.2911	.0876	10.94
59	.4801	.7967	3.4058	85.4167	165.2198	.0870	10.92
60	.4725	.7932	3.4752	86.8750	167.1512	.0870	10.96
61	.4653	.7757	3.5431	88.3333	170.5341	.0869	11.21
62	.5156	.9256	3.1795	89.7917	169.5735	.9256	100.00
63	.5156	.9256	3.1795	91.2500	170.0650	.9256	100.00
64	.5073	.8723	3.2440	92.7083	172.0210	.0877	10.05
65	.4989	.8685	3.3101	94.1667	173.9688	.0870	10.02
66	.4909	.8647	3.3761	95.6250	175.9196	.0870	10.06
67	.4832	.8609	3.4419	97.0833	177.8733	.0869	10.10
68	.4757	.8573	3.5077	98.5417	181.2785	.0869	10.14
69	.5205	.8813	3.1887	100.0000	180.3417	.8813	100.00
70	.5205	.8813	3.1887	100.0000	180.8568	.8813	100.00
71	.5129	.8319	3.2465	100.0000	182.7815	.0844	10.14
72	.5051	.8284	3.3074	100.0000	184.6503	.0808	9.75
73	.4972	.8247	3.3696	100.0000	186.4651	.0774	9.38
74	.4894	.8210	3.4333	100.0000	188.2275	.0740	9.01
75	.4816	.8173	3.4985	100.0000	191.1181	.0707	8.66
76	.5185	.8658	3.2202	100.0000	190.4752	.8658	100.00
77	.5185	.8658	3.2202	100.0000	191.0148	.8658	100.00
78	.5109	.8150	3.2764	100.0000	192.6508	.0656	8.05
79	.5031	.8115	3.3353	100.0000	194.2399	.0626	7.71
80	.4953	.8079	3.3956	100.0000	195.7834	.0596	7.38
81	.4875	.8043	3.4573	100.0000	197.2828	.0568	7.06
82	.4798	.8007	3.5205	100.0000	199.6391	.0540	6.74
83	.5148	.8140	3.2782	100.0000	199.2994	.8140	100.00
84	.5148	.8140	3.2782	100.0000	199.8629	.8140	100.00
85	.5073	.7634	3.3314	100.0000	201.2534	.0494	6.47
86	.5001	.7603	3.3868	100.0000	202.6162	.0476	6.26
87	.4927	.7571	3.4436	100.0000	203.9518	.0457	6.04

88	.4854	.7539	3.5017	100.0000	205.2609	.0440	5.83
89	.4781	.7507	3.5612	100.0000	206.5440	.0422	5.62
90	.4708	.7438	3.6219	100.0000	207.8015	.0405	5.44
91	.4636	.7266	3.6829	100.0000	209.0341	.0388	5.34
92	.4567	.7096	3.7444	100.0000	210.8617	.0372	5.24
93	.5146	.7038	3.2895	100.0000	210.8337	.7038	100.00
94	.5146	.7038	3.2895	100.0000	211.4282	.7038	100.00
95	.5082	.6593	3.3351	100.0000	212.5916	.0340	5.15
96	.5017	.6569	3.3823	100.0000	213.7318	.0324	4.93
97	.4953	.6545	3.4305	100.0000	214.8494	.0309	4.72
98	.4888	.6520	3.4796	100.0000	215.9447	.0294	4.51
99	.4824	.6496	3.5297	100.0000	217.0183	.0279	4.30
100	.4760	.6471	3.5809	100.0000	218.0706	.0265	4.09
101	.4696	.6380	3.6327	100.0000	219.5200	.0251	3.93
102	.5199	.5023	3.2432	100.0000	182.8526	.5023	100.00
103	.5199	.5023	3.2432	100.0000	183.7465	.5023	100.00
104	.5158	.4754	3.2790	100.0000	185.9025	.0784	16.50
105	.5114	.4741	3.3168	100.0000	187.9574	.0745	15.72
106	.5070	.4728	3.3547	100.0000	189.9214	.0708	14.97
107	.5025	.4715	3.3929	100.0000	191.8032	.0672	14.25
108	.4981	.4701	3.4313	100.0000	193.6100	.0637	13.56
109	.4937	.4688	3.4701	100.0000	195.3479	.0604	12.89
110	.4893	.4674	3.5092	100.0000	197.0219	.0573	12.25
111	.4848	.4660	3.5486	100.0000	198.6366	.0542	11.63
112	.4804	.4647	3.5883	100.0000	200.1956	.0512	11.02
113	.4759	.4633	3.6285	100.0000	201.7100	.0488	10.53
114	.4715	.4575	3.6688	100.0000	203.1875	.0468	10.23
115	.4672	.4511	3.7092	100.0000	204.6299	.0448	9.94
116	.4629	.4448	3.7497	100.0000	206.0387	.0429	9.64

```
IRR= 1 DAY=  1 APPLIED=16.6000 PERCOLATED=10.7658 APPLICATION EFF= 35.1456
IRR= 2 DAY= 29 APPLIED= 8.1000 PERCOLATED= 1.5609 APPLICATION EFF= 80.7300
IRR= 3 DAY= 45 APPLIED= 5.0000 PERCOLATED= 0.0000 APPLICATION EFF=100.0000
IRR= 4 DAY= 54 APPLIED= 6.0000 PERCOLATED= 0.0000 APPLICATION EFF=100.0000
IRR= 5 DAY= 62 APPLIED= 6.2000 PERCOLATED= 0.0000 APPLICATION EFF=100.0000
IRR= 6 DAY= 69 APPLIED= 7.0000 PERCOLATED=  .5839 APPLICATION EFF= 91.6579
IRR= 7 DAY= 76 APPLIED= 6.0000 PERCOLATED=  .7143 APPLICATION EFF= 88.0957
IRR= 8 DAY= 83 APPLIED= 5.0000 PERCOLATED= 0.0000 APPLICATION EFF=100.0000
IRR= 9 DAY= 93 APPLIED= 8.0000 PERCOLATED=  .3551 APPLICATION EFF= 95.5611
IRR=10 DAY=102 APPLIED= 7.0000 PERCOLATED= 1.1607 APPLICATION EFF= 83.4187
```

YIELD DATA, CROP 1
ACTUAL YIELD= 11.95 MAXIMUM YIELD= 14.25

SENSITIVITY ANALYSIS
DZ/DK= -.267E-05
DZ/DSYA= -.606E-05

COST SUMMARY FOR CLOSED DRAINS

LEVEL	SPACING METERS	DEPTH METERS	COST FOR FIELD DOLLARS
1	99.9874	5.0311	.5294036E+06

EGYPT WATER USE AND MANAGEMENT PROJECT

PROJECT TECHNICAL REPORTS

NO.	TITLE	AUTHOR
PTR#1	Problem Identification Report for Mansuriya Study Area, 10/77 to 10/78.	By: Egyptian and American Field Teams.
PTR#2	Preliminary Soil Survey Report for the Beni Magdul and El-Hammami Areas.	By: A. D. Dotzenko, M. Zanati, A. A. Abdel Wahed, & A. M. Keleg.
PTR#3	Preliminary Evaluation of Mansuriya Canal System, Giza Governorate, Egypt.	By: American and Egyptian Field Teams.
PTR#5	Economic Costs of Water Shortage Along Branch Canals.	By: A. El Shinnawi M. Skold & M. Nasr
PTR#6	Problem Identification Report For Kafr El-Sheikh Study Area.	Egyptian and American Field Teams.
PTR#7	A Procedure for Evaluating the Cost of Lifting Water for Irrigation in Egypt.	By: H. Wahby, M. Quenemoen, and M. Helal.
PTR#9	Irrigation & Production of Rice in Abu Raya, Kafr El-Sheikh Governorate.	Compiled By: R. Tinsley.
PTR#10	Soil Fertility Survey in Kafr El-Sheikh, El Mansuriya and El-Minya Pilot Projects.	By: Zanati, Soltanpour, Mostafa, & Keleg.
PTR#11	Kafr El-Sheikh Farm Management Survey Crop Enterprise Budgets and Profitability Analysis.	By: M. Haider & F. Abdel Al.
PTR#12	Use of Feasibility Studies in the Selection and Evaluation of Pilot Studies for Alternative Methods of Water Distribution in Egypt.	By: R. McConnen, F. Abdel Al, M. Skold, and G. Ayad.
PTR#13	The Role of Rural Sociologists in an Interdisciplinary, Action-Oriented Project: An Egyptian Case Study.	By: J. Layton and M. Sallam.

NO.	TITLE	AUTHOR
PTR#15	Village Bank Loans to Egyptian Farmers.	By: G. Ayad, M. Skold, and M. Quenemoen.
PTR#18	Population Growth and Development in Egypt: Farmers' and Rural Development Officials' Perspectives.	By: M. Sallam, E.C. Knop and S.A. Knop.
PTR#19	Effective Extension for Egyptian Rural Development: Farmers' and Officials' Views on Alternative Strategies.	By: E.C. Knop, M. Sallam, and S.A. Knop.
PTR#20	The Rotation Water Distribtuion System vs. The Continual Flow Water Distribution System.	By: M. El-Kady, J. Wolfe and H. Wahby.
PTR#21	El-Hammami Pipeline Design.	By: Fort Collins Staff Team.
PTR#22	The Hydraulic Design of Mesqa 10, An Egyptian Irrigation Canal.	By: W.O. Ree, M. El-Kady, J. Wolfe, and W. Fahim.
PTR#23	Farm Record Summary and Analysis for Study Cases at Abyuha, Mansuriya and Abu Raya Sites, 79/80.	By: F. Abdel Al, and M. Skold.
PTR#24	Agricultural Pests and Their Control.	By: E. Attalla.
PTR#26	Social Dimensions of Egyptian Irrigation Patterns.	By: E.C. Knop, M. Sallam, S.A. Knop and M. El-Kady.
PTR#28	Economic Evaluation of Wheat Trials at Abyuha, El-Minya Governorate. Winter 79/80-80/81 in Awad.	By: N. Farrag and E. Sorial.
PTR#29	Irrigation Practices Reported by EWUP Farm Record Keepers.	By: F. Abdel Al, M. Skold and D. Martella.
PTR#30	The Role of Farm Records in the EWUP Project.	By: F. Abdel Al and D. Martella.

NO.	TITLE	AUTHOR
PTR#35	Farm Irrigation System Design.	By: T.W. Ley.
PTR#36	Discharge and Mechanical Efficiency of Egyptian Water-Lifting Wheels.	By: R. Slack, H. Wahby and W. Clyma.
PTR#37	Allocative Efficiency and Equity of Alternative Methods of Charging for Irrigation Water: A Case Study in Egypt.	By: R. Bowen and R. Young.
PTR#38	Precision Land Leveling On Abu Raya Farms, Kafr El-Sheikh Governorate, Egypt.	EWUP Kafr El-Sheikh Team

EYGPT WATER USE AND MANAGEMENT PROJECT MANUALS

NO.	TITLE	AUTHOR
MAN.#1	Trapezoidal Flumes for the Egypt Water Use Project.	By: A. R. Robinson.
MAN.#2	Programs for the HP Computer Model 9825 for EWUP Operations.	By: M. Helal, D. Sunada, J. Loftis, M. Quenemoen, W Ree, R. McConnen, R. King, A. Nazr and R. Stalford.

TO ACQUIRE REPORTS LISTED IN THE ATTACHED
PLEASE WRITE TO:

EGYPT WATER USE AND MANAGEMENT PROJECT
COLORADO STATE UNIVERSITY
ENGINEERING RESEARCH CENTER
FORT COLLINS, COLORADO 80523

Reports available at nominal cost, plus postage and handling.