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A Rationale for Furrow Irrigation System Design and Management

Safa Noori Hamad
Utah State University

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A RATIONALE FOR FURROW IRRIGATION SYSTEM
DESIGN AND MANAGEMENT

by

Safa Noori Hamad

A dissertation submitted in partial fulfillment of the requirements for the degree
of
DOCTOR OF PHILOSOPHY
in
Agricultural and Irrigation Engineering

Approved:

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Logan, Utah
1976
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Safa N. Hamad
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\[ a = \text{coefficient of the empirical advance function, } x = a t^b \]
\[ A = \text{total farm area, acres (hectares)} \]
\[ b = \text{exponent of the empirical advance function, } x = a t^b \]
\[ b_j = \text{bestfit slope for any individual row profile, } j \]
\[ b_{je} = \text{bestfit slope for the } j^{\text{th}} \text{ row that has an even number of stations} \]
\[ b_{jo} = \text{bestfit slope for the } j^{\text{th}} \text{ row that has an odd number of stations} \]
\[ B = \text{bestfit slope in the row direction for the entire field} \]
\[ B_t = \text{bottom width of prismatic, trapezoidal furrow channel, ft (m)} \]
\[ c = \text{a parameter used to express the volume of water stored in the soil} \]
\[ c_i = \text{bestfit slope for any individual cross-row profile, } i \]
\[ c_1 = \text{centroid location in the } X\text{-direction expressed in stations} \]
\[ C = \text{bestfit slope in the cross-row direction for the entire field} \]
\[ CPF = \text{Crop Production Function, which is a relation between crop yield and amount of water received by the crop} \]
\[ d = \text{depth of water in the furrow channel at any given distance, } x \text{, ft (m)} \]
\[ d_a = \text{gross depth of applied water per irrigation, inches (mm)} \]
\( d_i = \) accumulated depth of infiltrated water at any time, \( t_i \), inches (mm)

\( d_l = \) accumulated depth of infiltrated water at the lower end of the furrow, inches (mm)

\( d_o = \) depth of water in the furrow channel at the head, ft (m)

\( d_p = \) depth of deep-percolated water, inches (mm)

\( d_r = \) depth of runoff water, inches (mm)

\( d_s = \) depth of stored water in the root zone, inches (mm)

\( d_t = \) total average depth of infiltrated water, inches (mm)

\( d_u = \) accumulated depth of infiltrated water at the upper end of the furrow, inches (mm)

\( d_{x_i} = \) accumulated depth of infiltrated water at any given point, \( x \), measured from the head of the furrow, inches (mm)

\( DU = \) Distribution Uniformity expressed as a percentage

\( DU_i = \) Instantaneous Distribution Uniformity expressed as a percentage

\( D_l = \) total seasonal depth of infiltrated water at the lower end of the furrow, inches (mm)

\( D_s = \) equivalent average depth of water on the ground surface, ft (m)

\( D_u = \) total seasonal depth of infiltrated water at the upper end of the furrow, inches (mm)

\( D_{x_i} = \) total seasonal depth of infiltrated water at a given point, \( x \), measured from the head of the furrow, inches (mm)

\( \overline{e} = \) a coefficient which accounts for furrow channel shape

\( E_a = \) Application Efficiency expressed as a percentage
\( f = \) a factor which accounts for the method of measuring intake function

\( f_i = \) a functional relationship which depends on the index, \( i \)

\( F = \) correction factor for the average depth of infiltrated water

\( g = \) acceleration due to gravity, \( \text{ft/} \text{sec}^2 \) (\( \text{m/} \text{sec}^2 \))

\( g_i = \) an index which is equal to \( i^{n+1} - (i-2)^{n+1} \)

\( g_s = \) grid spacing, \( \text{ft} \) (\( \text{m} \))

\( h = \) puddling factor

\( H = \) ground surface elevation of any point on the plane above a specified datum, \( \text{ft} \) (\( \text{m} \))

\( H_c = \) sum of depths of cuts at the corners of a given grid, \( \text{ft} \) (\( \text{m} \))

\( H_f = \) sum of depths of fills at the corners of a given grid, \( \text{ft} \) (\( \text{m} \))

\( H_{i,j} = \) grade elevation at any point on the plane above a specified datum, \( \text{ft} \) (\( \text{m} \))

\( H_i = \) original ground surface elevation at the \( i^{th} \) station along a profile above a specified datum, \( \text{ft} \) (\( \text{m} \))

\( H_{i,j} = \) ground surface elevation at any point on the plane above a specified datum, \( \text{ft} \) (\( \text{m} \))

\( H_m = \) average elevation of all points above a specified datum, or elevation of the centroid of the plane above a specified datum, \( \text{ft} \) (\( \text{m} \))

= elevation of the centroid of a given profile above a specified datum, \( \text{ft} \) (\( \text{m} \))
\( H_0 \) = elevation of the plane at the origin above a specified datum, ft (m)

\( i \) = an index

\( I \) = intake rate at any given time, \( t \), gpm/ft (lps/m) or inches/hr (mm/hr)

\( IRRS = \text{Irrigation Runoff Recovery System} \)

\( j \) = an index

\( k_i \) = coefficient of the intake function

\( K \) = coefficient of Kostakov intake function, gpm/ft (lps/m) or inches/hr (mm/hr)

\( K_1 \) = a constant which is equal to 12 for the English units and 1000 for the metric units

\( K_2 \) = a constant which is equal to 720 for the English units and 60,000 for the metric units

\( K_3 \) = a constant which is equal to 3600 for the English units and 3600 for the metric units

\( K_4 \) = a constant which is equal to 60 for the English units and 0.060 for the metric units

\( K_5 \) = a constant which is equal to 720 for the English units and 60 for the metric units

\( K_6 \) = a constant which is equal to 1.0 for the English units and 0.0631 for the metric units
\( K_7 \) = a constant which is equal to 108 for the English units and 4.0 for the metric units

\( K_8 \) = a constant which is equal to 324 for the English units and 12 for the metric units

\( K_9 \) = a constant which is equal to 36 for the English units and 4/3 for the metric units

\( K_{10} \) = a constant which is equal to 216 for the English units and 8 for the metric units

\( K_{11} \) = a constant which is equal to 27 for the English units and 1.0 for the metric units

\( K_{12} \) = a constant which is equal to 0.137 for the English units and 0.060 for the metric units

\( K_{13} \) = a constant which is equal to 7.48 for the English units and 1000 for the metric units

\( K_{14} \) = a constant which is equal to 0.6233 for the English units and 60 for the metric units

\( K_{15} \) = a constant which is equal to 0.00223 for the English units and 0.36 for the metric units

\( K_{16} \) = a constant which is equal to 96.3 for the English units and 3600 for the metric units

\( K_{17} \) = a constant which is equal to 448.8 for the English units and 1.0 for the metric units

\( K_{18} \) = a constant which is equal to 1/12 for the English units and 0.36 for the metric units

\( K_{19} \) = a constant which is equal to 7.48 for the English units and 16.667 for the metric units
L = length of irrigation run or furrow length, ft (m)

m = number of stations in the cross-row direction

me = number of rows that have an even number of stations

mi = number of stations in any given cross-row profile, i

mo = number of rows that have an odd number of stations

m' = a coefficient to express the cross-sectional area of the furrow

MNFP = Maximum Net Farm Profit, $/acre ($/hectare)

n = exponent of Kostakov intake function, always less than zero

n_j = number of stations in any given row, j

nje = number of stations in the jth row which has an even number of stations

njo = number of stations in the jth row which has an odd number of stations

np = number of stations of known elevations along a profile

nr = number of stations in the row direction

nx = number of stations in the X-direction

ny = number of stations in the Y-direction

N = total number of stations where elevations have been recorded

NAFP = Net Annual Farm Profit, $/acre ($/hectare)

Ni = number of irrigations per season

Ns = number of irrigation sets

Nf = number of furrows for the first irrigation set
\( P = \) percentage of deep-percolated water

\( PFD = \text{Physically Feasible Design} \)

\( P_{xl} = \) percentage of land receiving an average accumulated depth of infiltrated water, \( d_{xl} \)

\( q = \) furrow stream size, gpm (lps)

\( Q_c = \) maximum non-erosive furrow stream size, gpm (lps)

\( Q_r = \) runoff stream size, gpm (lps)

\( Q_u = \) units stream size, cfs/ft width (lps/m width)

\( Q_B = \) border inflow stream size, cfs (lps)

\( Q_d = \) maximum non-erosive border stream size, cfs/ft width (lps/m width)

\( Q_s = \) supply stream discharge, cfs (lps)

\( R = \) advance ratio, which is the ratio of the time required to fill the root zone to the time required for the water to reach the end of the run

\( R_f = \) percentage of runoff water

\( S = \) slope of the line which bestfits a given profile across or along the field

\( S_o = \) slope of the channel bottom expressed in percent

\( S_r = \) slope of the irrigated land in the row direction expressed as a percentage

\( S_x = \) slope of the graded surface in the \( X \)-direction

\( S_y = \) slope of the graded surface in the \( Y \)-direction
$t =$ time of application, minutes

$= 60 \frac{T s}{s}$

$t_a =$ time required for the water to reach the end of the furrow, minutes

$t_o =$ time of opportunity, minutes

$t_l =$ time of application at the lower end of the furrow, minutes

$t_r =$ runoff time period, minutes

$t_u =$ time of application at the upper end of the furrow, minutes

$= t$

$t_x =$ time to advance a given distance, $x$, measured from the head of the furrow, minutes

$\Delta t =$ increment of time, minutes

$T =$ total time of application required to irrigate the entire field, hours

$T_o =$ time of application per set per irrigation, hours, $= \frac{t}{60} = \frac{t_u}{60}$

$v =$ mean velocity of flow, ft/sec (m/sec)

$V_c =$ volume of earth work in cut on a particular grid, cu yd (cu m)

$V_f =$ volume of earth work in fill on a particular grid, cu yd (cu m)

$V_t =$ total volume of infiltrated water, cu ft/ft (cu m/m)

$W_{j,e} =$ a weighting factor in the $j^{th}$ row that has an even number of stations, $n_{j,e}$
$W_{j0}$ = a weighting factor in the $j^{th}$ row that has an odd number of stations, $n_{j0}$

$x$ = distance advanced down the channel in time, $t$, ft (m), = $x_i$

= any given distance down the furrow measured from the head, ft (m)

$\Delta x_i$ = distance advanced in time $i\Delta t$, ft (m)

$X_i$ = $X$-coordinate of a given point

$X_m$ = average distance in the $X$-direction from the origin, ft (m)

$\Delta X$ = incremental distance advanced in time $\Delta t$, m (ft)

$y$ = depth of flow in the channel at any distance, $x$, ft (m)

$Y_m$ = average distance in the $Y$-direction from the origin, ft (m)

$Z$ = side slopes of a prismatic, trapezoidal furrow channel
ABSTRACT

A Rationale for Furrow Irrigation System Design and Management

by

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Utah State University, 1976

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Mathematical and computerized models are developed to design and optimize furrow irrigation systems. The optimization process starts with land grading design, if any is needed, followed by a prediction of maximum non-erosive furrow stream size allowed on a given soil and the associated furrow-advance function. An average depth of application per irrigation is then assumed from which the wetting pattern along the furrow and the amounts of runoff water are predicted. A design of an Irrigation Runoff Recovery System, IRRS, is then executed, if desired, and system cost is determined. Using the predicted wetting pattern and the appropriate Crop Production Function, the gross return and the net farm profit associated with that particular average depth of application per irrigation are determined. The iterative procedure is continued by changing the average depth of application per irrigation and evaluating net farm profit until a depth and the associated system design and management program which yield the highest net profit are found.
A Fortran IV detailed computer program is developed to perform the above procedure. The program is comprehensive and very flexible so that it can be used both for research and practical design purposes and can accommodate further improvements and expansion. The results of sensitivity analysis conducted to study the effect on net farm profit of ten major design and management factors are included. Numerous conclusions, suggestions, and recommendations to improve furrow irrigation system design and operation are presented.
CHAPTER I
INTRODUCTION

Prehistoric tablets and carvings indicate that early civilizations developed along rivers that supplied irrigation water to the fields, such as the Mesopotamian where the ancient Babylonian developed a flourishing civilization based upon irrigated agriculture along the shores of Tigris and Euphrates rivers.

Discoveries in ancient Babylon ruins in Iraq reveal that irrigation works were in use before the time of King Hammurabi, about 2200 B.C. In fact, the concept of irrigation started when man planted crops in low areas that trapped flood and rainfall water. From this emerged the idea of basin or flood irrigation which led to border and furrow practices. King Hammurabi placed great emphasis on agriculture and irrigation and that was a major reason for establishing the great Babylonian civilization. However, one of the causes for the failure of his kingdom as well as other civilizations was the failure of their agriculture due to misuse of the irrigation practices, water table and salinity buildup, and improper or lack of maintenance operations.

Surface irrigation has received much attention from farmers and researchers in attempts to improve economic and water-use efficiency. Increasing emphasis is being placed on the use of water resources because of increased demand for irrigation development which is essential to meet world food requirements. Although surface irrigation is one of the easiest methods from the design and use standpoint, in
reality it is a very complicated practice. A major complexity arises from the physical changes which take place during the time of irrigation, during the growing season, and from season to season.

Much research has been and is being done on the various physical elements of surface irrigation systems in an effort to improve design and management criteria. Details about most of surface irrigation design factors can be found in the literature. However, only discrete elements are described and practically no effort has been made to synthesize the whole system. For example, many methods are available to determine field surface slope for land grading but none of these is related to the hydraulics of surface irrigation, to crop production, or to overall economics. Furthermore, there are many techniques available to predict the advance of the water front down the furrow and the soil wetting patterns, but these have not been tied in with overall system performance. Thus, it appears that a more comprehensive methodology is needed which will integrate the most important factors involved in furrow irrigation system design and permit the evaluation of the sensitivity of the design factors to overall field performance.

The important factors that need to be considered in the design of furrow irrigation systems are land grading, water advance down the furrow channel, amounts of applied and infiltrated water, runoff and deep-percolation losses, uniformity of infiltration, and design of Irrigation Runoff Recovery Systems, IRRS's.
Objectives

The primary objective of this research is to select promising methods for dealing with each of the elements of furrow irrigation design and develop a computerized program which integrates these elements into an optimal design and management scheme. The secondary objective is to operate the program to the sensitivity of the expected farm profit to variations in and procedures for dealing with the various design elements. These overall objectives may be broken down as:

1. Select a detailed procedure for the design and management of a furrow irrigation system to determine the most cost effective design and management program for a specific farm and a specific crop. (It will be assumed that all crop production and economic factors will be constant except those related to water application. The optimization procedure will include physical and economic evaluations of land grading operations, amount of water applied and lost, infiltration uniformity, and crop yield.)

2. Develop a computerized program to carry out the design optimization procedure.

3. Use the program to study the sensitivity of on-farm system design to the use of various land grading techniques.

4. Apply the developed procedure to study the sensitivity of net farm profits to:

   A. recovering or disposing of runoff water
B. inherent discrepancies in the design such as deviations in:

1. intake-function measurements
2. predicting the location of the wetting front
3. various approaches to analyze a certain element of the system

C. management malpractices such as:

1. variations in furrow stream size
2. variations in total time of application per irrigation.

The symbols and notations used in the text are defined only where they first appear and a list of repeated symbols is given in the front pages.

The report and the computer programs are written in both metric and English units. However, to keep the tables and figures clear and to avoid super-loading the report with numbers, the results are presented in the English units and an appropriate SI conversion table is provided in Appendix D.
CHAPTER II
REVIEW OF LITERATURE

Surface irrigation practice involves diversified design elements and factors and, as was mentioned earlier, that most of the design elements have been explored, to some extent, by researchers. However, to provide a clear picture of what has been done, the review of literature is divided into sections related to the major design elements and presented in chronological order.

Land Grading

Land grading or re-shaping is one of the first steps in the design of an efficient and successful surface irrigation system. In many cases, land grading is a multipurpose practice since it can be used to achieve uniform and quick irrigation-water application, to provide a means for surface drainage, especially in intensive rainfall areas, and to reduce surface erosion. The intensity of grading needed depends on the topography of the field, degree of smoothness required, and purpose of land grading practice.

For centuries land grading has been practiced, but the design slopes were determined mainly by trial and error. The first systematic land grading method was developed in the early 1940's by Givan (29), who used the theory of least squares to develop design equations which would minimize the amounts of cuts and fills and determine the desirable slopes for a uniformly graded surface. Those
equations will be presented and discussed in the section "Land Grading Techniques."

The technique presented by Givan (29) at that time was applicable only for rectangular fields. However, since most of the irrigated fields may not be rectangular, Chugg (16) extended the least squares method to calculate bestfit slopes for irregularly shaped fields. He presented a systematic procedure using transparent and coordinate paper to simplify and organize the computational process.

Marr (45), in 1957, developed the least squares and average profile method of land grading. This method requires the determination of the slopes of the lines which bestfit the average profile in the two coordinate-directions. For a given profile, the slope of the bestfit line is calculated by the least squares method in exactly similar manner to that presented by Givan (29). In a simplified form, it is

\[ S = \frac{n_p}{n_p \sum_{i=1}^{n_p} H_i X_i - \sum_{i=1}^{n_p} X_i \sum_{i=1}^{n_p} H_i} \frac{n_p}{n_p \sum_{i=1}^{n_p} X_i^2} - (\sum_{i=1}^{n_p} X_i)^2 \]  

[1]

where

- \( S \) = slope of the line which best-fits a given profile across or along the field
- \( \sum H_i \) = sum of elevations at stations along the profile, ft (m)
\[ \Sigma X_i = \text{sum of station distances along the profile, ft (m)} \]
\[ n_p = \text{number of stations of known elevations along the profile} \]
\[ \Sigma X_i^2 = \text{sum of the squares of the station distances along the profile} \]
\[ \Sigma H_i X_i = \text{sum of the products of the elevations at stations and station distances, ft (m)} \]

The elevation of the centroid of a given profile is determined by

\[ H_m = \frac{\sum_{i=1}^{n_p} H_i X_i}{n_p} \]  
\[ [2] \]

where

\[ H_m = \text{elevation of the centroid of a given profile, ft (m)} \]

The calculated slopes and centroid elevations of the profiles are used to delineate the plane that best fits the elevations of the grid corners. Furthermore, Marr (45) extended his method of calculating slopes to irregularly-shaped fields by subdividing the field, modifying the calculated slopes, and merging the slopes of the subdivision into each other.

Raju (64) developed the fixed-volume center method to calculate the slope of the graded surface to minimize the volumes of earth work required. His method is based upon two criteria, the first of which is that the total volume of earth before and after grading will be the same; this is to ensure a balance between cut and fill. The second
criterion is that the center of the volume will be the same before and after grading; this is to ensure least amount of grading and movement of earth. Based upon the above hypotheses, he developed the following design equations:

\[ S_x = \frac{12}{n_x n_y} \left( \sum_{i=1}^{n_p} H_i X_i - \frac{n_x + 1}{2} \right) \]  

and

\[ S_y = \frac{12}{n_x n_y} \left( \sum_{i=1}^{n_p} H_i Y_i - \frac{n_y + 1}{2} \right) \]

where

- \( S_x \) = slope of the graded surface in the \( X \)-direction
- \( S_y \) = slope of the graded surface in the \( Y \)-direction
- \( X_i \) = \( X \)-coordinate of a given station
- \( Y_i \) = \( Y \)-coordinate of a given station.

He presented a procedure to calculate the slopes in both coordinate directions for rectangular as well as irregularly-shaped fields.

Butler (12) described what is called average profile method of land grading which is used by the Office of the Soil Conservation in Arkansas. This method involves evaluating the slope in each 100-foot interval along a profile in a given direction using plus or minus signs to indicate up or down hill slope, respectively. A mean slope, found by averaging the calculated slopes, is then used for further calculations. In 1973, Paul (56) evaluated the average profile
method and compared it with some other techniques. More details about this comparison will be given in the section "Land Grading Techniques."

The Office of the Soil Conservation Service of the United States Department of Agriculture (77) uses four techniques of land grading, which are:

1. The plane method,
2. The profile method,
3. The plan inspection method,
4. The contour adjustment method.

The plane method is based upon the least squares technique as was developed by Givan (29). The profile method involves trial and error procedures to find the bestfit plane using the calculated slopes of individual profiles. The plan inspection and contour adjustment methods also require trial and error procedures to find a multislope plane.

Smerdon, et al. (76) proposed a method for calculating land grading parameters using high-speed computers. The method involves two basic hypotheses, the first is to determine slopes of the graded surface whereby the volumes of earth moved are minimized, and the second is to establish an earth-spreading pattern such that the average earth-haul distance is minimized. To simplify the computations, they developed a computer program to accomplish the design for rectangular fields only.
Harris, et al. (32) suggested a new method of land grading which they called the warped-surface method. This method allows having variable slopes parallel to the row, (negative slopes are prohibited to permit surface drainage), while the cross-row slopes follow natural topography of the ground with minor smoothing operations. The main advantage of this method is that it takes maximum advantage of natural topography; therefore, it minimizes the required depths of cuts and fills and lengths of haul, and appreciably reduces the cost of land grading operations.

Shih and Kriz (70) developed a method of calculating the volumes of earth work from land grading which they called end grid area method. It is based upon the following assumptions:

1. The original ground surface between two stations is an undulating wave curve.

2. Each grid may exhibit one of six possible combinations of cuts and fills corners.

3. The weighted depths of cuts and fills for the grid corners are obtained by averaging the sum of the grid-corner depths of cuts and fills.

Based upon the above assumptions they developed formulas to cover the six possible cases of cuts and fills at the grid corners. They also developed tables to determine the volumes of cuts and fills for the possible combinations of cuts and fills at the grid corners. Further discussion and design equations are presented in the section, "Land Grading Techniques."
Shih and Kriz (70) also presented an interesting comparison among different methods of calculating the volumes of earth work including summation method, four-point method, and end-grid area method and using four designs to calculate the slope of the graded surface which are least squares design, fixed-volume center design, average-profile design, and symmetrical-residuals design. The results of their comparison indicated that the end-grid area method gave about 8 percent less volume of earth work than the summation method and about 5 percent more volume of earth work than the four-point method. Furthermore, based upon their study, they developed the following empirical relationship that relates the various methods of calculating the volumes of earth work;

\[
\text{End-grid area method} = \text{Four-point method} \times 0.6 + \text{summation method} \times 0.4. \tag{5}\]

They also developed the following theoretical relationship between the design slopes calculated by the least squares method and the fixed-volume center method,

\[
S_v = S_L - \frac{N^2 - 1}{N^2} \tag{6}\]

where

\[
S_v = \text{slope of the graded surface calculated by the fixed-volume center method}
\]
$S_i$ = slope of the graded surface calculated by the least squares method

$N$ = total number of stations where elevations have been recorded.

In 1971, Shih and Kriz (66) prepared a detailed computerized technique to perform land grading designs on rectangular fields using the symmetrical residuals method. Their computer program is incorporated in the model presented in this report. Equations to calculate slopes of bestfit planes and volumes of earth work from land grading operations are presented in the section "Land Grading Techniques." A modified copy of the computer program is presented in Appendix E.

In late 1971, Shih and Kriz (73) extended the symmetrical residuals method to irregularly-shaped fields, and they derived the following relationships to calculate the slopes of the bestfit plane:

\[ b = \frac{m_e}{\sum_{j=1}^{m_e} w_{je} b_{je}} + \frac{m_o}{\sum_{j=1}^{m_o} w_{jo} b_{jo}} \]  \[7\]

where

\[ w_{je} = \frac{n_{je}^3}{\sum_{j=1}^{n_{je}} (n_{jo} + 1)} \]  \[8\]  

and
\[ W_{jo} = \frac{(n_{jo} + 1)^2 (n_{jo} - 1)}{\sum_{j=1}^{m_e} n_{je}^2 + \sum_{j=1}^{m_o} (n_{jo} + 1)^2 (n_{jo} - 1)} \]  \[ [9] \]

where

- \( b \) = slope of the best fit plane in the row direction
- \( W_{je} \) = a weighting factor in the \( j^{th} \) row that has an even number of stations, \( n_{je} \)
- \( W_{jo} \) = a weighting factor in the \( j^{th} \) row that has an odd number of stations, \( n_{jo} \)
- \( m_e \) = number of rows that have an even number of stations
- \( m_o \) = number of rows that have an odd number of stations
- \( n_{je} \) = number of stations in the \( j^{th} \) row which has an even number of stations
- \( n_{jo} \) = number of stations in the \( j^{th} \) row which has an odd number of stations
- \( b_{je} \) = best fit slope of the \( j^{th} \) row that has an even number of stations
- \( b_{jo} \) = best fit slope of the \( j^{th} \) row that has an odd number of stations.

They also developed a similar expression for the best fit slope in the cross-row direction.

Early in 1973, Shih, et al. (74) presented another design procedure to find the best row and cross-row slopes using the symmetrical residuals method. Essentially, they used the same technique.
presented by Shih and Kriz (66) to determine the slopes but used
the Lagrange interpolation formula to determine the volumes of earth
work. In so doing, they studied four cases, where the grid has one,
two, three, or four nodes and they presented an example to demonstrate
the application of the proposed procedure.

Sowell, et al. (78) utilized modern linear programming techniques
to perform simulated land grading operations. They applied this
technique to five land grading alternatives, compared their results
with the designs obtained by the symmetrical residuals method, and
found that the linear programming technique always gave a smaller total
sum of depths of cuts. However, they found that the linear programming
method needs more computer time shares than does the symmetrical
residuals method; thus no attempt has yet been made to develop a
general computer program to perform land grading designs using linear
programming.

In 1973, Paul (56) derived two new methods of land grading which
he calls double centroid method and computer-minimized-cost method.
The main theory of the double centroid method is that when the average
haul distance is reduced, the grading cost will be reduced also. In
developing the computer-minimized-cost method of land grading, Paul
(56) divided the grading cost into four groups, i.e., cost of:
1. surveying and calculations,
2. initial field preparation,
3. final smoothing,
4. primary earth movement during the grading process, which
includes:

a. excavating and spreading the earth,
b. transporting the earth from a cut to a fill position.

The major theme of the computer-minimized-cost method is to minimize the cost of primary earth movement during the grading process. The initial slope of the graded surface is calculated by the summation method. The grading cost is calculated by assuming that the equipment moves the volumes of cuts in a spiral fashion searching for a fill area in an attempt to reduce the hauling distance. Then an iterative procedure is used to minimize the cost by rotating the slopes of the graded plane about the centroid in increments of 0.01 percent, and the cost of grading for each iteration is calculated until the slope with the minimum cost is obtained. In calculating the cost of grading, Paul (56) introduced two previously unused factors, namely, the Load Factor and the Distance Factor. The Load Factor, LF, is defined as the cost in dollars per foot of cut, of loading and spreading a given volume of earth in a 100- by a 100-foot area. The Distance Factor, DF, is the cost, in dollars per 100 feet of haul distance, for hauling out a similar volume of earth and for the empty return trip. These factors will vary with equipment used, local costs, and soil type. Based on the above criteria, Paul (56) developed a computer program to perform the design of land grading using the least squares, average profile, double centroid, and computer-minimized-cost methods. When he applied the above techniques to field conditions, he found that the double centroid and the least squares method predicted
approximately the same costs. Among the four methods, the computer-minimized-cost method predicted the lowest grading cost. The computer program developed by Paul (56) was modified and incorporated in this model.

Overland Flow Hydraulics

The flow of water in surface irrigation can be described as unsteady, non-uniform, open channel flow over a porous bed. The research that has been done on the hydraulics of surface irrigation falls under two main categories, the continuity or inflow-outflow methods and the hydrodynamics methods. The flow hydraulics including advance and infiltration relationships in border and furrow irrigation methods are somewhat related, and understanding one of them will help understanding the other. Thus it is attempted to present the work that has been done on flow hydraulics of both irrigation methods of surface irrigation chronologically.

One major contribution to the analysis of flow in border irrigation was done in 1938 by Lewis and Milne (40) where they used the continuity concept to predict the advance of the water sheet down a border strip knowing the flow rate, flow depth, and infiltration characteristics of the soil. In so doing, they assumed that the depth of water at the head of the border is constant, neither tail water ponding nor runoff loss occurs, flow rate is applied uniformly along the width of the border, and that the slope and roughness factors are reflected in the depth parameter.
Since Lewis and Milne's work, extensive research has been conducted on the various factors affecting flow of water in surface irrigation. In 1960, the United States Department of Agriculture (63) held a workshop to study the hydraulics of surface irrigation. Shockley (18, 63) presented a quasi-rational procedure to design level and graded border irrigation systems. The procedure he developed, using a unit-stream proportional to the border-strip area, is still the major design approach for border irrigation systems. Lawhon (63) presented a complementary analysis for the design and evaluation of border irrigation systems. Recently, the Soil Conservation Service Office of the United States Department of Agriculture has published a design manual for border irrigation system design using the procedure developed by Shockley (18, 63).

Davis (20, 63) developed an analytical procedure to predict water advance down a furrow channel using intake data and some other parameters to describe furrow geometry. Analysis and comparison of the developed technique with other procedures are given in Appendix II.

In 1962, Bishop (3) related soil intake characteristics to length of run in surface irrigation. He assumed that the sub-surface wetting front varies linearly with the length of run along the furrow and developed the following relationships:

\[ V_t = \frac{d_1 L}{2 K_1} \left[ (R+1)^{n+1} + R^{n+1} \right] \]  \[ 10 \]

and
\[ P = \left( \frac{(R+1)^{n+1} - R^{n+1}}{(R+1)^{n+1} + R^{n+1}} \right) \times 100 \]  

where

\( d_1 \) = depth of water infiltrated in time \( t_1 \), inches (mm)

\( P \) = percentage of deep-percolated water

\( L \) = length of irrigation run, ft (m)

\( n \) = exponent of Kostakov intake function, always less than zero

\( R \) = advance ratio which is the ratio of the time required to fill the root zone to the time required for the water to reach the end of the furrow

\( V_t \) = total volume of infiltrated water, cu ft/ft width (cu m/m width)

\( K_1 \) = a constant which is equal to 12 for the English units and 1000 for the metric units.

Pair (53) studied the effects of irrigation methods and system management on Application Efficiency. Field studies showed that lower Application Efficiencies are associated with small amounts of soil moisture replacement and higher efficiencies with large soil moisture replacements regardless of the method of irrigation.

Philip and Farrell (59) extended Lewis and Milne's (40) approach and used Laplace transformations to find the general solution of the infiltration-advance phenomenon in surface irrigation and presented some particular solutions in a dimensionless form. They also developed
a method for calculating solutions for the advance problem using infinite series and asymptotic expansion.

In 1964, Bondurant (5) used an analog model to study the problem of predicting the two-dimensional advance of an irrigation stream down a border strip. Using dimensional analysis, he developed an exponential formula to express the advanced distance in terms of time of advance, flow rate, cumulative intake increment, roughness coefficient, fluid viscosity, acceleration due to gravity, and width of the border.

Kruse, et al. (24) studied the factors affecting flow resistance in irrigation borders and furrows. They conducted field and laboratory experiments from which expressions were developed to relate flow resistance coefficients to the dimension of the boundary roughness. They concluded that critical Reynolds Numbers for the transition from laminar to turbulent flow are 500 for rough boundaries and 700 for smooth boundaries. A critical Reynolds Number of 500 will probably be applicable to all wide irrigation channels.

In 1965, Kruger and Bassett (38) studied the problem of flow of water over a porous bed having constant infiltration or intake rate. They described the flow by the following equations:

\[
\frac{\partial y}{\partial t} = - y \frac{\partial v}{\partial x} - v \frac{\partial y}{\partial x} - \frac{I}{K_2}
\]  

[12]

and
\[
\frac{\partial v}{\partial t} = g K_3 (S_o - S_f - \frac{\partial y}{\partial x}) - v \frac{\partial v}{\partial x} + \frac{I}{K_3} \frac{v}{y} \tag{13}
\]

where

\( t \) = time of application, minutes

\( g \) = acceleration due to gravity, ft/sec\(^2\) (m/sec\(^2\))

\( I \) = intake rate at any given time \( t \), in/hr (mm/hr)

\( S_f \) = slope of the total energy line expressed as a percentage

\( S_o \) = slope of the channel bottom expressed as a percentage

\( v \) = mean velocity of flow, ft/min (m/min)

\( x \) = distance advanced down the channel in time \( t \), ft (m)

\( y \) = depth of flow in the channel at any distance, \( x \), ft (m)

\( K_3 \) = a constant which is equal to 720 for the English units

and 60,000 for the metric units

\( K_2 \) = a constant which is equal to 3600 for the English units

and 3600 for the metric units.

The above equations were used to predict the shape of the water surface profiles and velocity of advance down a dry channel having a constant intake rate. A computer program was developed to solve the above equations numerically.

Later, Olsen (52) developed a numerical method of analysis to study the unsteady flow of water over a porous bed having a variable infiltration rate during the advance phase of the water. He used a complex mathematical function to describe the advancing flow and presented a computer program to solve the function numerically.
Al-Abdulla (1), in 1965, studied the effect on intake rate of the depth of water on the soil, initial soil moisture content, and temperature of the water. From these studies, he developed some equations to relate the intake rate to the depth of the water on the soil.

Fok and Bishop (24) used the continuity concept and an empirical advance function to express the advanced distance in terms of border or furrow geometry, intake characteristics, inflow stream size, time of advance, and empirical advance coefficients. For border irrigation, their expression is as follows:

\[ x = \frac{K_4 + Q_b}{W \left[ \frac{d_o}{1 + b} + \frac{F K_2}{K_2 (n+1)(n+2)} \right] t^{n+1}} \]  

where:

- \( b \) = exponent of an empirical water advance function, \( x = a t^b \)
- \( W \) = width of the border, ft (m)
- \( Q_b \) = border inflow stream size, cfs (lps)
- \( d_o \) = depth of water in the channel at the head of the furrow or border, ft (m)
- \( K_4 \) = a constant which is equal to 60 for the English units and 0.060 for the metric units.

and

\[ F = b (n+2) \left[ \frac{1}{b} - \frac{n+1}{b+1} + \frac{n (n+1)}{2 (b+2)} \right] \]
or

\[ F = \frac{n - bn + 2}{I + b} \]

\( F \) is a correction factor for the average depth of infiltrated water.

For furrow irrigation, a similar relationship was developed and will be discussed later in **CHAPTER IV**.

Field application of the developed techniques showed a good agreement between measured and predicted values. However, in order to predict the advanced distance, an estimation of the advance and intake coefficients is required.

Lim (41) analyzed the infiltration, advance, and recession phenomena in surface irrigation. He considered a linear and an exponential recession function, and derived some expressions to calculate the **Application Efficiency** when runoff is and is not considered as a loss.

Christiansen, et al. (15) investigated the relationship between the intake function parameters and the advance of the water in surface irrigation. They used an intake function of the following form

\[ I = C_r + k_1 t^n \]  \hspace{1cm} [16]

and related the advance-infiltration parameters as follows:

\[ \frac{F k_1 t^{n+1}}{(n+1)(n+1)} \frac{k_2}{k_4} = \frac{q u t}{s K} - \frac{C_r t}{2 K_2} \]  \hspace{1cm} [17]
where

\( q_u \) = unit stream size, cfs/ft width (1ps/m width)

\( C_r \) = intake rate at infinite time, in/hr (mm/hr)

\( D_s \) = equivalent average depth of water on the ground surface, ft (m)

\( k_I \) = coefficient of the intake function.

Cheng (14) solved the boundary value problem for the velocity and depth of flow using the general hydrodynamics equations for a spatially varied, unsteady flow in prismatic open channel with an arbitrary cross-sectional shape. He also studied the theory of characteristics and introduced the method of finite difference in the solution of the basic equations of motion in surface irrigation based upon the above theory.

In 1967, Willardson and Bishop (86) analyzed surface irrigation efficiency and water losses. They assumed that: the runoff stream is a constant percentage of the inflow stream during the runoff period; the lower end of the reach is sufficiently irrigated; and that the depth of infiltration varied linearly with the distance down the reach. They developed the following relationship:

\[
E_a = \left[ 1 - \frac{t_r}{t_r + t_A} \frac{q_r}{q} - \frac{(R+1)^{n+1} - r^{n+1}}{(R+1)^{n+1} + r^{n+1}} \right]
\]

where

\( E_a \) = Application Efficiency expressed as a percentage
\( q = \) furrow stream size, gpm (lps)
\( q_r = \) runoff stream size, gpm (lps)
\( t_a = \) time required for the water to reach the end of the furrow, minutes
\( t_r = \) runoff time-period, minutes.

Using the above equation with various advance ratios, runoff percentages, and infiltration functions, they concluded that when the intake rate is slow, the length of run and rate of advance does not affect the Application Efficiency. However, when the intake rate is high, the Application Efficiency continually decreases with longer runs, i.e., long reaches or slow advance rates. They also studied the effect of advance, infiltration, and depth of application on the Application Efficiency. They concluded that if the field is not over-irrigated and if the ratio of the time of irrigation at the lower end to the time of advance is kept between 0.60 and 9.0, the Application Efficiency will generally be above 60 percent.

In 1968, Wilke (84) studied the hydrodynamics of surface irrigation and derived equations to describe the flow of water in irrigation furrows. He developed a procedure for determining intake rates by measuring surface-flow volume and stream advance. He used numerical solutions of the flow equations to predict water-advance design curves and estimates of cutback flow rates to reduce runoff losses. He found, however, that predicted flow profiles obtained from approximate numerical solutions of the equations of motion did not agree with the actual measured profiles.
Sakkas and Hart (68), in 1968, proposed a procedure to irrigate with cutback furrow stream sizes. Their method required cutting-back the furrow stream size to pre-determined values at pre-determined time intervals during the irrigation of a given set, and starting new furrows on the next set at the beginning of each time interval. To simplify the design procedure, extensive tables were developed to calculate the main design parameters. However, the method requires very complicated management schemes and labor skills.

Wilke and Smerdon (85) presented two techniques to determine the sizes of the cutback streams. One technique uses the volume-balance analysis and the second one utilizes the steady-state solutions of the equations of motion. Field tests indicated that the volume-balance approach agreed very well with field results and that more work needs to be done on the steady-state analysis.

In 1969, Fok and Bishop (26) related Application Efficiency to the exponent of the intake function, exponent of advance function, and to the advance ratio, by dividing the volume of applied water into three components, water which is stored in the root zone, water which runs-off the furrow, and water which is deep percolated. The volume of each of these components was computed using finite integration analysis.

Meanwhile, Wu (88) studied the overland flow hydrograph to determine the intake function. To do that, he divided the period of irrigation time into four distinct zones: (1) unsteady, non-uniform advance of water down the irrigation reach; (2) unsteady, non-uniform rising portion of the runoff hydrograph; (3) steady, non-uniform
out-flow under equilibrium conditions; and (4) unsteady, non-uniform recession portion of the runoff hydrograph. In his analysis, he used the same empirical advance function used by Fok and Bishop (24). Then, by knowing the volume of inflow water and volume of runoff water during each time zone, he determined intake function using mass curves of inflow and outflow.

In 1971, Rasmussen, et al. (65) presented a very interesting surface irrigation method which they called Multiset Irrigation System. The system is comparable to solid-set sprinkle but requires furrow channels instead of laterals and sprinklers. Water distribution is accomplished by portable laterals placed in the cross-row direction at regular intervals along the furrow and buried at a proper depth below the ground surface. The water is applied to the furrows through holes of proper diameters punched along the lateral line at distances equal to the furrow spacing. The water is applied under pressure. Thus it moves upward to the ground surface and flows through the furrow channel. The above system easily controls furrow stream size, furrow lengths, advance rate, and recession rate by controlling the spacings of the lateral lines, the sizes of the holes, and the pressure exerted on the applied water. Multiset Irrigation Systems have been used successfully on several fields for many years and they were found to reduce soil erosion, limit runoff water pollution, and improve Application Efficiency and Distribution Uniformity. In addition they can be very well adapted to automation.

Patterson (55) developed a procedure to predict the advance of water in furrow irrigation. To do this, he divided the length of the
furrow into segments and calculated the instantaneous intake rate on each segment and found the volume of infiltrated water. The volume of surface storage was calculated by using a previously developed criterion, which assumes that on each length segment, the average depth of surface stored water is 0.75 times the depth of water at the beginning of the segment. Thus, at a given time, the integrated intake rate on the advanced distance is found and subtracted from the furrow stream size to get the discharge at the beginning of the new length segment, then an estimation of the flow depth at that location is accomplished by using Manning's equation and the process is continued downstream. Comparison of Patterson's prediction method with other water advance prediction methods is given in Appendix B.

In 1972, Powell, et al. (61, 62) developed a mathematical and a computerized models to predict water advance down irrigation furrows having non-uniform slopes. They used a predictor-corrector numerical analysis in which the advance distance was predicted for a given time increment. Then it was corrected according to the computed surface and sub-surface storage volumes. Their model was verified against field data from furrow irrigation data where the land surface slope was concave upward. Field and computer results coincided fairly well. The concave-upward surface also showed significant improvement in the Distribution Uniformity of infiltrated water from furrow irrigation system.

Sakkas and Sterlkoff (69) studied the hydrodynamics of surface irrigation systems during the water advance phase. They assumed a
spatially varied, unsteady flow in a prismatic channel as described by Saint-Vernant Equations. They used numerical integration over an irregular grid covering the characteristic curves and utilized Euler's formula and the trapezoidal rule together with a predictor-corrector technique to predict the advance of the water down the furrow channel. The integration process is carried out towards the tip of the water front. No prediction can be made for the exact location of water tip because of the singularity of the solution at that point.

In 1976, Apichart (2) used dimensional analysis and a physical model to develop a rationale for determining the length of advance in surface irrigation. In so doing, he expressed the length of advance in terms of unit stream size, opportunity time, accumulated depth of infiltrated water at the upper end of the furrow, land slope, and an advance coefficient. This relationship is given by

\[ x = K_5 \frac{C_A}{d} \frac{q}{u} \frac{t}{u} \frac{S}{S_o}^{1/2} \]  

where

- \( C_A \) = advance coefficient
- \( d_u \) = accumulated depth of infiltrated water at the head of the reach, inches (mm)
- \( t_u \) = time of application at the upper end of the reach, minutes
- \( K_5 \) = a constant which is equal to 720 for the English units and 60 for the metric units.
The advance coefficient, \( C_A \), can be obtained from a single test on a given field and used to predict advance lengths for different design conditions on the same field.

**Runoff Recovery**

Runoff water from furrow irrigation is the major form of irrigation water loss. It causes low Application Efficiencies, and contributes to downstream contamination. Research on collecting and re-using runoff water for irrigation purposes was started in early 1960's and some preliminary techniques to design Irrigation Runoff Recovery Systems, IRRS's, have been developed. In order to properly design and evaluate such systems, comprehensive study of runoff quality, quantity, and time distribution is necessary.

Bondurant (6, 8) investigated the quality of surface runoff water from many existing IRRS's in the vicinity of Kimberly, Idaho. He found high sediment concentration in the runoff water and low concentrations of nitrate nitrogen and phosphate phosphorus. He also found that as the runoff percentage increased, the concentration of nitrogen, sodium, and phosphorous decreased. Bondurant (6, 8) suggested that pollution by runoff water can be appreciably decreased by collecting and ponding runoff water for a period of time to allow the sediment particles to settle out before the water is released or used.

Davis (21) developed a technique to design pumpback IRRS which uses small sumps and intermittent pumping. Methods to predict the optimum pumping rates in terms of furrow stream size, storage
capacity, and pump characteristics were also developed. For the cases he analyzed, the cost of such systems ranged from $2.00 to $3.00 per acre-ft of recovered water.

Bondurant, (7) analyzing data from existing IRRS's in Idaho, developed a set of design equations to predict the storage capacity and pumping rates of collected runoff water. The recovered water was to be applied on the next set of furrows. He concluded that the recovery of runoff water to establish cutback irrigation by adding pumped runoff water to the new water to push the water through the furrow on each set, might be a feasible scheme and may require smaller installation and operation costs.

Fischbach and Somerhalder (23) investigated the efficiencies of automated surface irrigation systems with and without IRRS's. From several field applications, they concluded that an automatic surface irrigation system with an IRRS can be successfully used to obtain a very high Application Efficiency, as high as 91.9 percent, and a Uniformity Coefficient of 91.8 percent. They also found that an IRRS eliminated the labor needed to establish cutback irrigation and large furrow stream sizes can be used, provided they are non-erosive.

Bondurant and Willardson (9), in the late 1960's surveyed the design procedures used for the existing IRRS's in Southern Idaho and found that no successful systematic design procedure was available. From their data and with the use of empirical advance and infiltration functions, they developed a rationale to predict the volume of expected runoff water and made some suggestions to properly approach the design of an IRRS.
Nienaber and Fischbach (50) investigated a method of determining furrow stream sizes for automated surface irrigation systems with IRRS's. They related furrow stream size to basic intake rate and, on the fields where they conducted their experiments, they found that furrow stream sizes of 1.5 to 3.0 times the basic intake rate gave Application Efficiencies of 83.9 percent to 99.5 percent, while Uniformity Coefficients varied from 79.5 percent to 91.3 percent. However, they suggested that still some more investigations ought to be done on the first irrigation in the season or after cultivation operations, because it was found that the first irrigation is accompanied by large amount of sediments in runoff water and high intake rates which are quite different from the intake rates during other irrigations.

In Kansas, Ohmes and Manges (51) developed relationships to express runoff rates from graded furrows in terms of runoff time-period, maximum runoff rate, and other related parameters. They divided the irrigation time period into four zones, used empirical exponential equations to express the intake and advance functions, and analyzed each time zone individually. The final results were integrated to predict the expected runoff volume. From their experiments they concluded that only two runoff rate readings during the rising stage of the runoff hydrograph and one during the falling stage plus the runoff time period are required to evaluate the coefficients of the developed formula.

Hamad (31), in 1973, evaluated the elements involved in the design of IRRS to study the effect of each design factor on the
total cost of the system. He developed a computer program to calculate the total system cost for a given set of conditions. Applications to some field conditions showed that large runoff percentages would decrease the cost per unit of recovered runoff water but at the same time would increase the cost of the system per unit area of the irrigated field. Furthermore, he concluded that the cost of recovered water can be reduced by using small ratios of storage capacity to total runoff volume or by utilizing sequential IRRS, where runoff water is applied to lower lying fields.

In Oklahoma, Pope and Barefoot (60) studied the variation in runoff percentages from different furrow irrigation sets of the same field. They found that the runoff percentages from individual irrigation sets approximated a log-normal distribution pattern. Such distribution can be used to predict the runoff percentage expected for a specified recurrence interval. They also investigated the runoff distribution pattern, which can be used to predict the runoff percentages expected for any specified recurrence interval. Furthermore, they studied the runoff distribution during the runoff time period and found that 60 to 80 percent of the runoff water has occurred by the time the set was changed.

In 1975, Stringham and Hamad (80) developed a new rationale to design a pumpback IRRS. The design permits the furrow stream size to be held constant and the set size to be changed at the beginning of irrigation of a new set. Furthermore, runoff water is applied sequentially as irrigation proceeds, that is runoff water from the
first set is applied to the second set, thus increasing the number of furrows that can be irrigated in the second set, and so on. As can be seen the number of furrows to be irrigated in each set is increasing as irrigation advances. It is therefore non-usable from an application viewpoint. Thus, later Stringham and Hamad (81) modified the above design procedure to hold furrow stream size constant and change the set size once after the irrigation of the first set. From then on the set and the furrow stream sizes are kept constant until the irrigation of the last set, whence the inflow stream is turned-off and the last set is irrigated only with runoff water from the set before the last. The proposed technique utilizes almost all the runoff water. Analysis showed that such a pumpback reduces the total number of sets irrigated from the supply stream, total time of application per irrigation, and downstream contamination by runoff water. Design formulas and discussion of the above procedure will be given in Chapter IV.

In 1976, Bliesner (4) developed a computerized technique to design and optimize pumpback IRRS's using the method presented by Stringham and Hamad. He found that, for the cases studied, Application Efficiencies were always higher than 92 percent.

Soil Erosion

Erosion of the top soil is a common phenomenon which limits surface irrigation methods to moderately sloped or flat areas. This is because surface erosion affects uniformity of land grades,
fertility of the soil, and contributes to downstream contamination problems. In some cases, non-uniform slopes were found to reduce the effect of erosion. However, to minimize or eliminate surface erosion, the size of the inflow stream should be non-erosive.

In the early 1940's, Nielsen (44) studied the effect of the slope of small irrigation furrows and stream size on soil erosion. He used two methods to determine the silt load in the runoff stream: (1) the runoff sampling method, where direct determinations of the silt concentrations are used; and (2) the cross-section method, where measurements of furrow-channel cross section before and after irrigation are used. By conducting experiments on a silt loam soil, he concluded that for relatively small irrigation furrows on slopes less than 1.0 percent erosion is negligible.

Gardner and Lauritzen (27) analyzed and related non-erosive stream sizes to the slopes of the eroding surfaces. They utilized the continuity concept together with some empirical relationships to predict the rate of erosion for a given stream size. Among the empirical boundary conditions that they used is the following:

\[ Q_c = \alpha S_0^{\beta} \]  

where

- \( Q_c \) = critical non-erosive stream size, cfs/ft width (lps/m width)
- \( \beta \) = an empirical exponent
- \( \alpha \) = an empirical constant which is assumed to be a soil parameter.
From experiments on Millville Silt Loam and Trenton Fine Sandy Loam soils, they found the values of the parameters $a_s$ and $b_s$ for these two soils.

Later, Gardner (28) conducted laboratory experiments to verify the assumption made by Gardner and Lauritzen (27) and given by Equation 20. By using hydraulic flumes with variable slopes and very precise equipment to measure the critical non-erosive stream size on Millville Silt Loam and Trenton Fine Sandy Loam soils to estimate the parameters $a_s$ and $b_s$ in Equation 20, he showed that the above equation seemed to closely fit experimental data. No more work has been done since then to find the parameters $a_s$ and $b_s$ for other types of soil.

In this research the data collected by Criddle, et al. (17) were used, together with Equation 20, to predict maximum, non-erosive furrow stream size as a function of soil type and bed slope for six major categories of soils. The results are presented in Appendix A.

In 1949, Mech (46) studied the effect of slope and length of run on erosion. He found that directing irrigation furrows across the slope increases the rate of infiltration and the necessary irrigation head. He also concluded that increasing infiltration by some practices, cultivation for example, decreases the percentage of runoff but increases erosion along the furrow because of loosening the topsoil of the field.

In 1956, Criddle (18) presented a detailed technique to evaluate irrigation systems including furrow and border methods.
Criddle (17, 18) gathered and analyzed field data from seventeen Western United States to relate the critical non-erosive stream size to the slope of the irrigation bed and developed the relationship

\[ q_c = \frac{10 K_6}{S_o} \]  

where

- \( q_c \) = critical, non-erosive furrow stream size, gpm (lps)
- \( K_6 \) = a constant which is equal to 1.0 for the English units and 0.063 for the metric units.

As can be seen, Equation 21 is a special case of Gardner and Lauritzen's (27) Equation.

Richardson, et al. (67) found that graded furrow systems can be used to control erosion on areas with slopes up to 3 percent and that the unit runoff and unit soil loss are directly proportional to furrow length.

The effect of variable-slope furrows on erosion was studied by Meyer and Kramer (48) where they investigated the effect of profile shape on soil loss. They concluded that uniform slopes gave 0.37 units of sediment load higher than the maximum load given by upwardly concaved slopes, and convexed slopes gave very high sediment loads.
System Management and Optimization

Successful irrigation systems may be defined as those systems which for a given amount of resources would yield the highest return, i.e., they maximize farm income per unit of input resources. To achieve such a design an optimization process is required to design and operate irrigation systems. The optimization process should, therefore, involve a trade-off among various system inputs, such as irrigation water, equipment used, labor skills, fertilizers, and mechanical power sources, if any are needed.

In 1966, Horn (19) presented a design procedure to minimize the cost of on-farm irrigation pipe systems. He included the cost of the pipe, outlet valves, and power, each expressed in terms of unit cost and quantity used. His conclusion was that the developed procedure could be successfully used to design a minimized cost pipeline system, thus eliminating guesswork.

Wu and Liang (87) analyzed surface irrigation parameters in an attempt to predict an optimum furrow length where the total cost of the system is at a minimum. In their analysis, they included cost of applied water; deep percolation and runoff losses; distribution ditches; and managerial labor. They developed a systematic procedure to optimize furrow length, by using furrow intake and advance functions and other pertinent parameters, with regard to the overall cost of the irrigation system. From their analysis, they concluded that for a given set of conditions, the cost of the irrigation system will be
close to a minimum over a wide range of length of run values and that the *Application Efficiency* is a function of that range.

Howell, et al. (34) developed an environmental simulation model for Temple, Texas, including temperature, rainfall, and potential evaporation. In their model, they used stochastic dynamic programming to maximize crop yield when subjected to the constraints of water availability. For the specific conditions studied, they concluded that with regard to *Water Use Efficiency*, irrigation timing is more critical than amount of water applied. Also, when the spring soil-water content is low, one irrigation prior to planting is preferable to total post-planting irrigation. Moreover, they found that *Water Use Efficiency* was increased significantly by using small, frequent irrigations. This occurs because runoff and deep percolation losses are minimized and water deficits are allowed in non-critical consumptive use periods.

In 1975, Brosz, et al. (11) studied the effect of irrigation application depths on the yield of corn and concluded that under the conditions considered, individual irrigation depths had no direct effect on corn yield. Then they developed a procedure to accomplish irrigation scheduling, which is based on average solar radiation and temperature data.

Keller (37), in 1975, developed an optimization procedure to minimize the total cost of a given pipeline system. This involves a trade-off between pumping cost, fixed cost, and pipe size which minimize the summation of the fixed and variable costs. His procedure
is incorporated in the design and optimization of *Irrigation Runoff Recovery Systems*, IRRS's, used herein.

The preceding discussion indicates that most of the elements involved in the design of surface irrigation systems have been explored by researchers. The previous work can now be integrated together to develop a systematic procedure for designing a successful irrigation system and for optimizing the management of these systems in order to maximize net farm return. The following chapters give a rationale for furrow irrigation system design and management, and are presented to illustrate the inter-relationships among the various elements of the system.
CHAPTER III
CONCEPTUAL MODEL OF FURROW IRRIGATION

The conceptual model of furrow irrigation system design and management optimization presented herein provides a general overview of the intended approach and leads through the proposed procedure and the mathematical model given in Chapter IV. To preserve the continuity of discussion, this chapter is divided into three sub-sections where the major elements involved in design and management are discussed first, then merged together to develop a rational systematic procedure for designing and analyzing furrow irrigation systems; the last section gives the assumptions that were made in order to execute the model.

Elements of Furrow Irrigation Systems

Furrow irrigation systems, like all other irrigation practices, involve a wide variety of interacting elements and components, some of which can be controlled by design and some by management. Thus, the execution of an efficient and successful system depends on the initial set of design conditions, economical restraints, labor availability, and management capability.

The performance of the system can be evaluated from estimates of runoff water, deep percolation losses, and Distribution Uniformity, while the overall integrator of system output is the crop yield per unit of applied water, unit of system cost, and/or unit of land area.
In essence, the elements which influence the performance of furrow irrigation systems can be grouped into two categories, those related to the physical design of the system and those related to the operation and management of the system. The physical elements include: soil erodibility, slope magnitude and uniformity, furrow stream size, intake characteristics, furrow shape, and water supply availability. The operational elements include: crops grown and crop rotation, frequency and depth of irrigation, time of application per irrigation, and utilization of *Irrigation Runoff Recovery Systems*, IRRS's, cutback irrigation, or runoff disposal.

The above components are interrelated and it is not feasible to study one element at a time. Therefore, the discussion below is provided to show some aspects of the interaction among the various items and to lead into a systematic procedure to design and evaluate furrow irrigation systems.

**Physical elements**

The physical elements pertain to the system itself. When a specific set of boundary conditions is given, these elements can be estimated or closely predicted from available design data.

Soil erodibility is one of the important elements that needs to be considered in the design of furrow irrigation systems. Because of erosion of the topsoil, furrow irrigation is not practical on terrains with steep slopes (or even sometimes on flat areas if large erosive streams must be applied). However, for a given field, soil erosion
can be kept in check by controlling flow velocity, through proper furrow slope design, and furrow stream size.

The magnitude and uniformity of row and cross-row slopes are functions of original topographic configurations and the extent of land grading operations. In some cases, uniform slopes may not be attainable because of rough topography which would require excessively deep cuts and fills. These fields might still be used, however, if non-uniform slopes in either row, cross-row, or both directions were used. This, of course, effects uniformity of irrigation, runoff, deep percolation losses, and erosion of the topsoil. Thus, in designing a given furrow irrigation system, a study of the interactions among the above items is necessary.

Furrow stream size is a function of the type of soil and the magnitude and uniformity of land slope. To obtain a uniform application and minimize erosion problems, the furrow stream size should be large enough to irrigate the required area and small enough to be non-erosive. Hence furrow stream size selection depends on first knowing the soil texture and land slope of the field for which the design is made. Other factors, such as availability of the supply stream and number of irrigation sets might place some restraints on the furrow stream size.

Intake characteristics of the soil complicate the design of irrigation systems because they change during and between irrigations. An evaluation of soil intake characteristics is mandatory for good design because intake characteristics effect length of run, time of
advance, size of irrigation stream, amount of runoff and deep-percolated water, and Distribution Uniformity.

The shape of the furrow-channel cross-section may or may not affect the overall performance of the system. If it does, its main effect is to change the time of water advance and recession and the intake rate. However, in most cases, depending on the soil type, furrow slope, and furrow stream size, after the first irrigation in the season or after the first irrigation following cultivation, the shape of the furrow channel tends to stabilize and becomes a wide, shallow channel.

The design of an irrigation system is dependent on the quantity and quality of the water supply. The quantity of water available controls the frequency of application, and the area which can be covered. It may even restrict the variety and number of crops that can be grown. The water supply also affects the management scheme and the number and size of the irrigation settings. The quality of the available water influences crop varieties and soil management practices. It will also influence the use of Irrigation Runoff Recovery Systems because it affects the quality of runoff water.

In modeling irrigation systems the problem of water quality can be resolved by conducting a preliminary study and deciding on the suitability for irrigation of the given water supply and the kinds of crops that can be grown. These decisions are then treated as boundary conditions for the design.
Operational elements

The operational elements are those which are functions of system management and should be chosen to meet the available managerial skills. These elements are discussed below.

The crops grown and crop rotation depend on the quantity and quality of the available water, market conditions and the personal preference of the farmer. These factors do not lend themselves to optimization for the purposes considered herein, hence should be considered as boundary conditions imposed on the model. It should be understood, however, that an optimal design for one crop may not be optimal for another, so the design should meet the needs of the most critical crop in the rotation.

The frequency and depth of irrigation are functions of the crop water use patterns and root depth, soil moisture holding capacity, yield response to soil water availability, and anticipated income. Some crops respond to shallow, more frequent irrigation, with increased yield; others do not, which suggests that a careful decision must be made about frequency and depth of irrigation. For instance, shallow, more frequent water application may not be attainable in certain cases, which necessitates a compromise between high yield and available managerial skills.

Once the frequency of irrigation is chosen, the depth of application per irrigation can be determined to meet crop requirements. Hence, all the preceding operational factors should be integrated together to find a feasible irrigation schedule that fits the
necessary or imposed boundary conditions, yet gives a maximum possible profit.

The time of application per irrigation is dependent on the soil characteristics, required depth of application per irrigation, allowable water losses, and availability of the water supply. For example, applying the water for long enough time to fully irrigate all the land considered may create tremendous deep percolation and runoff losses. Thus, in cases like this, stretching the time of application and under-irrigating parts of the field would be necessary in order to meet irrigation schedules and water turns. Under-irrigation implies that the water is turned off before the entire root zone has received the necessary depth of infiltrated water. Therefore, to arrive at an optimal plan, when modeling irrigation systems, limitations on the time of application per irrigation must be specified.

Another important operational element in irrigation system design is runoff control. Runoff water can be controlled by using cutback irrigation, Irrigation Runoff Recovery Systems, or runoff disposal. The use of such practices must be justified by the amounts of available irrigation water and allowable water losses. The decision as to whether any of these practices need to be used is dependent on the local restraints. For instance, the existing laws may prohibit the disposal of any excess water or may limit the amounts of applied water for a given irrigated area. Environmental conditions may restrict the allowable water losses in order to eliminate down-stream contamination by sediments, pesticides, or insecticides.
Farmer's desire and available capital is another factor which makes one scheme more favorable than the other. For example, installation of an IRRS calls for large capital investment at the beginning while it reduces water losses and labor requirements, or in other words, irrigation cost, in future years. On the other hand, utilization of cutback irrigation does not require any extra investment at the time of system installation but necessitates a great deal of managerial labor during each irrigation throughout the entire life of the system.

Furthermore, system automation is another constraint which may limit the use of one practice. Irrigation Runoff Recovery Systems, IRRS's, are more apt to be automated using sophisticated timers and controllers, thus minimizing the need for skilled labor, while cutback irrigation cannot be automated unless a specially designed distribution network is constructed.

Therefore, all of the preceding physical and operational elements, boundary conditions, and design limitations must be considered simultaneously in designing furrow irrigation systems.

Proposed Model of Furrow Irrigation

A proper model of furrow irrigation systems should consider all the pertinent components of system design and operation and their interaction in a systematic and efficient way. In this section, a general overview of the concept of the proposed model is presented, together with a discussion of the order in which various design
factors are analyzed. A flow chart, given in Figure 1, shows the sequence of design operations. The mathematical and computerized models are given in Chapters IV and V.

The first design element to be considered in surface irrigation systems design is land preparation. This may range from only minor land smoothing to heavy land grading operations. Feasibility of such operations will be determined by considering the maximum allowable depth of cuts and fills, range of desirable slopes of the graded plane in both directions, and uniformity of land grading operations. With all these factors integrated together, the designer may find several possible alternatives or none at all. Thus, at this point in the design procedure a decision must be made about system layout, furrow direction, slope, and length. At the time being such decision should be made manually in order to obtain a more successful system layout. This decision is indicated by the elliptical box of man-machine interface in Figure 1.

After the furrow slope has been fixed then a maximum non-erosive furrow stream size can be predicted, since it depends mainly on soil characteristics and land slope, which have already been determined by land grading design and system layout. The predicted stream size might need to be adjusted in order to fit the existed supply stream discharge, number of furrows per irrigation set, and a pre-determined furrow length.

By knowing furrow shape, soil intake characteristics, and furrow stream size, the rate and time of advance of the water front down the
Figure 1. A simplified flow chart of the conceptual model of furrow irrigation system design and management optimization.
Figure 1. Continued.
furrow channel, or the advance function, can be determined. This is indicated by the advance-infiltration interaction box in Figure 1. A Physically Feasibility Design, PFD, is now available where furrow slope, length, spacing, stream size, and advance time are all determined and checked with the pre-specified limits. Obviously, all of the above factors pertain to the physical aspects of the system, therefore, they should be related to the managerial decisions to evaluate system performance.

Recalling that by knowing the type of crop grown, soil characteristics, and water supply availability, the seasonal depth of irrigation, the depth of application per irrigation, the frequency of application can be determined (see Figure 1). If no data exist, an estimation for the depth of application per irrigation is necessary in order to start searching for an optimal depth that will maximize net farm profit.

Therefore, having decided upon the depth of application per irrigation and knowing soil intake characteristics, the time of application per irrigation can be determined. The rate of inflow and the rate of infiltration are now utilized to calculate the rate and volume of runoff water. The deep percolation losses, however, can be estimated by knowing the depth of infiltrated water and the depth of water that can be stored in the root zone. The deep percolated water is naturally considered as a loss, while the runoff water can be recovered and used for irrigation (or it can also be disposed of and considered as a loss too). When runoff water is to
be recovered then an *Irrigation Runoff Recovery System, IRRS,* is needed and must be designed properly.

From the preceding design data the patterns and uniformity of infiltrated water along the furrow can be determined. This requires combining the predicted advance function and soil intake characteristics to obtain the shape of the wetting pattern along the furrow.

For the particular design considered, the expected crop yield can be estimated by knowing the depths of infiltrated water along the furrow and crop production as a function of infiltrated water. This is shown by the crop yield box in Figure 1. The gross farm return, system cost, and net farm profit are now determined. When net farm profit is calculated a managerial decision can be made as to whether this is an acceptable return or not, as shown by the yes-no decision box in Figure 1.

In order to arrive at maximum possible profit, an iterative procedure should be used where the average depth of infiltration per irrigation, thus the seasonal depth of irrigation are changed. The new net farm profit is evaluated until an application depth which maximizes net farm profit is obtained, then the optimization process is terminated and the final design and management information is executed.

**Assumptions Made in the Model**

Certain assumptions are inherent in the preceding conceptual model. The main ones are as follows:
1. Any crop considered has an identifiable Crop Production Function, CPF, a function which simply relates the amount of water available to the crop and its yield. In this research CPF of corn and sugar-cane crops are used and CPF for other crops can be obtained from the literature or from experimental plots.

2. The maximum non-erosive furrow stream size is predictable for a given furrow slope and soil type. In this model, the empirical technique presented in Appendix A is used.

3. All irrigations during the season are identical regardless of the stage of growth of the crop grown. For example, the seasonal depth of water infiltrated at a given point in the field is simply equal to the depth of water infiltrated at that particular point per irrigation times the number of irrigations in the season.

4. The frequency of irrigation is held constant during the season with the individual irrigations evenly distributed over the growing season.

5. The effective rainfall and depth of pre-season irrigation are considered as usable depth of water in the model.

6. The basic field and managerial data are available and do not change with time. These data would include topographic information, soil texture, water quantity and quality, and representative costs of water, labor, equipment, energy, and farming operations.

7. Evaporation losses do not constitute a major system loss and hence can be ignored.
8. The optimal design is defined as the design which maximizes the net farm profit with respect to irrigation. For example, only the factors that affect on-farm water application and management will be considered, i.e., the furrow distribution system but not the water conveyance system that delivers the water to the farm head gate.
CHAPTER IV

MATHEMATICAL MODEL OF FURROW IRRIGATION

In this chapter the conceptual model presented in Chapter III, is translated to a systematic design and evaluation procedure which will maximize net farm profit for a particular farm design. Since a furrow irrigation system is being modeled, a definition sketch of a longitudinal section of a typical furrow showing the major disposition of applied water is given in Figure 2.

The purpose of the following sections is to present a condensed explanation of the proposed procedure. Functional relationships will be used to preserve the continuity of presentation. This will be followed by a detailed explanation of the model, including the mathematical relationships and flow charts used in its assembly.

Procedure of Design and Evaluation

The sequence of operations used in the model are sketched in the flow chart presented as Figure 3.

As shown, the first step in designing a surface irrigation system is land grading. A number of methods of doing the land grading design are available. Once one has been selected then the length of run, slope of the graded surface, and the land grading cost can be computed.

The next step is to determine the furrow stream size with existing soil characteristics and the design land slope as input
Figure 2. Longitudinal section along a furrow which shows the various components of applied water.
Figure 3. Flow chart of the developed procedure for furrow irrigation system design and management optimization.
data. The maximum non-erosive furrow stream size can be expressed by the functional relationship

\[ q_c = f_1(\alpha_s, \beta_s, S_o) \]  \[22\]

where

- \( q_c \) = maximum non-erosive furrow stream size, gpm (lps)
- \( f_1 \) = a functional relationship
- \( \alpha_s \) = a soil parameter
- \( \beta_s \) = an exponent
- \( S_o \) = slope of the irrigated land in the row direction.

Details of the above relationship can be found in Appendix A.

Furrow advance function, and hence the time to advance furrow length, can now be predicted by knowing soil intake characteristics, and furrow length, slope, geometry, and stream size. Numerous techniques to accomplish the prediction process are available, but in general the advance function can be written as follows

\[ t_{xt} = f_2(q, K, n, t_i, g_f) \]  \[23\]

or can be expressed empirically by

\[ t_{xt} = f_3(a, b, x_i) \]  \[24\]

where

- \( t_{xt} \) = time to advance a given distance, \( x_i \), measured from the head of the furrow, minutes
$f_E = \text{a functional relationship}$

$f_\beta = \text{a functional relationship}$

$q = \text{furrow stream size, gpm (lps)}$

$x_i = \text{a given distance measured from the head of the furrow, ft (m)}$

$g_f = \text{a furrow geometry factor}$

$a$ and $b$ are empirical coefficients

and when $x_i = L$, then $t_x = t_a$

where

$L = \text{length of irrigation run or furrow, ft (m)}$

$t_a = \text{time required for the water to reach the end of the furrow, minutes.}$

The preceding design factors can be checked and adjusted according to the desired or pre-specified limits to obtain a *Physically Feasible Design, PFD*. The following step in the design process is to use the selected PFD and optimize operations.

However, to start the management optimization phase of the process an estimation or decision of the minimum depth and frequency of irrigation is necessary. This is arrived at by evaluating water availability, soil moisture holding capacity, allowable soil moisture depletion, and crop evapotranspiration, in other words

$$d_i = f_4(K, n, f_r, R_d, d_e, ET) \quad [25]$$

where

$d_i = \text{accumulated depth of infiltrated water at the lower end of the furrow, inches (mm)}$
\[ f_d \] = a functional relationship
\[ f_r \] = frequency of irrigation, days
\[ R_d \] = depth of the root zone, ft (m)
\[ d_e \] = percentage of allowable soil moisture depletion
\[ ET \] = crop evapotranspiration, inches/day (mm/day).

After knowing the minimum depth of application per irrigation, \( d_z \), then the time of application at the lower end of the furrow can be determined by knowing soil intake characteristics. In the developed procedure, \( \text{Kostakov} \) intake function is used, i.e.,

\[ t_z = f_5 (d_z, K, n) \]  \[26\]

where

\[ t_z \] = time of application at the lower end of the furrow, minutes
\[ K \] = coefficient of \( \text{Kostakov} \) intake function
\[ f_5 \] = a functional relationship.

Using Equations 23 or 24 and 26, the time of application at the upper end of the furrow is calculated from

\[ t_u = t_z + t_a \]  \[27\]

where

\[ t_a \] = time of application at the upper end of the furrow, minutes.
The accumulated depth of infiltration is calculated from the intake function and time of opportunity, i.e., it can be expressed by

\[ d_i = f_5^{-1}(K, n, t_i) \]  \hspace{1cm} [28]

where

- \( d_i \) = accumulated depth of infiltrated water at any time \( t_i \), inches (mm)
- \( t_i \) = time of opportunity, minutes.

Equation 28 is a more general form of Equation 26 except that Equation 28 expresses the accumulated depth of infiltrated water in terms of the corresponding time of opportunity instead of the time in terms of the accumulated depth of infiltration as given in Equation 26.

The shape of the wetting pattern and the accumulated depth of infiltrated water at several locations along the furrow can now be predicted by combining Equations 23 or 24, 27, and 28, or

\[ d_{x_i} = f_6(t_{x_i}, t, K, n) \]  \hspace{1cm} [29]

where

- \( d_{x_i} \) = accumulated depth of infiltrated water at any given distance, \( x_i \), measured from the head of the furrow, inches (mm)
- \( f_6 \) = a functional relationship.
The percentage of land receiving an average accumulated depth of infiltrated water, \( d_{xi} \), is determined by dividing the length of the furrow into several reaches, say \( m_2 \), and the percentage of land represented by an individual reach becomes

\[
P_{xi} = \frac{x_{i+1} - x_{i-1}}{2L} \times 100 \tag{30}
\]

where

\( P_{xi} \) = percentage of land receiving an average accumulated depth of infiltrated water of \( d_{xi} \).

Thus, the total depth of infiltrated water will be

\[
d_t = \sum_{i=1}^{m_2} \frac{x_{i+1} - x_{i-1}}{2L} \times 100 \tag{31}
\]

where

\( d_t \) = total depth of infiltrated water, inches (mm)

\( m_2 \) = number of divisions along the furrow.

It can be seen from Figure 2 that the amount of deep percolated water is equal to

\[
d_p = \sum_{i=1}^{m_2 - 1} \left( d_{xi} - d_s \right) \frac{x_{i+1} - x_{i-1}}{2L} \times 100 \quad d_{xi} > d_s \tag{32}
\]

where

\( d_p \) = depth of deep percolated water, inches (mm)
\( d_s \) = depth of stored water in the root zone, inches (mm).

The depth of runoff water can be calculated by knowing the gross depth of applied water and total depth of infiltrated water. The gross depth of applied water, in turn, can be calculated by using the continuity concept which can be written as

\[
d_a = f_r(q, t, S_s, L) \tag{33}
\]

where

\( d_a \) = gross depth of applied water per furrow per irrigation, inches (mm)

\( f_r \) = a functional relationship

\( S_s \) = furrow spacing, ft (m).

The depth of runoff water will then be

\[
d_r = d_a - d_t \tag{34}
\]

and the percentage of runoff water will be

\[
R_f = \frac{d_r}{d_a} \times 100 \tag{35}
\]

where

\( d_r \) = depth of runoff water, inches (mm)

\( R_f \) = percentage of runoff water.

At this point, all components of applied water (see Figure 2) are calculated and should be checked with the physically feasible limits
in order to have a PFD. Then a decision must be made as to whether 
an Irrigation Runoff Recovery System, is needed or not; when no IRRS 
is needed then a direct estimation of the total annual cost of the 
system can be made from the above information. When an IRRS is to 
be used, then a runoff recovery system should be designed, and the 
total system cost is calculated.

The same wetting pattern is assumed to be repeated with every 
irrigation during the whole season, and therefore the seasonal depth 
of infiltrated water at a given point along the furrow, $x_i$, will be

$$D_{xi} = N_i \cdot d_{xi} \quad \text{[36]}$$

where

$D_{xi} = \text{total seasonal depth of infiltrated water at a given}$

$\text{distance, } x_i, \text{ measured from the head of the furrow, inches}$

$(\text{mm})$

$N_i = \text{number of irrigations in the entire growing season.}$

Evidently, when $d_{xi}$ equals $d_l$ then $D_{xi}$ will be $D_l$, and when $d_{xi}$ equals $d_u$ then $D_{xi}$ will be $D_u$, where

$D_l = \text{seasonal depth of infiltrated water at the lower end of}$

$\text{the furrow, inches (mm)}$

$D_u = \text{seasonal depth of infiltrated water at the upper end of}$

$\text{the furrow, inches (mm)}.$

Having determined the wetting pattern along the furrow, total 
seasonal depth of applied water, and the cost of the irrigation
system, then crop yield, gross return, and net farm profit can be calculated in order to evaluate the performance of the design under consideration. The crop yield is estimated by sub-dividing the length of the furrow, or the field, into small sub-divisions, $m_2$ for example. Then the total depth of infiltrated water, $d_{xi}$, received by each sub-division can be calculated from Equation 29 and the corresponding seasonal depth, $D_{xi}$, from Equation 36. The percentage of land, $P_{xi}$, represented by each sub-division is determined from Equation 30. The seasonal depth of infiltrated water and the appropriate Crop Production Function, CPF, can be used to determine the expected yield from the particular sub-division considered (see Figure 4). Therefore, the expected yield from an individual sub-division can be expressed by

$$y_i = f_{\gamma}(D_{xi})$$

[37]

where

- $y_i$ = gross yield from an individual field sub-division, units/acre, (units/ha)
- $f_{\gamma}$ = a functional relationship defined by the CPF.

The above procedure is repeated for all field sub-divisions, then the expected total farm yield is found as follows:

$$Y_e = \sum_{i=1}^{m_2} A_{xi} P_{xi} y_i$$

[38]
Seasonal depth of infiltrated water

Seasonal depth of water received by crop

Figure 4. Schematic representation of the interaction between water distribution pattern along the furrow and expected crop yield.
where

\[ Y_e = \text{expected farm yield, units} \]
\[ A = \text{total farm area, acres (hectares).} \]

Thus, the net farm profit is calculated from

\[ NAFP = Y_e C_{rv} - Y_e C_{cp} - C_{sy} \]

where

\[ NAFP = \text{Net Annual Farm Profit, \$} \]
\[ C_{rv} = \text{current crop value, \$/unit} \]
\[ C_{cp} = \text{cost of crop production, \$/unit} \]
\[ C_{sy} = \text{annual fixed and maintenance system cost, \$.} \]

To maximize net farm profit, the depth of application per irrigation should be changed and the whole process is repeated until the practical range of depths of application is investigated. Then the depth, and consequently the associated design and management schemes which maximize net farm profit, are selected.

**Land Grading Techniques**

In this section more details are given about land grading techniques, including the theories, ramifications, and basic assumptions involved in their derivations. The developed model provides ten configurations for the final surface following land grading operations. Some provide for a plane graded surface with uniform slopes in one or both directions, while others provide a
multi-slope surface which takes full advantage of existing field
topography.

Every land grading design requires two major independent steps,
namely, finding the proper design slopes and calculating the volumes
of earth work. Therefore, the discussion of land grading is
divided into two sections, first, the methods of calculating surface
slopes, and second, methods of calculating the volumes of earth work.
Any combinations of the two steps is possible in the design.

Methods of calculating design slopes

In this model, four methods to calculate design slopes are used,
These are the least squares method, symmetrical residuals method,
double centroid method, and average slope method.

Least squares method. The least squares method of statistically
fitting a plane through grid elevations of a field was first done by
Givan (29) in the early 1940's. The method finds a plane surface
through the elevation points which minimizes the sum of the squares
of the cuts and fills. By using the theory of least squares, the
row and cross-row slopes of the graded surface can be calculated
from

\[
S_x = \frac{\sum_{j=1}^{n} \sum_{i=1}^{n} y_{ij} x_{ij}^2 - N H X}{\sum_{j=1}^{n} \sum_{i=1}^{n} x_{ij}^2 - N X^2}
\]

[40]
and

$$S_y = \frac{\sum_{i=1}^{n_x} \sum_{j=1}^{n_y} H_{i,j} Y_{i,j} - N H_m Y_m}{\sum_{i=1}^{n_x} \sum_{j=1}^{n_y} Y_{i,j}^2 - N Y_m^2}$$

[41]

where

- \(N\) = total number of stations where elevations have been recorded
- \(H_m\) = average elevation of all points above a specified datum, ft (m)
- \(H_{i,j}\) = ground elevation at any point on the plane above a specified datum, ft (m)
- \(X_{i,j}\) = \(X\)-coordinate of a given point on the plane
- \(Y_{i,j}\) = \(Y\)-coordinate of a given point on the plane
- \(X_m\) = average distance in the \(X\)-direction from the origin
- \(Y_m\) = average distance in the \(Y\)-direction from the origin
- \(S_x\) = slope of the graded surface in the \(X\)-direction
- \(S_y\) = slope of the graded surface in the \(Y\)-direction
- \(n_x\) = number of stations in the \(X\)-direction
- \(n_y\) = number of stations in the \(Y\)-direction.

It should be mentioned that Equations 40 and 41 are applicable only for rectangular fields. The grade elevation at any point on the plane can be calculated by
\[ H_{gij} = H_o + X_{ij} S_x + Y_{ij} S_y \]  \[ [42] \]

where

\[ H_{gij} = \text{grade elevation at any point on the plane above a} \]
\[ \text{specified datum, ft (m)} \]
\[ H_o = \text{elevation of the graded surface at the origin above a} \]
\[ \text{specified datum, ft (m)}. \]

and the depth of cut or fill is calculated from

\[ h_{cj} \text{ or } h_{fj} = H_{gij} - H_{ij}. \]  \[ [43] \]

where

\[ h_{cj} = \text{depth of cut occurred at individual grid corner,} \]
\[ i^{th} \text{ cross-row and} \ j^{th} \text{ row, ft (m)} \]
\[ h_{fj} = \text{depth of fill occurred at individual grid corner,} \]
\[ i^{th} \text{ cross-row and} \ j^{th} \text{ row, ft (m)}. \]

a minus sign indicates a cut, \( h_{cj} \), and a plus sign indicates a fill, \( h_{fj} \).

**Symmetrical residuals method.** This technique was formulated by Shih and Kriz (71) in 1971. It is based upon residual properties, *Newton's-divided-difference* interpolation procedure, and statistical properties of the bestfit plane with unbiased estimate and minimum variance. It is used to investigate five design configurations of the graded surface. These five designs are:

1. Plane surface having uniform slopes with row and cross-row drainage;
2. Non-uniform surface having variable slopes with row and cross-row drainage;

3. Non-uniform surface having uniform slope in the row direction and variable slope in the cross-row direction with row and cross-row drainage;

4. Non-uniform surface having uniform slope in the row direction and maximum and minimum allowable cross-row slope with row drainage only;

5. Non-uniform surface having variable slope in the row direction and maximum and minimum allowable cross-row slope with row drainage only.

Figure 5 is a schematic representation of the above types of land grading designs.

The derivation of the design equations for this method is very complicated and can be found in the original paper (71). The final design equations are as follows:

1. When the number of stations in any individual row profile is even;

\[
b_j = \frac{n_j}{2} + 1
\]

2. When the number of stations in any individual row profile is odd;
Figure 5. Schematic representation of five alternatives of land grading designs.
Figure 5. Continued.
Having determined the bestfit slope for individual rows and cross-rows, the bestfit slope for the entire field can be calculated as follows:
A. in the row direction:

\[ B = \frac{\sum_{j=1}^{m} b_j}{m} \]  \[ ]^{48}

B. in the cross-row direction:

\[ C = \frac{\sum_{i=1}^{n_r} c_i}{n_r} \]  \[ ]^{49}

where

\[ g_s = \text{grid spacing, ft (m)} \]
\[ B = \text{bestfit slope in the row direction for the entire field} \]
\[ b_j = \text{bestfit slope for any individual row profile, } j \]
\[ C = \text{bestfit slope in the cross-row direction for the entire field} \]
\[ c_i = \text{bestfit slope for any individual cross-row profile, } i \]
\[ H_{i,j} = \text{original field elevation at any individual station } i^{th} \text{ cross-row and } j^{th} \text{ row, ft (m)} \]
\[ m = \text{number of stations in the cross-row direction} \]
\[ m_i = \text{number of stations in any cross-row profile, } i, \text{ (for rectangular fields, } m_i = m) \]
\[ n_r = \text{number of stations in the row direction} \]
\[ n_j = \text{number of stations in any given row, } j, \text{ (for rectangular fields, } n_j = n_r) \].
To reduce the necessary calculations required in exploring these five designs, the individual station elevations used to determine the bestfit slope in all five types of design are either the original field elevations or the previously calculated elevations obtained while performing the preceding types of design.

**Double centroid method.** This method was developed in 1973 by Paul (56). Its main theory states that the total land grading cost is reduced when the average haul distance is minimized. Therefore, to minimize the haul distance the field considered is sub-divided into two segments of equal areas and the volumes of cuts and fills are balanced about the centroid of each segment. The centroid elevation and location for each segment is determined in a similar way as for the least squares method; then the desired final slope of the graded surface is determined by the slope of the line joining the centroids of the two segments. For a given profile, this process can be illustrated as follows:

\[
C_{LH} = \frac{\sum_{i=1}^{n/2} H_i}{n/2} \quad [50]
\]

and

\[
C_{RH} = \frac{\sum_{i=\frac{n}{2}}^{n-1} H_i}{n/2} \quad [51]
\]
where

\[ C_{LH} = \text{elevation of the centroid of the left-hand half of the profile above a given datum, ft (m)} \]

\[ C_{RH} = \text{elevation of the centroid of the right-hand half of the profile above a given datum, ft (m)} \]

then the desired slope is calculated from

\[ S = \frac{C_{RH} - C_{LH}}{g_s \frac{n_p}{2}} \]  \hspace{1cm} [52]

or by combining equations 50, 51, and 52, the final slope calculated by the double centroid method will be

\[ S = \frac{4}{g_s \frac{n_p}{2}} \left[ \sum_{i=1}^{n_p} H_i - \sum_{i=1}^{\frac{n_p}{2}} H_i \right] \]

\[ i = \frac{n_p}{2} + 1 \]  \hspace{1cm} [53]

Equation 53 above is applicable to an even number of stations along the profile. For odd number of stations along the profile, the bestfit slope is calculated by

\[ S = \frac{4}{g_s \frac{n_p}{2}} \left[ \sum_{i=1}^{n_p} H_i - \sum_{i=1}^{\frac{n_p}{2}} H_i \right] \]

\[ i = \frac{n_p}{2} + 1 \]  \hspace{1cm} [54]
For irregularly-shaped fields, the slope of the graded plane in the X-direction will be

\[ S = \frac{n \sum_{i=X}^{n} \sum_{j=1}^{m} n_{ij} - \sum_{i=1}^{X} \sum_{j=1}^{n} H_{ij} A_{ij}}{n \sum_{i=X}^{n} \sum_{j=1}^{m} n_{ij} - \sum_{i=1}^{X} \sum_{j=1}^{n} H_{ij} A_{ij}} \]  

[55]

where

\[ A_{ij} = \text{individual area represented by each grid point, sq ft (sq m)} \]

and the slope in the Y-direction is expressed in a similar way. It should be noted that Equations 53 and 54 developed by Paul are similar to Equations 44 and 45 developed by Shih and Kriz, but that the derivation of the equations is entirely different.

**Average slope method.** This method was originally developed by Butler (12). The slopes of individual row profiles are calculated, then an average slope is calculated using a methodology similar to that given in Equations 48 and 49. The average slope is then checked with the range of allowable slopes for that particular field and adjusted accordingly. Further adjustments for the calculated average slope and design elevations may be needed after determining the volumes of earth work in order to obtain a desirable cut-fill ratio.
Methods of calculating volumes of earth work

There exist three methods of calculating volumes of earth work which may be considered as the major computer programmable techniques. These methods are the four-point method, the end-grid area method, and the summation method. A brief description of each technique is given below.

Four-point method. This method is based upon the following assumptions:

1. The ground surface between two stations is a smooth plane;
2. Each grid may have either cut at all four corners, fill at all four corners, or cut at two opposite corners and fill at the other two opposite corners;
3. The weighted depths of cuts and fills for the grid corners are obtained by averaging the sum of the depths of cuts and fills at the grid corners.

Using the above assumptions, the volumes of cuts and fills on an individual grid may be calculated as follows:

\[
V_c = \frac{g_s^2}{K_f} \left( \frac{h_c^2}{h_c + h_f} \right) \tag{56}
\]

and

\[
V_f = \frac{g_s^2}{K_f} \left( \frac{h_f^2}{h_c + h_f} \right) \tag{57}
\]
where

\[ V_c = \text{volume of earth work in cut on an individual grid, \( \text{cu yd (cu m)} \)} \]
\[ V_f = \text{volume of earth work in fill on an individual grid, \( \text{cu yd (cu m)} \)} \]
\[ H_c = \text{sum of depths of cuts at the corners of the grid, \( \text{ft (m)} \)} \]
\[ H_f = \text{sum of depths of fills at the corners of the grid, \( \text{ft (m)} \)} \]
\[ K_\gamma = \text{a constant which is equal to 108 for the English units and 4.0 for the metric units.} \]

**End-grid area method.** This method was first adopted by Shih and Kriz (71). It utilizes the same concept as the four-point method except that it weakens the restrictive assumptions involved in the four-point method to closely approximate original ground surface configurations and give more precise results. The final design equations to calculate the volumes of earth work by the end-grid area method are as follows:

1. When four corners of the grid are in cut;

\[ V_c = \frac{1}{K_\gamma} \left( \frac{2}{g_8} H_c \right) \quad [58] \]

2. When three corners of the grid are in cut;

\[ V_c = \frac{2}{K_\gamma} \left( 2 \frac{H_c}{H_c + \frac{H_f^2}{H_c}} + \frac{H_f^2}{H_f} \right) \quad [59] \]
and

\[ V_f = \frac{g_s}{K_9} \left( \frac{H_f^2}{H_c + 3H_f} \right) \]  \[\text{[60]}\]

3. When two adjacent corners of the grid are in cut;

\[ V_c = \frac{g_s}{K_{10}} \left( \frac{H^2}{H_c + \frac{H_f^2}{H_c + H_f}} \right) \]  \[\text{[61]}\]

and

\[ V_f = \frac{g_s}{K_{10}} \left( \frac{H_f^2}{H_c + \frac{H_f^2}{H_c + H_f}} \right) \]  \[\text{[62]}\]

4. When two opposite corners of the grid are in cut;

\[ V_c = \frac{g_s}{K_7} \left( \frac{H_f^2}{H_c + H_f} \right) \]  \[\text{[63]}\]

and

\[ V_f = \frac{g_s}{K_7} \left( \frac{H_f^2}{H_c + H_f} \right) \]  \[\text{[64]}\]

which are the same as the equations of the traditional four-point method.

5. When one corner of the grid is in cut;

\[ V_c = \frac{g_s}{K_9} \left( \frac{H_f^2}{3H_c + H_f} \right) \]  \[\text{[65]}\]
and

\[ V_f = \frac{g_s^2}{K_8} \left( 2H_f + \frac{H_f^2}{3H_c + H_f} \right) \]  \[66\]

6. When four corners of the grid are in fill;

\[ V_f = \frac{g_s^2 H_f}{K_7} \]  \[67\]

where

- \( K_8 \) = a constant which is equal to 324 for the English units and 12 for the metric units
- \( K_9 \) = a constant which is equal to 36 for the English units and 4/3 for the metric units
- \( K_{10} \) = a constant which is equal to 216 for the English units and 8 for the metric units.

**Summation method.** This technique provides an estimate of the volumes of earth work for an individual grid or for the total field in one step. In its simplest form, it can be written as:

\[ V_c = \frac{1}{K_{11}} g_s^2 H_c \]  \[68\]

and

\[ V_f = \frac{1}{K_{11}} g_s^2 H_f \]  \[69\]
where

\[ K_{11} = \text{a constant which is equal to 27 for the English units and 1.0 for the metric units.} \]

When the volume of earth work for the total field is desired then the total depths of cuts and fills are summed and used in Equations 68 and 69, respectively.

**Overland Flow Description**

The theme of this section is to present the phase of water advance down the furrow channel, depth and uniformity of infiltrated water, and amounts and time-distribution of runoff water. Each of these areas can be analyzed in several ways using pertinent research that has been done. In the next few sections, the above three areas of analysis are explored in some details to provide an idea about the procedural assumptions involved in the various methods used to carry out a given design or management operation.

**Water-advance phase**

So far all the methods used to analyze the water-advance phase in furrow irrigation have been based on either the continuity theory, the hydrodynamics analysis, or both. The hydrodynamics approaches are not readily adaptable to computer analysis, therefore, five methods which use the continuity theory to study the water-advance phase are used in this model. For brevity, each method is named in the text either by the name of the author who first developed it or by the concept used in its derivation. These methods are Davis' method (20),
empirical method (24), Fok and Bishop's method (24), Patterson's method (55), and Intake method presented in Appendix B.

Davis (20) developed a method to predict water advance down a furrow channel by dividing the volume of applied water into two parts, the water infiltrated, as determined by the Kostakov intake equation, and the water stored on the surface. From this, he derived the following relationship to predict the advanced distance at any given instant of time

\[ x_i = \frac{K_{12} q \Delta t - \frac{\int K (\Delta t)^{n+1}}{2 K_{13} (n+1)^2} [g_i \Delta x_i + g_{i-1} \Delta x_{i-1} + \ldots + g_2 \Delta x_2]}{\epsilon \Delta t^2 + h} \]

where

- \( \Delta x_i \) = increment of distance advanced in time \( i \Delta t \), ft (m)
- \( \Delta t \) = increment of time, minutes
- \( i \) = an index
- \( h \) = puddling factor
- \( g_i \) = an index which is equal to \( i^{n+1} - (i-2)^{n+1} \)
- \( K \) = coefficient of Kostakov intake function, gpm/ft (lps/m)
- \( c \) = a parameter used to express the volume of water stored in the soil
\( \bar{e} \) = a factor which accounts for channel shape

\( f \) = a factor which accounts for the method of measuring intake function

\( K_{12} \) = a constant which is equal to 0.1337 for the English units and 0.060 for the metric units

\( K_{13} \) = a constant which is equal to 7.48 for the English units and 1000 for the metric units.

Davis' equation requires two trial and error solutions. This is done by assuming initial values for \( c \), \( f \), and \( \bar{e} \). The first two increments of advanced distances are predicted and checked with actual measured values. If they do not match, the assumed values of \( c \), \( f \), and \( \bar{e} \) are adjusted and the process is repeated until they do. The value of \( f \) can be assumed as a unity without introducing a large error. The value of \( \bar{e} \) depends on the shape of the furrow channel and water front and has to be determined for individual cases. The puddling factor, \( h \) which accounts for irregularities in furrow shape, can be assumed equal to \( 3 \times 10^{-3} \) cu ft/ft when no other information is available.

The empirical method (24) assumes that the advanced distance can be empirically expressed by an exponential relationship. Several forms of empirical functions have been developed, the simplest of which is

\[ x = a t^b \]  

[72]
where

\[ a = \text{empirical coefficient of the advance function} \]

The coefficients \( a \) and \( b \) are determined from actual field trials. They depend on furrow slope, stream size, channel shape, and soil intake characteristics. By knowing \( a \) and \( b \) the advanced distance at any given time, \( t \), can be determined.

Fok and Bishop (24) used the continuity theory and the above empirical advance function and developed the following relationship

\[
x = \frac{K_{12} q t}{\frac{u d_0}{1 + b} + \frac{W F K \epsilon^{n+1}}{K_2 (n+1) (n+2)}}
\]

[73]

where

\[ u = \text{a coefficient of the cross-sectional area of the furrow channel} \]
\[ m' = \text{a coefficient of the cross-sectional area of the furrow channel} \]
\[ W = \text{parameter of intake, which may be furrow spacing, furrow channel width, or wetted parameter.} \]

This technique requires estimations of the empirical coefficient, \( b \), in order to calculate the correction factor, \( F \), and of the coefficients \( u \) and \( m' \), which can be made given the furrow channel geometry.
Patterson (55) assumed a given time interval and calculated the volume of applied water during that time interval. Then the distance advanced during the time interval considered can be calculated by equating the volume of applied water to the sum of the volumes of applied and infiltrated water.

The Intake method, explained in Appendix B, is based upon the concept used by Patterson (55). In this method, the volume of surface-stored water is determined by assuming the shape of the wetting front and furrow-channel shape. The volume of infiltrated water is calculated by dividing the advanced distance into small segments and determining the accumulated volume of infiltrated water on each segment then integrating the final results.

Uniformity and distribution of the infiltrated water

The distribution of infiltrated water along the furrow can be approximated by knowing furrow intake function, advance function, and time of application. Two main procedures exist to obtain water distribution profile along the furrow, the linear and curvalinear methods.

The linear method assumes that the depth of infiltrated water varies linearly with the length of run down the furrow. Therefore, only two depths are needed along the furrow in order to determine the wetting profile down the furrow. The wetting profile can then be determined as follows:
\[ d_{z} = \frac{K}{K_{14} S_{8} (n+1)} (t_{z})^{n+1} \] \[ [74] \]

and

\[ d_{u} = \frac{K}{K_{14} S_{8} (n+1)} (t_{u})^{n+1} \] \[ [75] \]

where

\[ K_{14} \] is a constant which is equal to 0.6233 for the English units and 60 for the metric units.

and \( t_{u} \) and \( t_{z} \) are related by Equation 27.

Hence, at any distance, \( x \), down the furrow, the depth of infiltrated water is obtained from

\[ d_{x} = d_{u} - \frac{x}{L} (d_{z} - d_{1}) \] \[ [76] \]

The above approach assumes a constant intake rate during application and a linear advance function, i.e., advanced distance is equal to a constant times the advance time. In many cases, especially in heavy soils, the error introduced by making the above assumptions is very small.

The curvilinear method requires a very detailed prediction of the depth of infiltrated water at several locations along the furrow. From this the water distribution profile for a given time of application, \( t \), can be obtained by plotting the accumulated depth of infiltrated water vs. distance down the furrow. Hence, for a specified
\( t \), the accumulated depth of infiltration at distance \( x \) measured from the head of the furrow can be obtained from

\[
d_x t = \frac{K}{K_1 + \frac{S}{n+1}} (t - t_x) n+1
\]  \[77\]

To get a representative wetted profile, the length of the furrow should be divided into small sub-divisions. The time, \( t_x \), required for the water to travel \( x \) units from the head of the furrow to the center of a particular distance sub-division, is calculated. Then Equation 77 is used to determine the accumulated depth of infiltration on the sub-division considered. This process is repeated until the whole furrow length is covered.

**Amounts and distribution of runoff water**

Two ways are considered for estimating the volume of runoff water from irrigation, the direct inflow-outflow measurement and the runoff hydrograph analyses. The direct method assumes that the volume of runoff water is equal to the total volume of applied water less the accumulated volume of infiltrated water. This is expressed in mathematical terms by Equation 35, where the depth of runoff water is given as a percent of the total depth of applied water. One of the shortcomings of this method is that the results give no idea about the time-distribution of runoff water and peak runoff rate.

The runoff hydrograph analysis requires an evaluation of the rate and/or volumes of infiltrated and runoff water at several time
intervals during the total time of irrigation. Thus, it gives the expected volume and the time-distribution of runoff water. Some methods to predict the runoff hydrographs from furrow irrigation were developed for this study. The original derivations, internal comparisons, and computer programs are given in Appendices C and D. Details are excluded from the main text because they are lengthy and require detailed presentation.

Design of Irrigation Runoff Recovery Systems, IRRS's

The design of an Irrigation Runoff Recovery System forms a major part in the analysis and execution of a successful furrow irrigation system. In this model the design procedure first developed by Stringham and Hamad (81) is used because it is a practical approach for field use and is very well adapted to optimization processes.

The process of designing an IRRS is started by knowing the average depth of infiltrated water needed per irrigation, \( d_t \). This depth is used to determine the total time required to apply that average depth over the entire field, and is found by

\[
T = \frac{A d_t}{K_{15} Q_s}
\]  

[78]

where

- \( T \) = total time of application required to irrigate the entire field, hours
- \( Q_s \) = supply stream discharge, gpm (lps)
\( K_{15} \) is a constant which is equal to 0.00223 for the English units and 0.36 for the metric units.

The time of application per set, \( T_s \), can be obtained from the actual depth of infiltrated water at the lower end of the furrow, \( d_L \), and the depth of infiltrated water at the upper end of the furrow, \( d_u \), such that

\[
d_t = \frac{d_L + d_u}{2}
\]  

[79]

Thence, by using Kostakov intake function, the time of application will be

\[
T_s = \frac{1}{60} \left[ \frac{K_{14}}{K} \frac{d_u S_s}{(n+1) 1/(n+1)} \right]
\]  

[80]

where

\( T_s \) = time of application per set per irrigation, hours.

Thus, the total number of irrigation sets needed would be

\[
N_s = \frac{T}{T_s}
\]  

[81]

where

\( N_s \) = number of irrigation sets.

The number of sets as calculated by Equation 81 is usually not a whole number and must be rounded-off to get a practical number of
sets. In this model two cases were investigated, when $N_s$ equals the next whole number larger and when $N_s$ equals the next whole number smaller than that obtained from Equation 81.

The depth of applied water per furrow is then calculated from

$$
\frac{q}{a} = K_{16} \frac{q}{S_a} \frac{T_a}{L}
$$

where

$$K_{16} = \text{a constant which is equal to 96.3 for the English units and 3600 for the metric units.}$$

The depth and percentage of runoff water can then be determined by using Equations 34 and 35. The volume of runoff water from each irrigation set will simply equal the volume of water applied on the set times the runoff percentage expressed as a decimal.

The remainder of the design procedure involves determining the number of furrows per set. For the first irrigation set the number of furrows will be determined by

$$
N_1 = \frac{K_{17}}{q_s} \frac{Q_s}{q}
$$

where

$$N_1 = \text{number of furrows in the first irrigation set}$$

$$K_{17} = \text{a constant which is equal to 448.8 for the English units and 1.0 for the metric units.}$$
The total number of furrows in the field that are irrigated with the supply stream can be calculated from Equations 81 and 83. The number of furrows to be irrigated with pumped runoff water will be the difference between the total number of furrows in the field and the number fed by the supply stream. The number of furrows irrigated with pumped runoff water per set will be the total number of furrows irrigated with pumped runoff water divided by the number of irrigation sets.

The pump discharge is equal to the furrow stream size times the number of furrows irrigated with pumped runoff water per set. The volume of runoff water in the storage pond at the end of irrigation of each set is equal to the total volume of runoff water accumulated in the pond minus the volume of runoff water that has been pumped back. The volume of runoff water in storage should be evaluated at the end of irrigation of each set and the capacity of the storage pond should be enough to store the largest expected volume.

The last irrigation set is irrigated only with runoff water left in the pond after irrigating the set before the last one.

Currently, some of the shortcomings of the above rationale for IRRS design are inflexibility of the design procedures with regards to variations in the expected runoff volumes and system layout.
CHAPTER V
COMPUTERIZED MODEL OF FURROW IRRIGATION

The mathematical model presented in Chapter IV was translated to a computerized model to simplify and speed the iterative procedure. The model is composed of two parts: (a) land grading, and (b) hydraulic system design and management with a man-machine interface to connect them (see Figure 1).

The first part designs and determines the final land slopes, excavation volumes, and costs of land grading for a particular field by one or more grading design methods. Some of the methods may give undesirable final slopes, high costs, or excessive depths and volumes of cuts and fills, hence, can be eliminated and not given any further consideration. Other methods may give approximately the same final design configurations, any of which can then be used representatively. When the final design is selected (not a computer decision), row and cross-row directions with furrow length and slope can be chosen.

The second part of the design and management optimization process begins with the land grading design, computes the water advance, predicts individual and seasonal water infiltration depths and the resultant crop production, and determines the net farm profit. Several iterations of the above processes are used to optimize the farm profits. Details of this process are explained in the remaining sections of this chapter.
In order to explain, verify, and illustrate the expected results of the developed model, flow charts, definitions, and a sample analysis are given herein.

**Land Grading Model**

The land grading model was developed using various combinations of methods for calculating design slopes and volumes of earth work. These methods are:

1. For calculating design slopes
   a. Least squares method given in Equations 40 through 43;
   b. Symmetrical residuals method given in Equations 44 through 49;
   c. Double centroid method given in Equations 50 through 55;
   d. Average slope method given in Equations 48 and 49.

2. For calculating volumes of earth work
   a. Four-point method given in Equations 56 and 57;
   b. End-grid area method given in Equations 58 through 67;
   c. Summation method given in Equations 68 and 69.

In this model ten combinations of the above methods are used. The first option is a combination of the least squares and four-point methods, a combination commonly used by the Soil Conservation Service of the United States Department of Agriculture (77) and referred to herein as the *SCS* method.
Five other options result from combining the symmetrical residuals and the end-grid area methods to obtain five different configurations of the final graded surface as shown in Figure 5. These options were originated by Shih and Kriz (66) and are therefore called Shih and Kriz, or Kriz's methods.

Another four alternatives developed by Paul, hereafter referred to as Paul's methods, are based upon combinations of the least squares, double centroid, and average slope methods to calculate design slopes, and the summation method to calculate the volumes of earth work. The four combinations include combining the least squares and the summation methods, together with an earth-distribution pattern which minimizes haul distances, and a simple combination of the least squares and the average slope methods of grading with the summation method of computing the volumes of earth work. These are called the computer-minimized-cost, least squares, double centroid, and average slope methods, respectively.

The costs of land grading operations for the SCS and Shih and Kriz methods were calculated on the basis of average cost per unit volume of earth moved. The costs of land grading operations for Paul's methods were calculated on the basis of loading and distributing the earth. These methods of calculating the cost of land grading operations do not allow direct comparison of the various methods but give a relative comparison instead.

Figure 6 shows a flow chart to illustrate the options of land grading used in this model and the way of selecting a given
Figure 6. Simplified flow chart of the land grading model.
alternative. More comprehensive flow chart and explanations are
given in the following section.

**Computerized Model of Land Grading**

The above options of land grading techniques were translated to
Fortran IV computer language in order to use modern electronic
computers and simplify the lengthy, time-consuming operations.
Copies of the original computer programs were obtained and then
modified to accommodate any specified grid spacing. The original
computer programs for the SCS method are long and complicated so a
simpler program was developed. A detailed explanation of the computer
model with full details of the various subroutines subprograms and
their function and interaction follows.

The selection of any land grading design alternative depends on
the desired configurations of the graded surface and preference of
the designer. For example, when plane graded surfaces with uniform
slopes in both directions are needed then either the SCS, Paul's, or
Kriz's type I options can be used.

Figure 7 shows a more detailed version of the flow chart given
in Figure 6. It can be noted from the sequence of operations shown
in Figure 7 that the general procedure used with each land grading
method first includes determining the design slopes and elevations,
depths of cuts and fills, and volumes of earth work. Then the cut-fill
ratio, \( C/F \), is calculated and compared with the expected or desired
\( C/F \) plus or minus some allowable deviation. If the calculated \( C/F \)
is within the limits a final design information is executed,
Figure 7. Detailed flow chart of computerized model of land grading
otherwise the design elevations are adjusted to modify the volumes of cuts and fills until a proper C/F is found and the design information is executed.

Table 1 gives a list of the various subroutines used and their functions. For example, the subroutine named SCS is used to perform land grading design using the SCS method. Table 2 gives a list of the various control indices used to select a particular land grading method. The values of these indices are to be specified as input data to the program. For instance, to select design type IV of Kriz's methods the control index LAND should be set equal to 2 in order to enter subroutine KRTZ first, then the control index KKK is set equal to 4 to select design type IV.

A copy of the Fortran IV land grading computer program, a list of terminology, and comment statements are found in Appendix E.

Computerized Model of Hydraulic System Design and Management Optimization

The second part of the system design and management optimization process begins with the furrow length and slope, field width, and land grading costs selected from first part of the model. The computer model consists of the main program, several subroutine subprograms, each of which performs a portion of the design and optimization process, and a set of control indices which select the desired route through the model. The detailed flow chart of the model is shown in Figure 8. The definitions and functions of each subroutine and the control indices are given in Tables 3 and 4, respectively.
Table 1. List and functions of the subroutine subprograms used in the land grading model.

<table>
<thead>
<tr>
<th>Number</th>
<th>Subroutine</th>
<th>Subprogram</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>AVERAG</td>
<td>Calculating row and cross-row design slopes using the average slope technique</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>BAL</td>
<td>Balancing and checking the maximum allowable limits of the depths of cuts and fills</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>BALC</td>
<td>Balancing and checking the maximum allowable limits of the depths of cuts and fills</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>BRKN</td>
<td>Calculating and adjusting design elevations for Shih and Kriz's design type III</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>BRNA</td>
<td>Calculating and adjusting design elevations for Shih and Kriz's design type IV</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>CNF</td>
<td>Calculating depths and volumes of cuts and fills using the summation method</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>DOUBLE</td>
<td>Calculating row and cross-row design slopes using the double centroid technique</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>FLXFLY</td>
<td>Determining earth-movement pattern to minimize haul distance</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>HMGB</td>
<td>Checking row and cross-row slopes, calculating design elevations, and calculating depths of cuts and fills</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>KRIZ</td>
<td>Performing land grading designs using Shih and Kriz's methods</td>
</tr>
<tr>
<td>Number</td>
<td>Subroutine</td>
<td>Subprogram</td>
<td>Function</td>
</tr>
<tr>
<td>--------</td>
<td>------------</td>
<td>------------</td>
<td>----------</td>
</tr>
<tr>
<td>11</td>
<td>LEAST</td>
<td></td>
<td>Calculating row and cross-row design slopes using the least squares technique, and calculating centroid elevation and location</td>
</tr>
<tr>
<td>12</td>
<td>PAUL</td>
<td></td>
<td>Performing land grading designs using Paul's methods</td>
</tr>
<tr>
<td>13</td>
<td>SCS</td>
<td></td>
<td>Performing land grading designs using the SCS method</td>
</tr>
<tr>
<td>14</td>
<td>SLOPE</td>
<td></td>
<td>Calculating row and cross-row design slopes using the least squares technique, and calculating centroid elevation and location</td>
</tr>
<tr>
<td>15</td>
<td>SPTCMS</td>
<td></td>
<td>Determining the cost of moving the earth using the Load-Distance factor theory</td>
</tr>
<tr>
<td>16</td>
<td>SRAB</td>
<td></td>
<td>Calculating row and cross-row design slopes using the symmetrical residuals method, and calculating centroid elevation and location</td>
</tr>
<tr>
<td>17</td>
<td>VLNC</td>
<td></td>
<td>Calculating the volumes of earth work using the end-grid area method</td>
</tr>
<tr>
<td>18</td>
<td>VOL</td>
<td></td>
<td>Calculating the volumes of earth work using the four-point method</td>
</tr>
<tr>
<td>19</td>
<td>WARPB</td>
<td></td>
<td>Calculating, adjusting and checking the design slopes in the row and cross-row directions for non-uniformly graded surfaces</td>
</tr>
<tr>
<td>20</td>
<td>WARPB</td>
<td></td>
<td>Calculating, adjusting, and checking the design slopes in the row and cross-row directions for non-uniformly graded surfaces</td>
</tr>
</tbody>
</table>
Table 2. List, definitions, and functions of the control indices used in the land grading model.

<table>
<thead>
<tr>
<th>Number</th>
<th>Index</th>
<th>Definition and function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>KKK</td>
<td>An index to select a design type using Shih and Kriz's methods. When it is</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 1 perform design type I</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 2 perform design types I and II</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 3 perform design types I, II, and III</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 4 perform design types I, II, III, and IV</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 5 perform design types I, II, III, IV, and V</td>
</tr>
<tr>
<td>2</td>
<td>KKP</td>
<td>An index to select a design type using Paul's methods. When it is</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 1 use least cost method</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 2 use least squares method</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 3 use double centroid method</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 4 use average slope method</td>
</tr>
<tr>
<td>3</td>
<td>LAND</td>
<td>An index to select the desired method of land grading. When it is</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 1 use SCS method</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 2 use Shih and Kriz's methods</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 3 use Paul's methods</td>
</tr>
</tbody>
</table>
Figure 8. Detailed flow chart of the computerized model of furrow irrigation system design and management optimization.
Table 3. List and functions of the subroutines subprograms used in the furrow irrigation system design and optimization model.

<table>
<thead>
<tr>
<th>Number</th>
<th>Subroutine</th>
<th>Subprogram</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>ADJU$\text{SQ}$</td>
<td>Adjusting furrow stream size to obtain a practical number of irrigation sets for furrow irrigation systems without IRRS's</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>ADPACK</td>
<td>Predicting the advance of the water front down the furrow channel</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>ADVANC</td>
<td>Estimating the time of advance using the empirical method of prediction</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>COEFF</td>
<td>Calculating the advance coefficients (see Appendix B)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>COMP</td>
<td>Calculating the depth and percentage of runoff water using the traditional inflow-outflow method</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>COSTIR</td>
<td>Calculating fixed and operating costs of IRRS for two consecutive set numbers</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>COWIRR</td>
<td>Estimating the cost of irrigation for furrow irrigation systems without IRRS's</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>CRPPRD</td>
<td>Integrating the depth of infiltration and Crop Production Function, CPF, to estimate gross yield and net farm profit</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>DAVIS</td>
<td>Predicting the advance of the water front down the furrow channel using Davis's method</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>DEETH</td>
<td>Predicting the runoff hydrograph using the integrated infiltration depth method (see Appendix C)</td>
<td></td>
</tr>
</tbody>
</table>
Table 3. Continued

<table>
<thead>
<tr>
<th>Number</th>
<th>Subroutine</th>
<th>Subprogram</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>ELLEP</td>
<td></td>
<td>Predicting the advance of the water front down the furrow channel using front shape method (see Appendix B)</td>
</tr>
<tr>
<td>12</td>
<td>FLOW</td>
<td></td>
<td>Predicting non-erosive furrow stream size for a given furrow slope and soil type</td>
</tr>
<tr>
<td>13</td>
<td>FOK</td>
<td></td>
<td>Predicting the advance of the water front down the furrow channel using Fok and Bishop's method</td>
</tr>
<tr>
<td>14</td>
<td>FRONT</td>
<td></td>
<td>Predicting the runoff hydrograph using the front shape method (see Appendix C)</td>
</tr>
<tr>
<td>15</td>
<td>GRAPH</td>
<td></td>
<td>Plotting the predicted advance function, wetting front, or runoff hydrograph</td>
</tr>
<tr>
<td>16</td>
<td>INTAKE</td>
<td></td>
<td>Predicting the advance of the water front down the furrow channel using the integrated intake method (see Appendix B)</td>
</tr>
<tr>
<td>17</td>
<td>IRRS</td>
<td></td>
<td>Executing a complete design for Irrigation Runoff Recovery Systems, IRRS's, using two consecutive set numbers</td>
</tr>
<tr>
<td>18</td>
<td>MANN</td>
<td></td>
<td>Calculating the normal depth of flow at the head of the furrow using Manning's Equation</td>
</tr>
<tr>
<td>19</td>
<td>PATTER</td>
<td></td>
<td>Predicting the advance of the water front down the furrow channel using Patterson's method</td>
</tr>
<tr>
<td>20</td>
<td>RECESS</td>
<td></td>
<td>Predicting the time of recession (see Appendix C)</td>
</tr>
<tr>
<td>21</td>
<td>RUNOFF</td>
<td></td>
<td>Predicting the runoff hydrograph using the integrated intake method (see Appendix C)</td>
</tr>
</tbody>
</table>
Table 3. Continued.

<table>
<thead>
<tr>
<th>Number</th>
<th>Subroutine Subprogram</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>RUNPAC</td>
<td>Estimating the expected volumes and percentages of runoff water using the runoff hydrograph methods</td>
</tr>
<tr>
<td>23</td>
<td>SEASON</td>
<td>Calculating the minimum depth of irrigation, number of irrigations per season, and time of application per set per irrigation</td>
</tr>
<tr>
<td>24</td>
<td>SHAPE</td>
<td>Predicting a curvilinear pattern of infiltration along the furrow and calculating the average depths of infiltrated and deep percolated waters</td>
</tr>
<tr>
<td>25</td>
<td>SURF</td>
<td>Using a linear pattern of infiltration along the furrow to calculate the average depths of infiltrated and deep percolated waters</td>
</tr>
</tbody>
</table>
Table 4. List, definitions, and functions of the control indices used in the furrow irrigation system design and optimization model.

<table>
<thead>
<tr>
<th>Number</th>
<th>Index</th>
<th>Definition and function</th>
</tr>
</thead>
</table>
| 1      | INDEX | An index to select the proper shape of the furrow channel. When it is  
|        |       | = 1 use trapezoidal, triangular, or rectangular furrow channel  
|        |       | = 2 use parabolic furrow channel |
| 2      | INI   | An index to specify the method of calculating the number of irrigations per season, $N_i$. When it is  
|        |       | = 1 calculate $N_i$ on the basis of average depth applied per irrigation  
|        |       | = 2 Calculate $N_i$ on the basis of average frequency of application |
| 3      | ILOT  | An index to plot the wetting pattern or the runoff hydrograph. When it is  
|        |       | = 1 don't plot the desired graph  
|        |       | = 2 plot the desired graph |
| 4      | LAD   | An index to select the method of predicting the advance of the water front down the furrow channel. When it is  
|        |       | = 1 use front shape advance method (see Appendix B)  
|        |       | = 2 use intake advance method (see Appendix B)  
|        |       | = 3 use Fok and Bishop's method  
|        |       | = 4 use Davis' method  
|        |       | = 5 use Patterson's method |
| 5      | LAP   | An index to select the front shape for predicting the runoff hydrograph by the front shape method (see Appendix C). When it is  
|        |       | = 1 use elliptical wetting front  
|        |       | = 2 use parabolic wetting front  
|        |       | = 3 use linear wetting front |
| 6      | LAP   | An index to select a route of design. When it is  
|        |       | = 1 use the analytical methods to predict the advance of the water front down the furrow channel  
|        |       | = 2 use the empirical advance method |
Table 4. Continued.

<table>
<thead>
<tr>
<th>Number</th>
<th>Index</th>
<th>Definition and function</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>LAR</td>
<td>An index to select the method of predicting the runoff hydrograph (see Appendix C). When it is</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 1 use front shape method</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 2 use the integrated infiltration depth method</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 3 use the integrated intake method</td>
</tr>
<tr>
<td>8</td>
<td>LAS</td>
<td>An index to specify the method of calculating the time of advance. When it is</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 1 use the predicted advance function</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 2 use the empirical advance method</td>
</tr>
<tr>
<td>9</td>
<td>LAV</td>
<td>An index used in the design of IRRS. When it is</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 1 include the value of the land used and the cost of excavation for the storage pond and the collection ditches</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 2 don't include the value of the land used nor the cost of excavation for the storage pond and the collection ditches</td>
</tr>
<tr>
<td>10</td>
<td>LELLEP</td>
<td>An index to select the proper front shape when using the front shape advance prediction method (see Appendix B). When it is</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 1 use elliptical water and wetting fronts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 2 use elliptical water front and parabolic wetting front</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 3 use elliptical water front and linear wetting front</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 4 use parabolic water front and elliptical wetting front</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 5 use parabolic water and wetting fronts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 6 use parabolic water front and linear wetting front</td>
</tr>
<tr>
<td>11</td>
<td>LINTAK</td>
<td>An index to select the proper water front shape when using the integrated intake advance prediction method (see Appendix B). When it is</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 1 use elliptical water front</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 2 use parabolic water front</td>
</tr>
<tr>
<td></td>
<td></td>
<td>= 3 use linear water front</td>
</tr>
</tbody>
</table>
Table 4. Continued.

<table>
<thead>
<tr>
<th>Number</th>
<th>Index</th>
<th>Definition and function</th>
</tr>
</thead>
</table>
| 12     | LIRRS | An index to select a design route. When it is  
|        |       | = 1 design and use an IRRS  
|        |       | = 2 don't use an IRRS |
| 13     | LRUNO | An index to select the method of calculating the amount of runoff water. When it is  
|        |       | = 1 use the traditional inflow-outflow method  
|        |       | = 2 use the runoff hydrograph method |
| 14     | LSOIL | An index to specify soil type when predicting non-erosive furrow stream size. When it is  
|        |       | = 1 use soil type I  
|        |       | = 2 use soil type II  
|        |       | = 3 use soil type III  
|        |       | = 4 use soil type IV  
|        |       | = 5 use soil type V  
|        |       | = 6 use soil type VI |
The first step of the design procedure as shown in Figure 8 is to read the pertinent input data. These include the end results of the land grading design; physical and/or hydraulic properties of soil, pipes, pumps, furrows, and crop grown; costs of labor, water, energy, pipes, pumps, earth work, crop production, and construction machines; and values of crop yield, land area which might be taken out of production, and water losses, if any are applicable. The control indices which direct the route through the computer program are also input.

Next, the maximum non-erosive furrow stream size for the given soil type and furrow slope must be determined. If an Irrigation Runoff Recovery System is not going to be used \((LIRRS = 2)\), the furrow stream size must be adjusted to give an integer number of irrigation sets. If an IRRS is used \((LIRRS = 1)\), the design will automatically adjust the number of irrigation sets to an integer number. With the furrow stream size known, the rate of advance of the water down the furrow channel can be predicted by analytical or empirical means. If analytical methods are used \((LAP = 1)\), the advance will be computed by one of five methods as dictated by \(LAD\). The output of the prediction is plotted and given to subroutine \(SEASON\) as an array of time vs. distance. If the advance is predicted by an empirical equation \((LAP = 2)\), the actual equation is used by \(SEASON\).

The main function of \(SEASON\) is to calculate an initial starting depth of application per irrigation, average seasonal depth of
applied water, and number of irrigations in the season. If desired
(as indicated by LAS) it will also take the array from the
analytical advance prediction and determine a corresponding equation.
The control index NI determines the number of irrigations in the
entire season on the basis of average depth stored in the root zone
(INI = 1) or the average frequency of application (INI = 2).

The management part of the optimization process requires a
knowledge of the depth of application at the lower end of the furrow,
the intake opportunity time at that end, time of advance, and the
depth and time of application at the upper end of the furrow. With
these known, the depths of water infiltrated at several points along
the furrow, the percentage of land receiving a given depth, the
average depth of infiltrated water, and the depth of deep percolated
water are calculated by assuming a linear wetting pattern (subroutine
SURF) or a curvilinear one (subroutine SHAPE) as dictated by LAP.

The runoff water is next considered. If an IRRS is not used
(LIRRS = 2), the cost of the irrigation system will be computed
directly by subroutine COWIRR. If an IRRS is used (LIRRS = 1), the
runoff quantity must be determined either by inflow-outflow measure-
ments (LRUNO = 1 , implying that the design is made for an existing
system) or from one of several analytical methods (LRUNO = 2, by
using the runoff hydrograph method). With the amount of runoff water
known, the IRRS can be designed and the cost of the system calculated
(subroutine COSTIR). In calculating the cost of IRRS the cost of
constructing the storage pond and the collection ditches can be
included (LAV = 1), or it can be ignored (LAV = 2).
Subroutine CRPPRD can now be used to: obtain a seasonal depth of infiltrated water along the furrow; combine the predicted infiltration pattern along the furrow with the pre-specified Crop Production Function, CPF; and predict the expected crop yield and gross return.

The estimated system cost, land grading cost, and gross return are then used to calculate the Net Annual Farm Profit, NAFP. Repeated iterations of the above procedure starting from the second decision junction LAP (see Figure 8) for different depths of application per irrigation will locate the Maximum Net Farm Profit, MNFP.

The above iterative procedure can be shortened by using a nested interval approach. In this approach the entire range of seasonal depth of application is divided into large sub-intervals, and the sub-interval containing the MNFP is located. This sub-interval is in turn divided into sub-subintervals and the optimum sub-subinterval is found. This procedure is followed for as many levels of divisions as the desired limits of the problem justify.

The computer program is given in Appendix F accompanied with a list of terminology and comment statements.

Application

To illustrate the presented rationale and the operational sequence of the model, a design and management scheme for the irrigation of a sample corn field is presented. The specific input data for the presented land grading design are given in Table 5 and the input data for the hydraulic design and management optimization
Table 5. Data and design limitations used for land grading of the sample field.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Expected cut-fill ratio = 1.250</td>
</tr>
<tr>
<td>2</td>
<td>Exported volumes of cut = 0 cu yd</td>
</tr>
<tr>
<td>3</td>
<td>Imported volumes of fill = 10 cu yd</td>
</tr>
<tr>
<td>4</td>
<td>Deviation from the expected cut-fill ratio = 0.050</td>
</tr>
<tr>
<td>5</td>
<td>Cost of excavation = $0.40/cu yd</td>
</tr>
<tr>
<td>6</td>
<td>Number of stations in the row direction = 20</td>
</tr>
<tr>
<td>7</td>
<td>Number of stations in the cross-row direction = 9</td>
</tr>
<tr>
<td>8</td>
<td>Maximum proposed depth of cut = 1.0 foot</td>
</tr>
<tr>
<td>9</td>
<td>Maximum proposed depth of fill = 1.0 foot</td>
</tr>
<tr>
<td>10</td>
<td>Tolerance in the calculated depth of cut or fill = 0.10 foot</td>
</tr>
<tr>
<td>11</td>
<td>Maximum slope in the row direction = 2.50 percent</td>
</tr>
<tr>
<td>12</td>
<td>Minimum slope in the row direction = 0.10 percent</td>
</tr>
<tr>
<td>13</td>
<td>Maximum slope in the cross-row direction = 1.50 percent</td>
</tr>
<tr>
<td>14</td>
<td>Minimum slope in the cross-row direction = 0.05 percent</td>
</tr>
</tbody>
</table>
of furrow irrigation system are given in Table 6. Current cost data pertinent to the design are given in Tables 7 and 8. Table 9 lists the decision indices for the model and the consequences of each.

The corn Crop Production Function, CPF, used in this sample design is shown in Appendix D (Figure 40). The dimensions of the field used are 900 feet by 2000 feet and the original ground surface elevations at a 100- by a 100-foot grid are given in Appendix D (Figure 41).

Land grading design

The data for the land grading phase as given in Table 5 and in Figure 41 must be read in according to the sequence shown in the computer program in Appendix E. The ground surface elevation at the stakes should be read in by cross-rows. The pattern of final design outputs from all the land grading methods used are similar and in this section only the results of the SCS method are given.

The discussion below is provided to illustrate the decisions that should be made at the man-machine interface between the land grading and the hydraulic system design models. It can be noted that the depths of cuts exceed the maximum proposed depth at 13 stations while the depths of fills exceed the maximum proposed depth at 5 stations, or a total of 18 stations beyond the desired limits. This design alternative was considered to be an acceptable design because 18 stations represent 10 percent of the total field area and exceeding the maximum proposed depth of cuts and fills on these stations will probably not affect overall system design and performance appreciably.
Table 6. Input data used for the sample field analysis and verification of the model.

<table>
<thead>
<tr>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Supply stream discharge, $Q_s = 3.0$ cfs</td>
</tr>
<tr>
<td>2</td>
<td>Furrow spacing, $S_s = 3$ feet</td>
</tr>
<tr>
<td>3</td>
<td>Bottom width of the furrow channel = 0.3333 ft</td>
</tr>
<tr>
<td>4</td>
<td>Side slopes of the furrow channel = 1:1</td>
</tr>
<tr>
<td>5</td>
<td>Soil type is A (see Appendix D)</td>
</tr>
<tr>
<td>6</td>
<td>Soil class is II (see Appendix A)</td>
</tr>
<tr>
<td>7</td>
<td>$c$-factor used for Davis's advance prediction method = 0.50</td>
</tr>
<tr>
<td>8</td>
<td>$f$-factor used for Davis's advance prediction method = 1.00</td>
</tr>
<tr>
<td>9</td>
<td>Puddling factor, $h$, used for Davis's advance prediction method = 0.003 cu ft/ft</td>
</tr>
<tr>
<td>10</td>
<td>$\bar{c}$-factor used for Davis's advance prediction method = 1.00</td>
</tr>
<tr>
<td>11</td>
<td>Allowable depletion = 50%</td>
</tr>
<tr>
<td>12</td>
<td>Soil moisture holding capacity = 2.00 inches/foot</td>
</tr>
<tr>
<td>13</td>
<td>Depth of the root zone = 4.00 feet</td>
</tr>
<tr>
<td>14</td>
<td>Design daily consumptive use rate = 0.25 in/day</td>
</tr>
<tr>
<td>15</td>
<td>Number of days in the irrigation season = 100 days</td>
</tr>
<tr>
<td>16</td>
<td>Recommended frequency of irrigation = 16 days</td>
</tr>
<tr>
<td>17</td>
<td>Range of expected seasonal depth of irrigation = 0.40 to 1.20 times the expected average depth</td>
</tr>
<tr>
<td>18</td>
<td>Water cost = $3.0/acre-foot</td>
</tr>
<tr>
<td>19</td>
<td>Value of crop production = $3.00/bushel</td>
</tr>
<tr>
<td>20</td>
<td>Life of the system = 10 years</td>
</tr>
<tr>
<td>21</td>
<td>Current Compound Interest Rate = 10%</td>
</tr>
</tbody>
</table>
Table 7. Fixed and variable costs used in the construction and maintenance of furrow irrigation systems.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation work for IRRS design</td>
<td>$0.40/cu yd</td>
</tr>
<tr>
<td>Earth work for land grading</td>
<td>$0.40/cu yd</td>
</tr>
<tr>
<td>Ditcher</td>
<td>$3.00/100 feet</td>
</tr>
<tr>
<td>Pumping unit</td>
<td>$120/BHP</td>
</tr>
<tr>
<td>Pumping-unit platform</td>
<td>$300</td>
</tr>
<tr>
<td>Corn crop production costs</td>
<td>$60/acre</td>
</tr>
<tr>
<td>Sugar-cane crop production costs</td>
<td>$277/acre</td>
</tr>
<tr>
<td>Labor cost</td>
<td>$1.5/hour</td>
</tr>
</tbody>
</table>

* Annual maintenance cost is assumed to be 2 percent of the total initial system cost.

Table 8. Fixed costs of PVC class 100 pipes used in the design of IRRS.

<table>
<thead>
<tr>
<th>Nominal pipe size -inches-</th>
<th>Inside pipe diameter -inches-</th>
<th>Fixed cost -$/100 feet-</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>3.284</td>
<td>37.84</td>
</tr>
<tr>
<td>4</td>
<td>4.224</td>
<td>62.22</td>
</tr>
<tr>
<td>5</td>
<td>5.221</td>
<td>95.88</td>
</tr>
<tr>
<td>6</td>
<td>6.217</td>
<td>135.15</td>
</tr>
<tr>
<td>8</td>
<td>8.095</td>
<td>229.50</td>
</tr>
<tr>
<td>10</td>
<td>10.088</td>
<td>357.50</td>
</tr>
<tr>
<td>12</td>
<td>11.966</td>
<td>469.71</td>
</tr>
</tbody>
</table>
Table 9. Control indices for the hydraulic system design and management optimization model used in the sample problem.

<table>
<thead>
<tr>
<th>Control Index</th>
<th>Value</th>
<th>Consequence</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSOIL</td>
<td>2</td>
<td>Use type II soil (heavy)</td>
</tr>
<tr>
<td>LIRRS</td>
<td>1</td>
<td>Use an IRRS</td>
</tr>
<tr>
<td>INDEX</td>
<td>1</td>
<td>Use trapezoidal furrow channel</td>
</tr>
<tr>
<td>LAP</td>
<td>1</td>
<td>Predict water advance function</td>
</tr>
<tr>
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<td>Use Davis's advance prediction method</td>
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<td>Express advance function in an exponential form</td>
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<td>Use depth of stored water to predict number of irrigations in the season</td>
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<td>Use inflow-outflow method to predict the amount of runoff water</td>
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<td>Include cost of construction for the storage pond and the collection ditches for IRRS</td>
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Chart 1. Sample land grading design using the SCS method.

******************************************************************************
* DATA FROM FIELD YOLO # 1 DESIGNED FOR LAND GRADING USING SCS METHOD *
* PROGRAMMED BY SAFA NOORI HAMAL  OCTOBER 26, 1976                        *
******************************************************************************

DESIGN REQUIREMENTS

EXPECTED CUT/FILL RATIO BY VOLUME=1.250
EXTRA VOLUME OF CUT  = 0.0 CY  EXTRA VOLUME OF FILL  = 10.0 CY
DEVIATION OF EXPECTED CUT/FILL RATIO=0.050,  COST=$0.400 PER CUBIC YARD
NUMBER OF STATIONS IN ROW=20,  PROPOSED MAXIMUM DEPTH OF CUT= 1.00 FT
NUMBER OF STATIONS IN CROSS ROW= 9,  PROPOSED MAXIMUM DEPTH OF FILL= -1.00 FT

DISTANCES TO FIELD BOUNDARIES FROM:
FIRST ROW ------  R1(Y)= 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00
FIRST ROW ------  R1(Y)= 50.00 50.00 50.00 50.00
LAST ROW ------  R2(Y)= 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00
LAST ROW ------  R2(Y)= 50.00 50.00 50.00 50.00
FIRST CROSS ROW -- R3(X)= 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00
LAST CROSS ROW -- R4(X)= 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00

ORIGINAL FIELD ELEVATION

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TOTAL AREA= 41.322 ACRES

CENTROID ELEVATION = 7.51 XBAR = 5.00 STATIONS AND YBAR = 10.50 STATIONS

SLOPE IN THE X-DIRECTION = -0.32758 FT/100 FT AND SLOPE IN THE Y-DIRECTION = -0.01481 FT/100 FT
### DEPTHS OF CUTS AND FILLS

**NOTE:** CUTS ARE SHOWN AS POSITIVE AND FILLS AS NEGATIVE

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### FINISH DESIGN ELEVATIONS

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**TOTAL VOLUME OF CUT = 16722.967 CY**  
**FINAL CUT/FILL RATIO CY VOLUME = 1.253**

**NUMBER OF STATIONS WITH CUT = 86**  
**NUMBER OF STATIONS WITH FILL OVER THE PROPOSED MAXIMUM DEPTH = 5**  
**AVERAGE VOLUME = 404.696 CY/ACRE**  
**AVERAGE COST = $161.88 PER ACRE**

**TOTAL COST = $6689.19**
Moreover, it was first assumed that the furrows would be run in the long or $Y$-direction, i.e., 2000-foot furrows. But since the calculated slope in the $Y$-direction was only $-0.0148$ percent, which is very flat and will lengthen the advance-time cycle, the furrows will be run in the $X$-direction, i.e., 900-foot furrows, with a bed slope of $-0.3276$ percent. The negative signs indicate that the slope decreases from left to right and from top to bottom (see final design printout). Finally, the cost of land grading operations was found to be about $162$ per acre.

Up to this point, the first part of the design is completed and the selected furrow length of 900 feet, furrow slope of $-0.3276$ percent, land grading cost of $162$ per acre, and field width of 2000 feet are used as input data to start the second part of the design.

**Hydraulic system design and management optimization**

The input data shown in Tables 6, 7, 8, and 9 together with the end results of land grading design were used with this phase of optimization.

Recalling that the first step in this part of the design process is to predict a maximum non-erosive furrow stream size, which for soil type $II$ and furrow slope of $0.3276$ percent would be $28.93$ gpm (see Appendix A). The optimal design was found to occur when the design stream size was reduced to 30 percent of the non-erosive stream size. Therefore, a modification factor of $-70$ percent was read in as input information and the new calculated $q$ was $8.68$ which will be used for further design purposes.
In this example, it was decided to predict the advance function by using Davis' prediction method, i.e., \( LAP = 1 \) and \( LAD = 4 \). The time increments used to predict the advance function were specified to be 10 minutes and the maximum number of time increments allowed was 100, i.e., a maximum allowable time of advance, \( t_a \), of 1000 minutes. Generally, furrow length is used as the criterion for terminating the prediction process; in other words, when the predicted advance distance exceeds the specified furrow length, which is 900 feet in this case, then the prediction process is terminated. The corresponding time of advance plus another extra time increment will be used. This extra time increment is added only to insure that the water reaches the end of the furrow. The results of the prediction process together with a plot of the advance function were reproduced from the computer printout and shown in Table 10 and Figure 9. Recalling that an extra time increment is used, hence the time of advance will be approximately \( 250 + 10 = 260 \) minutes.

The predicted advance function can be represented by an exponential equation as follows

\[
x = 39.91 t^{0.564}
\]

The depth of water that is stored in the root zone per irrigation, \( d_s \), is calculated from

\[
d_s = 4 \text{ feet} \times 2.0 \text{ inches/foot} \times 50\% = 4.00 \text{ inches}
\]
Table 10. Predicted values of the time of advance and corresponding advanced distances using Davis' advance prediction method.

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<td>26</td>
<td>672</td>
</tr>
<tr>
<td>160</td>
<td>25</td>
<td>698</td>
</tr>
<tr>
<td>170</td>
<td>25</td>
<td>723</td>
</tr>
<tr>
<td>180</td>
<td>24</td>
<td>747</td>
</tr>
<tr>
<td>190</td>
<td>23</td>
<td>770</td>
</tr>
<tr>
<td>200</td>
<td>23</td>
<td>793</td>
</tr>
<tr>
<td>210</td>
<td>22</td>
<td>815</td>
</tr>
<tr>
<td>220</td>
<td>22</td>
<td>837</td>
</tr>
<tr>
<td>230</td>
<td>21</td>
<td>858</td>
</tr>
<tr>
<td>240</td>
<td>21</td>
<td>879</td>
</tr>
<tr>
<td>250</td>
<td>20</td>
<td>899</td>
</tr>
</tbody>
</table>
Figure 9. Predicted water advance function using Davis' advance prediction method.

and the seasonal depth of application required, $D_a$, can be approximated by assuming an average crop consumptive use rate as follows

$$D_a = 100\ \text{days/season} \times 0.25\ \text{inch/day} = 25\ \text{inches}$$
Therefore, the number of irrigations in the season is

\[ N_i = \frac{25}{4} = 6.25 \text{ or } 7 \text{ irrigations} \]

which gives an average seasonal depth of application of 28 inches.

The next step is to determine the seasonal depth of water which maximizes profit which may not be equal to 28 inches. In this case, for the first level of optimization the range of seasonal depth of application was limited from 0.40 to 1.20 times the average depth, or 11.2 to 33.6 inches. Also it was further specified this range be divided into four equal segments, thus a seasonal-depth increment, \( \Delta D \), of \( \frac{33.6 - 11.2}{4} = 5.6 \text{ inches} \) would be used. The optimization process was then started to obtain the profit at seasonal depths of application of 11.2, 16.8, 22.4, 28.0, and 33.6 inches.

For an average seasonal application depth of 11.2 inches \((0.40 \times 28)\) and 7 irrigations per season, the average depth of infiltrated water per irrigation should be \( \frac{11.2}{7} = 1.60 \text{ inches} \) \((\text{or } 0.40 \text{ } d^*_i)\), and the depth of infiltration at the lower end of the furrow would then be approximately

\[ d^*_l = 0.40 \text{ inches } \times (0.40 - 0.05) = 1.40 \text{ inches} \]

The reduction factor of 0.05 was arbitrarily chosen since \( d^*_l \) is normally less than \( d^*_t \), and a \( d^*_l \) of 1.40 inches might give a \( d^*_t \) of approximately 1.60 inches. The time of application at the lower end of the furrow is then calculated from Equation 74 as follows

\[ t^*_l = \left( \frac{0.6233 \times 1.40 \times 3.0 \times 0.49}{0.09} \right)^{1/0.49} = 226 \text{ minutes} \]
and from Equation 27, the time of application at the upper end of
the furrow, or the time of application per set per irrigation, would
be
\[ t_u = 226 + 260 = 486 \text{ minutes or 8.1 hours} \]

This time of application per set per irrigation and the predicted
advance function are now used to determine the pattern of infiltration
along the furrow and the percentage of land receiving a given depth
of infiltration as indicated by Equations 28, 29, and 77 (see Table 11).

The total depth of applied water is calculated from Equation
82 as
\[ d_a = \frac{26.3 \times 8.68 \times 8.1}{3 \times 900} = 2.50 \text{ inches} \]

The applied depth calculated by the computer is about 2.46 inches.
This discrepancy exists because of the roundoff of furrow stream size
and time of application.

The weighted average depth of infiltrated water, \( d_t \), is 1.82
inches as calculated from Equation 31. However, a \( d_t \) of 1.82 inches
gives an average seasonal depth, \( D_a \), of \( 1.82 \times 7 = 12.74 \text{ inches} \), as
compared to 11.2 inches. Thus for actual field application, a \( D_a \) of
12.74 inches must be used. Since the depth of water that can be
stored in the root zone per irrigation is 4.0 inches and the maximum
depth of water infiltrated was only 2.03 inches, then there was no
deep percolated water and the depth of runoff water would be
\[ d_r = 2.46 - 1.82 = 0.64 \text{ inch} \]
Table 11. Infiltration pattern along the furrow using a time of application per irrigation of 8.1 hours (average infiltration depth per irrigation of 1.82 inches).

<table>
<thead>
<tr>
<th>Depth infiltrated -inches-</th>
<th>Percentage of land receiving the depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.03</td>
<td>15.9</td>
</tr>
<tr>
<td>2.00</td>
<td>5.2</td>
</tr>
<tr>
<td>1.98</td>
<td>7.0</td>
</tr>
<tr>
<td>1.96</td>
<td>5.1</td>
</tr>
<tr>
<td>1.94</td>
<td>5.0</td>
</tr>
<tr>
<td>1.92</td>
<td>4.4</td>
</tr>
<tr>
<td>1.90</td>
<td>4.1</td>
</tr>
<tr>
<td>1.88</td>
<td>3.9</td>
</tr>
<tr>
<td>1.85</td>
<td>3.7</td>
</tr>
<tr>
<td>1.83</td>
<td>3.5</td>
</tr>
<tr>
<td>1.81</td>
<td>3.3</td>
</tr>
<tr>
<td>1.78</td>
<td>3.2</td>
</tr>
<tr>
<td>1.76</td>
<td>3.1</td>
</tr>
<tr>
<td>1.74</td>
<td>3.0</td>
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<td>1.71</td>
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<tr>
<td>1.69</td>
<td>2.8</td>
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<tr>
<td>1.66</td>
<td>2.7</td>
</tr>
<tr>
<td>1.64</td>
<td>2.6</td>
</tr>
<tr>
<td>1.61</td>
<td>2.5</td>
</tr>
<tr>
<td>1.58</td>
<td>2.5</td>
</tr>
<tr>
<td>1.56</td>
<td>2.4</td>
</tr>
<tr>
<td>1.53</td>
<td>2.4</td>
</tr>
<tr>
<td>1.50</td>
<td>2.3</td>
</tr>
<tr>
<td>1.47</td>
<td>2.3</td>
</tr>
<tr>
<td>1.45</td>
<td>2.2</td>
</tr>
<tr>
<td>1.42</td>
<td>2.2</td>
</tr>
</tbody>
</table>
which gives a runoff percentage, $R_f$, of

$$R_f = \frac{0.64}{2.46} \times 100 = 25.9\%$$

The IRRS design is now needed and proceeds as follows:

**General information**

| Total number of furrows in the field | = 666 |
| Number of furrows per set irrigated with the supply stream | = 155 |
| Total time needed for irrigating the field | = 25 hours |
| Calculated number of irrigation sets | = 3.093 |

**1st alternative (3 irrigation sets)**

| Number of furrows per set irrigated with pumped runoff water | = 67 |
| Total number of furrows irrigated with the supply | = 465 |
| Total number of furrows irrigated with pumped runoff water | = 201 |
| Recirculating-pump flow rate | = 581 gpm |
| Volume of runoff water after set #1 | = 6.4 ac-in |
| Volume of runoff water after set #2 | = 5.0 ac-in |
| Volume of runoff water after set #3 | = 3.7 ac-in |
| Volume of water applied on the last set from the pond | = 7.6 ac-in |
| Surplus or deficit in the pond | = -3.9 ac-in |
| Volume of the sump | = 6.4 ac-in |
Depth of the sump = 6.0 feet
Width of the sump = 51 feet
Length of the sump = 102 feet
Pipe size selected = 6 inches
Total dynamic head = 65 feet
Break horsepower required = 12.9 BHP
Total annual cost of IRRS only with 3 sets = $1403
Total annual cost of IRRS only with 3 sets = $33.95/acre
Total annual cost of IRRS including water cost = $1530

2nd alternative (4 irrigation sets)

Number of furrows per set irrigated with pumped runoff water = 11
Total number of furrows irrigated with the supply stream = 620
Total number of furrows irrigated with pumped runoff water = 46
Recirculating-pump flow rate = 95.5 gpm
Volume of runoff water after set #1 = 6.4 ac-in
Volume of runoff water after set #2 = 11.5 ac-in
Volume of runoff water after set #3 = 16.6 ac-in
Volume of runoff water after set #4 = 21.8 ac-in
Volume of water applied on the last set from the pond = 1.2 ac-in
Surplus or deficit in the pond = 20.5 ac-in
Volume of the sump = 21.8 ac-in
Depth of the sump = 6.0 feet
Width of the sump = 88 feet
Length of the sump = 177 feet
Pipe size selected = 3 inches
Total dynamic head = 54.2 feet
Break horsepower required = 1.7 BHP
Total annual cost of IRRS only with 4 sets = $923
Total annual cost of IRRS only with 4 sets = $22.34/acre
Total annual cost of IRRS including water cost = $1093
Thus, total annual cost of IRRS used = $26.46/acre

Since the first alternative resulted in high total annual cost than the second alternative and the sump ran out of water before the last set was completed, it was not considered any further and the four-set alternative was chosen.

The depths of water infiltrated per irrigation at several locations along the furrow are multiplied by seven irrigation per season to obtain a seasonal pattern of infiltration. This seasonal pattern is then combined with the Crop Production Function, CPF, to get a total expected yield, which in this case was 3315 bushels or an average of 80 bushels per acre, or can be obtained from CPF using a \( D_a \) of 12.74 inches. This is because the CPF is approximately a linear function for the rising portion and there was no deep percolated water in this case. Thus the average depth of infiltration gave the same result as the detailed integration using the infiltration depths given in Table 11.
The total cost of the system is calculated as follows:

Annual irrigation cost = \$26.46/acre \times 41.32 \text{ acres} = \$1093

Annual crop production cost = \$60/acre \times 41.32 \text{ acres} = \$2479

Annual land grading cost = \$162/acre \times 41.32 \text{ acres} \times 0.177 = \$1185

Thus, subtotal annual system cost would be \$4757, and if maintenance cost is assumed to be 2 percent of the total initial cost, then total annual system cost would be

\$4757 \times 1.02 = \$4852

and

\textit{NAFP} = 3315 \text{ bushels} \times \$3/\text{bushel} - \$4852 = \$5092

or an average of \$123 per acre.

In trying to locate a higher NAFP, the next iteration would be conducted as follows

\textit{New } d_u = 2.03 \times \frac{16.8}{11.2} = 3.06 \text{ inches}

and this \(d_u\) is now used in a very similar manner to get a new NAFP.

This process was repeated five times in this case and a tentative maximum NAFP of \$12,875 was found to occur at a seasonal depth of about 27.8 inches. Therefore, since 27.8 inches falls between 22.4 and 28.0 inches, in the second level of optimization the new range of seasonal depth to be considered would be 22.4 to 28.0 inches. This range is further divided as was specified into four equal segments each of width 2.8 inches and the same procedure is repeated. In
In this case the same maximum NAFP of $12,875 was obtained at a corresponding seasonal infiltration depth of 27.8 inches, and it was considered to be the maximum or MNFP for this particular design. No attempt was made to use more levels of optimization. A summary of the design and management program at the MNFP is given below.

In this case $d_1 = 10.11$ inches; $d_t = 3.98$ inches; $d_p = 0.02$ inches; $d_r = 6.13$ inches; $R_f = 60.7\%$; and the design of IRRS is as shown below:

### General information

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of furrows in the field</td>
<td>666</td>
</tr>
<tr>
<td>Number of furrows per set irrigated with the supply stream</td>
<td>155</td>
</tr>
<tr>
<td>Total time needed for irrigating the field</td>
<td>54.8 hours</td>
</tr>
<tr>
<td>Calculated number of irrigation sets</td>
<td>1.64</td>
</tr>
</tbody>
</table>

#### 1st alternative (1 irrigation set)

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of furrows per set irrigated with pumped runoff water</td>
<td>511</td>
</tr>
<tr>
<td>Total number of furrows irrigated with the supply stream</td>
<td>155</td>
</tr>
<tr>
<td>Total number of furrows irrigated with pumped runoff water</td>
<td>511</td>
</tr>
<tr>
<td>Recirculating-pump flow rate</td>
<td>4435 gpm</td>
</tr>
<tr>
<td>Volume of runoff water after set #1</td>
<td>60.7 ac-in</td>
</tr>
<tr>
<td>Volume of water applied on the last set from the pond</td>
<td>125.9 ac-in</td>
</tr>
</tbody>
</table>
Table 12. Infiltration pattern along the furrow using a time of application per irrigation of 33.4 hours (average infiltration depth per irrigation of 3.98 inches).

<table>
<thead>
<tr>
<th>Depth infiltrated (inches)</th>
<th>Percentage of land receiving the depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.07</td>
<td>15.9</td>
</tr>
<tr>
<td>4.06</td>
<td>5.2</td>
</tr>
<tr>
<td>4.05</td>
<td>7.0</td>
</tr>
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<td>4.04</td>
<td>5.1</td>
</tr>
<tr>
<td>4.03</td>
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<td>4.02</td>
<td>4.4</td>
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<td>4.00</td>
<td>4.1</td>
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<tr>
<td>4.00</td>
<td>3.9</td>
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<td>3.99</td>
<td>3.7</td>
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<td>3.98</td>
<td>3.5</td>
</tr>
<tr>
<td>3.97</td>
<td>3.3</td>
</tr>
<tr>
<td>3.96</td>
<td>3.2</td>
</tr>
<tr>
<td>3.95</td>
<td>3.1</td>
</tr>
<tr>
<td>3.94</td>
<td>3.0</td>
</tr>
<tr>
<td>3.93</td>
<td>2.9</td>
</tr>
<tr>
<td>3.92</td>
<td>2.8</td>
</tr>
<tr>
<td>3.91</td>
<td>2.7</td>
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<tr>
<td>3.89</td>
<td>2.6</td>
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<td>3.88</td>
<td>2.5</td>
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<tr>
<td>3.87</td>
<td>2.5</td>
</tr>
<tr>
<td>3.86</td>
<td>2.4</td>
</tr>
<tr>
<td>3.85</td>
<td>2.4</td>
</tr>
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<td>3.84</td>
<td>2.3</td>
</tr>
<tr>
<td>3.83</td>
<td>2.3</td>
</tr>
<tr>
<td>3.82</td>
<td>2.2</td>
</tr>
<tr>
<td>3.81</td>
<td>2.2</td>
</tr>
</tbody>
</table>
Surplus or deficit in the pond $= -65.0$ ac-in
Volume of the sump $= 160.1$ ac-in
Depth of the sump $= 6.0$ feet
Width of the sump $= 227$ feet
Length of the sump $= 455$ feet
Pipe size selected $= 12$ inches
Total dynamic head $= 108.2$ feet
Break horsepower required $= 161.6$ BHP
Total annual cost of IRRS only with 1 set $= 6835$
Total annual cost of IRRS only with 1 set $= 165.41/acre$
Total annual cost of IRRS including water cost $= 7010$

2nd alternative (2 irrigation sets)

Number of furrows per set irrigated with pumped runoff water $= 178$
Total number of furrows irrigated with the supply stream $= 310$
Total number of furrows irrigated with pumped runoff water $= 356$
Recirculating-pump flow rate $= 1545$ gpm
Volume of runoff water after set #1 $= 60.7$ ac-in
Volume of runoff water after set #2 $= 76.3$ ac-in
Volume of water applied on the last set from the pond $= 43.9$ ac-in
Surplus or deficit in the pond $= 32.4$ ac-in
Volume of the sump $= 76.3$ ac-in
Depth of the sump = 6.0 feet
Width of the sump = 159 feet
Length of the sump = 319 feet
Pipe size selected = 12 inches
Total dynamic head = 24.8 feet
Break horsepower required = 12.9 BHP
Total annual cost of IRRS only with 2 sets = $2160
Total annual cost of IRRS only with 2 sets = $52.28/acre
Total annual cost of IRRS including water cost = $2511
Thus, total annual cost of IRRS used = $60.76/acre

Since the second alternative has the least cost, it was chosen as the desired management scheme.

The remainder of the process is exactly the same as discussed in the previous iteration, which in this case gives a MNFP of $12,875.
CHAPTER VI
SENSITIVITY ANALYSIS

The model can be used as a research tool or for furrow irrigation system design. As presented herein, however, it is primarily as a research tool to permit an analysis of the sensitivity of farm profits to variations in the major components of furrow irrigation system design and management by tracing the interaction of these components. For example, several approaches to land grading design are included to analyze the effect of those alternatives on the Net Annual Farm Profit, NAFF.

Several ways to predict the location of the water front down the furrow channel, the wetting front below the furrow channel, and the amounts of runoff water from a particular irrigation are included for the same reason. Upper or lower physical bounds must be placed on the range of variation of a given factor to limit the extent of unnecessary search, yet permit a wide enough range of variation to explore most of the expected values. For example, for a given set of conditions, depths of application per irrigation from 1 to 10 inches were analyzed to study the effects of over- or under-irrigation and the amount of runoff water on system design and Net Annual Farm Profit, NAFF. The results of a sensitivity analysis for the main design and management components are given in this chapter to show its power in the optimization of furrow irrigation system design, and thus achieve improved system performance. It ought to
be mentioned, however, that in the presentation of the results, the decimal points do not indicate the estimated accuracy to be expected from the model, but simply result from the calculational procedures and are used to preserve continuity of the discussion.

**Effect of Furrow Intake Function on Maximum Net Farm Profit and System Cost**

The furrow intake function seems to have tremendous effects on overall system design and performance, since it affects sensitive design areas including depth of infiltrated water, time of application per irrigation, amount of runoff water, deep-percolation losses, and *Distribution Uniformity, DU*. This necessitates a very careful evaluation of the intake function (or functions) and its variation for a given field.

The developed optimization model assumes that, for a given furrow stream size, average intake characteristics can be expressed by an exponential function relating intake rate and intake opportunity time. This assumption introduces some discrepancy in the proposed design, however, because the intake function continually changes throughout the irrigation season; it is not the same from furrow to furrow, especially for furrows which happen to be under a tractor-wheel nor constant with furrow stream size.

To emphasize the sensitivity of *MNFP* to variation in the intake function, Table 13 shows the results of two separate evaluations of furrow irrigation system on a 41-acre field. Furrows are 900 feet long spaced at 3 feet and an *IRRS* is used. The crop is corn assumed
Table 13. Effect of variation in intake function on *Maximum Net Farm Profit* and cost of furrow irrigation systems when an *IRRS* is used.

<table>
<thead>
<tr>
<th>Description</th>
<th>Furrow stream size, q -gpm-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28.93</td>
</tr>
<tr>
<td>Intake function, ( I = K t^n )</td>
<td></td>
</tr>
<tr>
<td>Held constant at ( I = 0.09 t^{-0.51} )</td>
<td></td>
</tr>
<tr>
<td><strong>MNFP -$/acre-</strong></td>
<td>503</td>
</tr>
<tr>
<td>Average seasonal infiltrated depth -inches- *</td>
<td>23.3</td>
</tr>
<tr>
<td>System cost -$/acre-</td>
<td>191</td>
</tr>
<tr>
<td>Intake function, ( I = K t^n )</td>
<td></td>
</tr>
<tr>
<td>( 0.274 t^{-0.550} ), ( 0.230 t^{-0.550} ), ( 0.183 t^{-0.550} ), ( 0.133 t^{-0.550} ), ( 0.106 t^{-0.550} )</td>
<td></td>
</tr>
<tr>
<td><strong>MNFP -$/acre-</strong></td>
<td>775</td>
</tr>
<tr>
<td>Average seasonal infiltrated depth -inches- *</td>
<td>44.5</td>
</tr>
<tr>
<td>System cost -$/acre-</td>
<td>67</td>
</tr>
</tbody>
</table>

* Crop is corn with an assumed gross return of $6.00/bushel. Crop production costs are assumed to be $60/acre.

* Only depths of stored water are considered in calculating crop yield.
to be worth $6.00/bushel and crop production costs are assumed to be $60/acre. Other pertinent data are given in Tables 6, 7, and 8 and in Appendix D. The first evaluation assumes that the intake function is independent of furrow stream size. The measured intake function, \( I \), corresponding to a stream size of 8.0 gpm is assumed to be valid for all stream sizes investigated. It can be seen from the results, as \( q \) is decreased by about 70 percent, \( MNFP \) increases by about 50 percent, while system cost varied only by about 30 percent. Recalling that system cost includes only the cost of irrigation, i.e., cost of labor, water, energy, and fixed cost of \( IRRS \). The reason is that the measured intake function corresponds to a \( q \) of 8.0 gpm and because of the change in \( I \) with change in \( q \), as \( q \) deviates away from this value, the discrepancy between actual \( I \) values and those used increases and causes distorted system cost values.

In the second evaluation, \( I \) is permitted to vary with \( q \). The method of determining the variation requires a brief explanation. Since it is impractical to measure intake functions for many values of \( q \), an empirical method is suggested. If two, or at the most three, field trials can be made and the relationships between \( I \) and \( q \) established by plotting \( I \) vs. \( t \) on log-log paper as shown in Figure 10, then a log-log plot of intercepts (\( K \) values) and the corresponding \( q \) values can be made and an appropriate \( K-q \) function established. It can be expressed as
Figure 10. Relationship between furrow stream size and intake function for furrow irrigation.

\[ K = \alpha_d q^\beta_d \]  \hspace{1cm} \text{[84]} \]

where

\( \alpha_d \) and \( \beta_d \) are empirical coefficients depending on \( I \) and \( q \).

This procedure has been used by the writer to analyze the data from numerous field trials and found to be valid. These analyses have shown that on the same soil the exponent of the intake function, \( n \), is almost independent of \( q \). Therefore, \( n \) can be kept constant, and \( K \) varied.
Returning then to the second evaluation mentioned above, where $I$ varies with $q$, it can be seen from the lower part of Table 13 that significant changes occur in the values of $MNFP$ and system costs. Thus, the model is very sensitive to the intake function and must be very carefully evaluated in order to obtain a successful design program.

Further study of Table 13 shows that the difference in system cost and $MNFP$ predicted by the two approaches became very small as $q$ approached 8.0 gpm. This is consistent because the actual field evaluations of $I$ were conducted at that stream size.

Table 14 illustrates a similar analysis to that shown in Table 13 except no $IRRS$ is used and runoff water is assumed to be disposable. Almost the same conclusions that are obtained when an $IRRS$ is utilized are also true when no $IRRS$ is used which emphasizes the need for precise measurements of the intake function, $I$, and its change with furrow stream size, $q$.

In Table 14, when $I$ is held constant regardless of $q$, the system cost continually decreased as $q$ decreased. However, when $I$ is treated as a function of $q$, the system cost function is $S$-shaped. In the first case system cost decreased because of the increasing number of furrows per set thus decreasing total number of irrigation sets, which reduced total application time, water applied, and labor requirements. In the second case as $q$ is reduced the total number of sets is also reduced, but at the same time $I$ is decreased which necessitated longer application times per set in order to apply the
Table 14. Effect of variation in intake function on Maximum Net Farm Profit and cost of furrow irrigation system when no IRRS is used.†

<table>
<thead>
<tr>
<th>Description</th>
<th>Furrow stream size, ( q ) -gpm-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intake function, ( I = K t^n )</th>
<th>MNFP -$/acre-</th>
<th>Seasonal infiltrated depth -inches-*</th>
<th>System cost -$/acre-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Held constant at ( I = 0.09 t^{-0.51} )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MNFP -$/acre-</td>
<td>591</td>
<td>641</td>
<td>690</td>
</tr>
<tr>
<td>Seasonal infiltrated depth -inches-*</td>
<td>26.4</td>
<td>27.3</td>
<td>28.6</td>
</tr>
<tr>
<td>System cost -$/acre-</td>
<td>222</td>
<td>188</td>
<td>151</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intake function, ( I = K t^n t^{-0.550} )</th>
<th>MNFP -$/acre-</th>
<th>Seasonal infiltrated depth -inches-*</th>
<th>System cost -$/acre-</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNFP -$/acre-</td>
<td>774</td>
<td>774</td>
<td>778</td>
</tr>
<tr>
<td>Seasonal infiltrated depth -inches-*</td>
<td>29.3</td>
<td>33.7</td>
<td>31.0</td>
</tr>
<tr>
<td>System cost -$/acre-</td>
<td>50</td>
<td>69</td>
<td>65</td>
</tr>
</tbody>
</table>

†Crop is corn with an assumed gross return of $6.00/bushel. Crop production costs are assumed to be $60/acre.

* Only depths of stored water are considered in calculating crop yield.
required depth of irrigation. Thus system cost did not follow a smoothly decreasing function.

Another simple analysis was made for one $q-I$ relationship by making a small, arbitrary change in the measured $K$ and $n$ values for the intake function. It was found that changes as small as $\pm 10$ percent in the $n$ value produced significant changes in the final design. Changing the $K$ value does affect the results, as was shown earlier in Table 13 and 14, but not as much as changes in the exponent $n$ did.

**Effect of Furrow Stream Size on Maximum Net Farm Profit and System Cost**

Furrow stream sizes should be selected to keep soil erosion at a minimum and/or maximize net farm profit, therefore either one or both criteria can govern the selection of the optimum furrow stream size. Since erosion should not be allowed, the maximum non-erosive stream size can be determined and used as an upper limit and beginning point to start searching for an optimum design.

In this study, for a given set of conditions, a maximum non-erosive stream size is predicted and used to design and optimize the system, and evaluate $MNFP$. Then the furrow stream size is reduced by some arbitrarily chosen increments and an optimum design is determined for each iteration until a feasible range of stream sizes has been covered. From this, the stream size and associated design which maximizes net farm profit is determined.
To illustrate the sensitivity of furrow stream size on MNFP, the results of the model analysis for sugar-cane and corn crops grown on four different soil types are given in Table 15. Case 1 is for a light-textured soil and shows that MNFP increases to a maximum as $q$ decreases then starts decreasing as stream size decreases. Case 2 is for a heavy-medium-textured soil and reveals the same phenomenon. Case 3, on a medium-textured soil, shows a relatively high initial intake rate and in this case it is assumed that intake function is independent of furrow stream sizes. It can be noticed that furrow stream size cannot be reduced much before the pre-specified practical design limits are exceeded. A close examination of this case shows that holding the intake function constant and reducing furrow stream size implies that water is infiltrating through the soil at a faster rate than it is being applied; therefore, no feasible prediction of water advance can be made. Even if a prediction is possible then a distorted picture will be obtained because large amount of deep percolation losses occur at the upper end of the furrow. Case 4 is for a heavy-textured soil and also the intake function is being held independent of stream sizes as in Case 3 above. The results show that as $q$ decreases MNFP keeps increasing until the pre-specified limits of PFD are exceeded. In the above analysis actual field data are used for all four cases; however, the last two cases are not very close to actual field conditions because field data were obtained for one $q$ value and it is assumed that the intake function is constant and not related to $q$. Cases 1 and 2 are closer to the
Table 15. Effect of furrow stream size on Maximum Net Farm Profit and system cost when an IRRS is used.

<table>
<thead>
<tr>
<th>$I = K t^{-0.555}$;</th>
<th>$K = 0.0125 q^{1.09}$; Sugar-cane @ $10.9/ton$†</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q$ -gpm-</td>
<td>16.84γ 13.47 10.10 8.42 6.73</td>
</tr>
<tr>
<td>1 MNFP -$/acre-$</td>
<td>407 414 417 354 **</td>
</tr>
<tr>
<td>System cost -$/acre-$</td>
<td>79 75 80 94 --</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$I = K t^{-0.333}$;</th>
<th>$K = 0.023 q^{0.225}$; Corn @ $6.00/bushel$*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q$ -gpm-</td>
<td>28.93γ 23.14 17.36 11.57 8.68</td>
</tr>
<tr>
<td>2 MNFP -$/acre-$</td>
<td>756 766 784 801 794</td>
</tr>
<tr>
<td>System cost -$/acre-$</td>
<td>107 97 80 60 70</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$I = K t^{-0.372}$;</th>
<th>$K = 0.141 q^{0.0}$; Corn @ $6.00/bushel$*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q$ -gpm-</td>
<td>22.00γ 20.90 19.80 18.70 17.60</td>
</tr>
<tr>
<td>3 MNFP -$/acre-$</td>
<td>836 840 835 835 **</td>
</tr>
<tr>
<td>System cost -$/acre-$</td>
<td>67 55 66 66 --</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$I = K t^{-0.510}$;</th>
<th>$K = 0.090 q^{0.0}$; Corn @ $3.00/bushel$*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q$ -gpm-</td>
<td>22.93γ 23.15 17.36 8.68 7.23</td>
</tr>
<tr>
<td>4 MNFP -$/acre-$</td>
<td>190 241 293 363 **</td>
</tr>
<tr>
<td>System cost -$/acre-$</td>
<td>119 100 140 72 --</td>
</tr>
</tbody>
</table>

†Crop production costs are $277/acre and water cost is $5.00/ac-ft
*Crop production costs are $60/acre and water cost is $3.00/ac-ft
γMaximum non-erosive furrow stream sizes
**Impractical design conditions and exceeding the pre-specified design limits
actual field situation because data from three trials were obtained and used to construct an empirical relationship between $K$ and $q$ as depicted in Figure 10.

Table 16 shows the variation of the major design and management elements with furrow stream size for case 2 presented in Table 15. Obviously, large streams reach the end of the furrow in a short period of time and cause large amounts of runoff water; consequently, they require large IRRS with its increase in system cost. Examining the results in Table 16 shows that the highest MNFP is obtained when some under-irrigation is allowed at the lower end of the furrow, since the required depth of stored water, $d_s$, is 4.0 inches in this case. Therefore, adequately irrigating the whole field is not always beneficial from the net profit standpoint. It can also be noted that up to a certain point, reducing furrow stream size reduces the number of irrigation sets, $N_g$, required. Reducing $N_g$ cuts the total time of application for the whole field, since the total time of application for the entire field is equal to the time of application per set, $T_g$, times $N_g$, thence no advantage can be obtained by reducing $q$ any further. In fact, cost will start increasing again because as the time of application per irrigation increases, so do labor and water costs.

A similar analysis was made for the same example above but no IRRS was included in the system. The results are shown in Tables 17 and 18. Once again it should be clear from the results of cases 1 and 4 shown in Table 17 that the MNFP obtained with the maximum non-erosive furrow stream sizes are always less profitable. The
Table 16. Variation of system design and management with furrow stream size when an IRRS is used.

<table>
<thead>
<tr>
<th>Design item</th>
<th>Furrow stream size, q - gpm-</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28.93</td>
</tr>
<tr>
<td>MNFP - $/acre*</td>
<td>756</td>
</tr>
<tr>
<td>Advance time - min-†</td>
<td>15</td>
</tr>
<tr>
<td>Application time - hrs-</td>
<td>17.15</td>
</tr>
<tr>
<td>System cost -$/acre-</td>
<td>107</td>
</tr>
<tr>
<td>$R_f$ -%-</td>
<td>76.38</td>
</tr>
<tr>
<td>$N_s$</td>
<td>4</td>
</tr>
<tr>
<td>$N_t$</td>
<td>7</td>
</tr>
<tr>
<td>$d_u$ - inches-</td>
<td>4.02</td>
</tr>
<tr>
<td>$d_l$ - inches-</td>
<td>4.00</td>
</tr>
<tr>
<td>$d_t$ - inches-</td>
<td>4.02</td>
</tr>
</tbody>
</table>

* Crop is corn with an assumed gross return of $6.00/bushel. Crop production costs are estimated to be $60/acre. Soil is type E (see Appendix D for other pertinent data).
† As predicted by Davis' method
γL = 900 feet; $S_s = 3$ feet; and $d_s = 4.00$ inches.
Table 18. Variation of system design and management with furrow stream size when no IRRS is used.

<table>
<thead>
<tr>
<th>Design item</th>
<th>28.05</th>
<th>22.07</th>
<th>16.22</th>
<th>10.12</th>
<th>4.04</th>
<th>2.02</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNFP -$/acre-</td>
<td>730</td>
<td>748</td>
<td>765</td>
<td>794</td>
<td>818</td>
<td>815</td>
</tr>
<tr>
<td>Advance time - min-</td>
<td>16</td>
<td>21</td>
<td>36</td>
<td>93</td>
<td>670</td>
<td>3100</td>
</tr>
<tr>
<td>Application time -hrs-</td>
<td>17.18</td>
<td>19.08</td>
<td>22.33</td>
<td>25.35</td>
<td>41.71</td>
<td>81.94</td>
</tr>
<tr>
<td>System cost -$/acre-</td>
<td>132</td>
<td>116</td>
<td>98</td>
<td>70</td>
<td>46</td>
<td>45</td>
</tr>
<tr>
<td>$N_s$</td>
<td>14</td>
<td>11</td>
<td>8</td>
<td>5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>$N_t$</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>$d_u$ -inches-</td>
<td>4.02</td>
<td>4.04</td>
<td>4.20</td>
<td>4.21</td>
<td>4.66</td>
<td>6.26</td>
</tr>
<tr>
<td>$d_l$ -inches-</td>
<td>3.98</td>
<td>4.01</td>
<td>4.13</td>
<td>4.04</td>
<td>3.80</td>
<td>3.37</td>
</tr>
<tr>
<td>$d_t$ -inches-</td>
<td>4.01</td>
<td>4.03</td>
<td>4.18</td>
<td>4.16</td>
<td>4.44</td>
<td>5.55</td>
</tr>
</tbody>
</table>

*Crop is corn with an assumed gross return of $6.00/bushel. Crop production costs are estimated to be $60/acre. Soil is type E, (see Appendix D for other pertinent data).

†As predicted by Davis' Method

$Y_L = 900$ feet; $S_s = 3$ feet; and $d_s = 4.00$ inches
explanation for this fact is shown in Table 18, where case 4 is given in more detail. When large \( q \) is used the number of irrigation sets is increased which increases the total time of application for the entire field, causes tremendous amounts of runoff water, and increases labor cost. A compromise between stream size and number of irrigation sets can be obtained by changing \( q \) which changes the time of advance and time of application per irrigation. However, when \( q \) is reduced, the time of advance becomes excessively long, large deep percolation losses occur at the upper end of the furrow, and crop yields are thus reduced because of leaching out most of the fertilizer.

**Effect of Water Advance Phase on Maximum Net Farm Profit**

The method of predicting the rate of advance of water front down the furrow appears to have insignificant effect on the predicted Maximum Net Farm Profit, MNFP, especially for medium- and heavy-textured soils. This could be true for two main reasons. First, almost all the available prediction techniques give results close to each other and in many cases the difference between the predicted advance functions can be overlooked, (see Appendix B for further discussion).

The second reason for the insignificant difference among these methods is because the water advance phase, in many cases, constitutes a minor fraction of the total irrigation time. For example, a difference of one hour in the total time of application per irrigation will only change the total accumulated depth of infiltrated water by
few hundredths of an inch. When integrating the infiltrated depths and the *Crop Production Function*, CPF, the difference introduced will be negligible. Moreover, the approximations and uncertainties in the CPF can easily offset the effect of the difference in advance time.

To illustrate and confirm the above argument, Table 19 shows five cases of analysis for furrow irrigation system design with an IRRS and different soils, crops, lengths of run, and furrow stream sizes. The values in the table were obtained by first selecting a given prediction method and conducting a comprehensive series of optimization analyses until an optimum furrow stream size was located. Thence, that optimum \( q \) is held constant and only the advance-prediction route is changed. The design and optimization process is repeated to find the MNFP associated with the new route. This strategy of comparing the prediction methods at the MNFP level also helps to minimize the difference in the results given by the various methods, because the MNFP requires a nearly full irrigation or proper filling of the root zone which makes the advance phase of minor importance. It should be understood, however, that if the comparison of MNFP was done at other water application depths then the above conclusions may not hold true. For instance, if MNFP is predicted for very small depth of application per irrigation, say 1 inch, then only a 2-hour irrigation is needed and the advance phase may be nearly half that period. In this case, a small variation in the time of advance will greatly influence the wetting profile and therefore crop yield. On the other hand, if the time of application is increased
Table 19. Effect of method of predicting water advance on Maximum Net Farm Profit when an IRRS is used.

<table>
<thead>
<tr>
<th>Description</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>q -gpm-</td>
<td>11.57</td>
<td>11.57</td>
<td>8.68</td>
<td>10.10</td>
<td>16.84</td>
</tr>
<tr>
<td>Crop</td>
<td>Corn*</td>
<td>Corn†</td>
<td>Corn*</td>
<td>Sugar-caneγ</td>
<td>Sugar-caneγ</td>
</tr>
<tr>
<td>$I = K t^n$</td>
<td>0.040 $t^{-0.333}$</td>
<td>0.090 $t^{-0.510}$</td>
<td>0.090 $t^{-0.510}$</td>
<td>0.154 $t^{-0.555}$</td>
<td>0.154 $t^{-0.555}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Method of predicting water advance</th>
<th>Maximum Net Farm Profit, MNFP -$/acre-</th>
</tr>
</thead>
<tbody>
<tr>
<td>Davis</td>
<td>800</td>
</tr>
<tr>
<td>Fok and Bishop</td>
<td>797</td>
</tr>
<tr>
<td>Intake (Appendix B)</td>
<td>800</td>
</tr>
<tr>
<td>Patterson</td>
<td>801</td>
</tr>
<tr>
<td>Empirical</td>
<td>799</td>
</tr>
</tbody>
</table>

*Assumed gross return is $6.00/bushel and crop production costs are $60/acre.
†Estimated gross return is $3.00/bushel and crop production costs are $60/acre.
γEstimated gross return is $10.90/ton and crop production costs are $277/acre.
to 30 hours, then a large difference in the predicted time of advance will have only a small effect on the MNFP.

Table 20 shows other cases of furrow irrigation system design when no IRRS is used and confirms the conclusion that the final system layout and anticipated performance is independent of the method of predicting water advance down the furrow.

Another observation can be made about the method of predicting water advance from Tables 19 and 20. The empirical method was based upon an assumed empirical advance function and a linear wetting pattern, with the values of $a$ and $b$ in Equation 72 being estimates only. Examination of the results indicates that even though the coefficients $a$ and $b$ were approximated, fairly close MNFP values were obtained to those calculated by detailed time-consuming methods.

Predicting the Wetting Profile Along the Furrow

The configuration of the wetting pattern can be approximated as a linear or curvilinear pattern as was explained in Chapter IV. The model was used to analyze and compare the two approaches, and to trace their effect on Maximum Net Farm Profit, MNFP, and runoff percentage, $R_f$. Four cases are presented in Figures 11 through 14.

Figure 11 shows a comparison between the linear approach, which is based upon the empirical method of advance prediction, and the curvilinear approach, which is based upon Davis' Method of advance prediction. The coefficients $a$ and $b$ used for the empirical method were deduced from the curvilinear approach for the same case. In
Table 20. Effect of method of predicting water advance on Maximum Net Farm Profit when no IRRS is used.

<table>
<thead>
<tr>
<th>Description</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q \text{-gpm-}$</td>
<td>4.04</td>
<td>14.25</td>
<td>4.04</td>
<td>28.95</td>
<td>4.04</td>
</tr>
<tr>
<td>Crop</td>
<td>Corn</td>
<td>Sugar-cane</td>
<td>Corn</td>
<td>Sugar-cane</td>
<td>Corn</td>
</tr>
<tr>
<td>$I = K t^n$</td>
<td>$0.031 t^{-0.333}$</td>
<td>$0.226 t^{-0.555}$</td>
<td>$0.090 t^{-0.510}$</td>
<td>$0.141 t^{-0.372}$</td>
<td>$0.080 t^{-0.510}$</td>
</tr>
</tbody>
</table>

Method of predicting water advance

| Method of predicting water advance | Maximum Net Farm Profit, MNFP -$/acre-
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Davis</td>
<td>816</td>
</tr>
<tr>
<td>Fok and Bishop</td>
<td>819</td>
</tr>
<tr>
<td>Intake (Appendix B)</td>
<td>817</td>
</tr>
<tr>
<td>Patterson</td>
<td>821</td>
</tr>
<tr>
<td>Empirical</td>
<td>822</td>
</tr>
</tbody>
</table>

*Assumed gross return is $6.00/bushel and crop production costs are $60/acre.

*Estimated gross return is $3.00/bushel and crop production costs are $60/acre.

*Estimated gross return is $10.90/ton and crop production costs are $277/acre.
Figure 11. Linear and curvilinear wetting patterns using Davis' and the empirical advance methods and soil type D.
other words, first a detailed advance prediction method was used for the analysis, then the resulting advance function was used to estimate the coefficients $a$ and $b$. This was primarily done to allow more precise comparison, for that will give approximately the same time of advance in both cases and the same accumulated depths of infiltration at the ends, i.e., $d_l$ and $d_u$.

The analysis shown in Figure 11 was conducted for times 30, and 75 hours, of application per irrigation while holding all other input elements constant. The curvilinear function tends to approach the linear as the time of application increases. This can be attributed to the intake rate being a diminishing function of intake opportunity time; therefore, one hour, more or less, at the end of an irrigation will contribute a much smaller depth of infiltration than one hour at the beginning of irrigation. Hence, as the opportunity time increases, the accumulated depths of infiltrated water predicted by the two techniques approach each other asymptotically.

Figure 11 also shows that in using a linear wetting pattern the runoff percentage, $R_f$, will be over-estimated due to under-estimation of deep percolation losses. As the time of application increases the $R_f$'s calculated from either technique will approach the same values. In any case, the difference in the predicted $R_f$'s seems to be of minor importance and may not affect the final design of IRRS, because any given IRRS design can accommodate some changes in $R_f$.

A similar analysis is done on a type A soil with the same slope used in Figure 11 but with an $L$ of 900 feet as shown in Figure 12.
Figure 12. Linear and curvilinear wetting patterns using Davis' and the empirical advance methods and soil type A.
However, the intake characteristics of type D and type A soils are close enough to allow some comparison of the accumulated depths of infiltrated water. It can be seen that \( q \) used in the analysis shown in Figure 12 is much smaller than that used in Figure 11. Even though the length of run was reduced, it took the smaller stream a longer time to advance the shorter length. Thus, a similar time of application per irrigation, i.e., 34 vs. 30 hours resulted in a large difference between the respective \( d_z \) and \( d_u \) values but a smaller difference in \( R_f \) values.

Figure 13 shows another evaluation of advance time on soil type D, but Fok and Bishop's method was used for predicting the curvilinear function instead of Davis'. Examining the results of Figures 11 and 13, at an application time of about 30 hours, indicates that smaller \( R_f \)'s were predicted in the second case. This could be true because \( q \) and \( I \) were increased proportionally. Therefore, more water was assumed to infiltrate, giving a smaller \( R_f \). At this point no definite conclusion can be made about the two results because the logical conclusion would be more runoff water associated with larger stream sizes. This dichotomy could result from the fact the \( I \) and \( q \) were mis-proportioned and thus giving very high intake rates for the larger streams. Further investigation of the relationship between \( q \) and \( I \) is mandatory before a conclusion can be made.

The case exhibited in Figure 14 was conducted on soil type E (a medium-textured soil) and using the intake method to predict the curvilinear wetting pattern. The same conclusions and comments made above seem to hold true for this case. Comparisons of the
Figure 13. Linear and curvilinear wetting patterns using Fok and Bishop's and the empirical advance methods and soil type D.
Figure 14. Linear and curvilinear wetting patterns using the intake and the empirical advance methods and soil type \( E \).
results shown in Figures 11 through 14 suggest that for medium- or heavy-textured soils the linear and curvilinear functions will be closer to each other than on light-textured soils. It is clear from Figure 14 that after 23 hours of application on the medium-textured soil the maximum difference in the predicted depth of infiltrated water was 0.04 inch, while for the lighter-textured soils shown in Figures 11 and 13, after 30 hours of application, the maximum difference in the depth of infiltration was still only about 0.15 inch and 0.35 inch, respectively. These small differences will account for the fact that the difference in the MNFP's calculated for each case was negligible.

It should be mentioned that the above argument may be only theoretically true and may not represent actual field conditions, because of soil non-homogeneity may distort the shape of the wetting pattern. The nice smooth curves shown in Figures 11 through 14 resulted from theoretical calculations when in reality irregular curves should be anticipated. Even though these factors are overlooked, it is believed that the theoretical argument provides a logical insight to system design and performance.

Effect of Infiltration Uniformity on Maximum Net Farm Profit and System Cost

The depth of infiltrated water, or the depth of water received by the crop, has a direct effect on crop growth, evapotranspiration, and yield. Research has shown that crop yield
improves as the depth of water available to the plants increases up to a certain maximum point. Beyond that, yields decrease as water applied increases. (See Figure 4 and Appendix D). Therefore, to closely predict crop yield from a particular irrigation water application program, an evaluation of the depths of water infiltrated should be checked at several locations over the field surface.

The analysis presented in the preceding section illustrated several cases of water distribution patterns along the furrow. It was indicated that some application practices give more uniform distribution patterns than others. Hence, crop yield associated with each application pattern will be somewhat different, provided no excessive deep percolated water occurs. This suggests that the more uniform the applications the greater the crop yield will be. However, the MNFP's may not be maximized at the maximum yield. In order to study this phenomenon in more detail several cases were studied and the results shown in Figures 15 through 19.

In the following discussion two terms are used to express the uniformity of water application. The first one is the Distribution Uniformity, $DU$, which is defined to be the ratio of the average of lowest $1/4$ depths to the average depth infiltrated when the average depth is some fixed amount. Of course for a given average depth of infiltrated water various $DU$ values can be obtained simply by changing the furrow stream size, $q$. This changes the advance function and consequently the wetting pattern. The second term used in the discussion is called the Instantaneous Distribution Uniformity, $DU_1$. 


which is defined instantaneously at a given time as the ratio of the average of lowest 1/4 depths to the average depth infiltrated at that particular time instant. But there is an important difference imbeded in the two definitions, and that is the $DU$ is evaluated for a given specified average depth of infiltration, in other words, all system designs considered should apply the same depth of infiltrated water but may be in different patterns, for instance, changing furrow stream size and adjusting the time of opportunity to give the required depth. The $DU_i$, however, is evaluated for the average depth infiltrated at the particular moment considered. Therefore, for a given system design, $DU_i$ changes with the time of opportunity. In essence, $DU$ can be used to compare several system designs while $DU_i$ is used to investigate certain system design during the time of irrigation, i.e., a system design with different depths of infiltrated water.

Figure 15 shows a typical variation of $MNFP$ and a typical system cost as a function of $DU$ for a sugar-cane crop. It indicates that net farm return can be increased, to some extent, by improving the uniformity of application. The range of variation of $MNFP$ and system cost with $DU$ can be broken into three distinct intervals. The first interval extends up to a $DU$ of about 80 percent. The distinguishing feature of this range is that as $DU$ increases both $MNFP$ and system cost increase but the gain in crop yield due to better uniformity tends to overcome the increase in the cost; therefore, net return will improve. The second range extends from a $DU$ of 80 percent to about 92 percent. In this interval no net gain in farm return was
Figure 15. Variation of Maximum Net Farm Profit and system cost with the Distribution Uniformity on a sugar-cane field.
obtained because the increase in system cost as $DU$ is increased barely offset the increase in gross return. Thus no net advantage can be obtained by increasing $DU$. The third interval extends beyond a $DU$ of 92 percent. It is very clear from Figure 15 that system cost increases so sharply that it overcomes any gain in crop return. Therefore $MNFP$ declines.

Figure 16 illustrates the variation of $MNFP$ and system cost with $DU_i$ on a corn field where an $IRRS$ is used. The same three sub-intervals discussed above appear again, which emphasizes the fact that very low or very high $DU$ or $DU_i$ values are not recommended. It is important to notice that normally low $DU_i$ values are associated with small depths of infiltration which leave part of the root zone unwatered and result in low $MNFP$'s. By the same token, high $DU_i$ values are usually consequences of large depths of infiltration which might be excessive, leach the fertilizers below the root zone, and reduce $MNFP$'s.

Figure 17 is another way of analyzing the same case presented in Figure 16, but instead of tracing the effect of $DU_i$ it shows the effect of $DU$ on $MNFP$ and system cost, i.e., effect of different system designs on $MNFP$. Once more the same patterns of variation found earlier are present in Figure 16.

Figure 18 illustrates the interaction between $DU_i$, $MNFP$, and system cost when no $IRRS$ is used. In this case, no sharp peak of $MNFP$ is found, which implies that for $DU_i$ values between 65 and 87 percent, there is little improvement in $MNFP$. This is because no $IRRS$ is used, and as $DU_i$ increases the average depth of infiltration
Figure 16. Variation of Maximum Net Farm Profit and system cost with the Instantaneous Distribution Uniformity on a corn field when an IRRS is used.
Figure 17. Variation of Maximum Net Farm Profit and system cost with the Distribution Uniformity on a corn field when an IRRS is used.
Figure 18. Variation of Maximum Net Farm Profit and system cost with the Instantaneous Distribution Uniformity on a corn field when no IRRS is used.
increases along with the depth of runoff water and the time of application; therefore, total system cost increases sharply and offsets any gain in crop return.

Figure 19 shows the variation of \( \text{MNFP} \) and system cost with \( \text{DU} \) when no \( \text{IRRS} \) is used. It can be noticed that \( \text{MNFP} \) reached a peak with a medium-sized furrow stream. That was the case because large furrow stream sizes greatly increase \( R_f \) which increases system cost because runoff water is not recovered. With very small furrow stream sizes, longer advance times are required and this lengthens the time of application, which in turn increases system cost.

**Effect of Runoff Recovery on Maximum Net Farm Profit and System Cost**

The most important decision that needs to be made when designing a furrow irrigation system is recovering or wasting runoff water. Besides considering the existing legal aspects, the designer should make an economic evaluation.

The break-even point between the two schemes can be expressed in terms of one or many of the cost elements involved. When no \( \text{IRRS} \) is used, system cost will comprise land grading, water, and labor costs. While when an \( \text{IRRS} \) is used, system cost includes, in addition to those listed above, equipment and pumping costs for the recovered water. Land grading costs could be the same whether an \( \text{IRRS} \) is used or not. Thus the two major cost components that affect \( \text{IRRS}'s \) economics are water and labor costs. Since labor
Figure 19. Variation of Maximum Net Farm Profit and system cost with the Distribution Uniformity on a corn field when no IRRS is used.
cost seems to contribute a minor part to the total cost figure only.

water cost needs to be explored.

In this section several cases will be analyzed to investigate the MNFP, and water and total system costs for different system designs.

Figure 20 shows the variation of MNFP and system costs for various \( R_f \) values when an IRRS is used in the system. The system was for a 41-acre corn field with an average depth of infiltrated water, \( d_t \), of 4.1 inches. The furrow stream size, \( q \), was varied and the system cost and MNFP evaluated for every \( q \).

Figure 20. Variation of Maximum Net Farm Profit and IRRS's cost with runoff percentage for a total depth of infiltrated water of 4.1 inches.
The total system cost, composed of fixed, pumping, water, and labor costs, decreases to a minimum then increases (see Figure 20). So does the fixed costs of the system, except that the minimum is not very sharp. The pumping cost is an increasing function of $R_f$. The increase is negligible below an $R_f$ of 68 percent, because the amount of runoff water demands more pumping but simultaneously reduces the number of irrigation sets, which in turn reduces the time of pumping needed. This tends to keep the pumping cost stable until the increases in the pumping costs are greater than the saving due to the reduction in pumping time, thus pumping cost starts increasing. The MNFP keeps improving up to an $R_f$ of about 60 percent then tends to stay at the same value until an $R_f$ of 66 percent, because $d_t$ is constant, thus DU does not change. Since the system cost is almost the same over this range, MNFP stayed the same. For $R_f$ values above 66 percent MNFP declines because of increasing system cost with no gain in crop return to overcome this cost increase.

Figure 21 shows MNFP and corresponding total system costs with and without an IRRS where the $q$ was held constant and the $d_t$ and Instantaneous Distribution Uniformity, DU, are changed for various water costs. Several interesting observations can be made. The first is that the break-even points where the with and without IRRS lines cross based on total system cost and MNFP do not occur at the same water cost. At a water cost of $1/ac-ft the total cost of a system with an IRRS is higher. At the same time IRRS given a greater depth of infiltration at a higher DU, which tends to increase crop
Figure 21. Interaction of Maximum Net Farm Profit, system cost, water cost for furrow irrigation system with and without an IRRS for a 61-acre, sugar-cane field.
yield and hence MNFP. This offsets the higher costs associated with
IRRS and the with and without system designs break even.

It can also be noticed from Figure 21 that an IRRS should be
used when the water cost is $1/ac-ft only because the two systems
were compared at a randomly-selected \( q \), namely 17.5 gpm, which tends
to give a large amount of runoff water that is wasted when no IRRS
is used. A completely different picture would be obtained if the two
alternatives were compared at two different furrow stream sizes as
shown below.

Figure 22 is a comparison of a furrow irrigation system with
and without IRRS at their corresponding optimum furrow stream sizes.
In this case the break-even point occurred at a water cost of $25/ac-
ft as compared to $1/ac-ft in the case above. This large difference
between these two figures occurs because in Figure 21 both systems
were compared at one relatively large furrow stream size, which was
very large and caused large runoff when no IRRS was used. For
Figure 22 the systems were each analyzed at its optimum furrow
stream size, 4.04 gpm for the system without an IRRS and 8.68 gpm
for the one with it. Thus the runoff and system cost were less,
which made the no IRRS alternative more feasible at the lower water
costs.

At the break-even water cost of $25/ac-ft the maximum profit
obtained with an IRRS occurred at an \( R_f \) of 66 percent, a \( d_t \) of 4.1
inches, a time of application per irrigation, \( T_o \), of 36 hours, and a
\( DU_t \) of 97 percent. When no IRRS is used the maximum profit occurred
at an $R_f$ of only 25 percent, a $d_e$ of 3.7 inches, a $T_b$ of 34 hours, and a $DU_i$ of 85 percent (see Figure 23). A comparison of the total system cost for various $R_f$ values for the two alternatives is shown in Figure 23. At the optimum design of an IRRS the cost of the system per unit volume of applied water was about $40/ac-ft while without an IRRS the total system cost is only $29/ac-ft. Yet the
Figure 23. Variation of total furrow irrigation water application cost with and without an IRRS for different runoff percentages.

Two designs have the same MNFP. This is attributed to the higher DU values obtained with an IRRS with its accompanying higher returns to balance the higher capital costs.

It is interesting that when no IRRS is used the total cost, i.e., water and labor costs, per unit of applied water is independent of the time of application per set, $T_8$, and $R_f$. This is true because the unit total irrigation cost can be expressed as follows
UTC = \frac{\text{Water cost} + \text{Labor cost}}{\text{Volume of applied water}}

= \frac{K_{18} Q_s T_s C_w + T_s C_l}{K_{18} Q_s T_s} \frac{N_s N_i}{N_s N_i}

= (C_w + \frac{C_l}{K_{18} Q_s}) N_s N_i \tag{85}

where

UTC = \text{total irrigation cost per unit of applied water, \$/ac-ft,}  \quad (\$/ha-mm)

C_w = \text{cost of water, \$/ac-ft,}  \quad (\$/ha-mm)

C_l = \text{cost of labor, \$/hr}

K_{18} = \text{a constant which is equal to 1/12 for the English units}

\text{and 0.36 for the metric units}

Equation 85 shows that UTC is independent of the time of application per set.

Figure 24 shows the variation of MNFP along with the fixed, pumping, variable (water and labor), and total irrigation costs for a furrow stream size, q, of 8.68 gpm and with variable R_{f}'s. The total and fixed cost functions follow S-shaped curves as R_{f} changes, while the variable cost, which is composed of water and labor costs, is independent of R_{f}, as was demonstrated by Equation 85. The pumping cost increases very rapidly for greater R_{f} than 50 percent. The MNFP increases until an R_{f} of about 60 percent is reached because of the greater depths and uniformity of application. Beyond an R_{f} of 60 percent the MNFP tapers-off because of increasing total irrigation...
Figure 24. Analysis of Maximum Net Farm Profit and systems cost for various runoff percentages.
cost and decreasing yield due to over-irrigating the root zone and leaching out the fertilizers.

**Effect of Land Grading Design on Furrow Irrigation System Characteristics**

Land grading design affects system characteristics because of its relation to the slope of the graded surface and hence the maximum non-erosive furrow stream size, and to MNFP through the land grading costs. In this research the magnitude of the effect of land grading design on overall system performance was studied by considering three fields with different topographic configurations and using the various options of land grading presented earlier. The original field elevations at the grid stakes are shown in Appendix D.

Table 21 shows an analysis of a 41-acre field. Examining the options where uniform slope is proposed in the row direction, i.e., Kriz's types I, II, and III, Paul's, and the SCS methods, reveals that all the calculated slopes were practically the same. Also, several methods gave very close slopes in the cross-row direction which indicates that some of these alternatives can be eliminated from the model because the final results are reflected in the other options. The calculated cut-fill ratio, \( C/F \), was almost the same regardless of the design route. This was the case because the desirable \( C/F \) was specified as 1.25 in all designs and the final slopes are adjusted to yield the required ratio plus or minus some allowance.
Table 21. Comparison of several land grading designs on a 41-acre field.\(^\gamma\)

<table>
<thead>
<tr>
<th>Method of land grading</th>
<th>Row slope -%</th>
<th>X-row slope -%</th>
<th>C/F</th>
<th>Cu yd/acre</th>
<th>$/acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kriz Type I</td>
<td>-0.320</td>
<td>-0.100</td>
<td>1.253</td>
<td>577</td>
<td>231*</td>
</tr>
<tr>
<td>II</td>
<td>-0.320</td>
<td>-0.100 to -0.520</td>
<td>1.253</td>
<td>570</td>
<td>228*</td>
</tr>
<tr>
<td>III</td>
<td>-0.320</td>
<td>-0.100 to -0.110</td>
<td>1.253</td>
<td>581</td>
<td>232*</td>
</tr>
<tr>
<td>IV</td>
<td>-0.080 to -0.450</td>
<td>-0.100</td>
<td>1.253</td>
<td>568</td>
<td>227*</td>
</tr>
<tr>
<td>SCS</td>
<td>-0.328</td>
<td>-0.015</td>
<td>1.255</td>
<td>404</td>
<td>162*</td>
</tr>
</tbody>
</table>

Paul (Least squares)  
(Least cost)  
(Double centroid)  
(Average slope)  

\(\gamma\)Original field elevations are shown in Figure 41 (Appendix D).

*Cost is based upon $0.40/cu yd.

†Cost is based upon a Load Factor of $82.96/ft and a Distance Factor of $12.62/ft/100 ft.
The volumes of earth work ranged between 404 and 581 cubic yards per acre. For this field the SCS method gave the lowest volume of earth work which could be attributed to the assumption used in the method that the original ground surface between any two grid points is a plane. Thus, it may under-estimate or over-estimate the actual volumes depending on the original ground configurations.

The volumes of earth work calculated by Shih and Kriz's methods were close to each other since they were all based upon the end-grid area method. The volumes obtained from Paul's methods were of the same order because they were all based upon the summation method. Comparing the SCS and Paul's least squares methods in Table 21 shows a significant difference in the calculated volumes of earth work even though the least squares technique is used in both of them to determine design slopes. This difference results from using the four-point method in SCS program and the summation method in Paul's program to calculate the volumes of earth work.

Tables 22 and 23 illustrate similar analyses on a 45-acre and a 61-acre field with slightly rougher topography than the field analyzed in Table 21. The SCS method was not used on these fields because the program is relatively inefficient for rough fields and requires large computer time.

The design option labeled Kriz type V gave the least costs among all the designs because this option involves only slight land smoothing instead of heavy grading operations.
Table 22. Comparison of several land grading designs on a 45-acre field.\(^\gamma\)

<table>
<thead>
<tr>
<th>Method of land grading</th>
<th>Row slope -%-</th>
<th>X-row slope -%-</th>
<th>C/F</th>
<th>Cu yd/acre</th>
<th>$/acre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kriz type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>-0.518</td>
<td>0.119</td>
<td>1.263</td>
<td>906</td>
<td>362*</td>
</tr>
<tr>
<td>II</td>
<td>-2.200 to -0.170</td>
<td>-0.170 to -0.050</td>
<td>1.258</td>
<td>535</td>
<td>214*</td>
</tr>
<tr>
<td>III</td>
<td>-0.620 to -0.480</td>
<td>-0.310 to -0.050</td>
<td>1.263</td>
<td>914</td>
<td>366*</td>
</tr>
<tr>
<td>IV</td>
<td>-0.520 to -0.510</td>
<td>-0.010 to +0.110</td>
<td>1.263</td>
<td>902</td>
<td>361*</td>
</tr>
<tr>
<td>V</td>
<td>-0.700 to 0.000</td>
<td>-0.200 to +0.960</td>
<td>1.260</td>
<td>362</td>
<td>145*</td>
</tr>
<tr>
<td>Paul (Least squares)</td>
<td>-0.492</td>
<td>-0.118</td>
<td>1.245</td>
<td>952</td>
<td>322(^\dagger)</td>
</tr>
<tr>
<td>(Least cost)</td>
<td>-0.532</td>
<td>-0.118</td>
<td>1.245</td>
<td>939</td>
<td>318(^\dagger)</td>
</tr>
<tr>
<td>(Double centroid)</td>
<td>-0.518</td>
<td>-0.119</td>
<td>1.245</td>
<td>942</td>
<td>318(^\dagger)</td>
</tr>
<tr>
<td>(Average slope)</td>
<td>-0.422</td>
<td>-0.120</td>
<td>1.244</td>
<td>1003</td>
<td>348(^\dagger)</td>
</tr>
</tbody>
</table>

\(^\gamma\)Original field elevations are shown in Figure 42 (Appendix D).

\(^*\)Cost is based upon $0.40/cu yd.

\(^\dagger\)Cost is based upon a Load Factor of $82.96/ft and a Distance Factor of $12.62/ft/100 ft.
Table 23. Comparison of several land grading designs on a 61-acre field.\(^\gamma\)

<table>
<thead>
<tr>
<th>Method of land grading</th>
<th>Row slope -%</th>
<th>(X)-row slope -%</th>
<th>C/F</th>
<th>Cu yd/acre</th>
<th>$/acre*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kriz type</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>-0.472</td>
<td>-0.110</td>
<td>1.259</td>
<td>798</td>
<td>319*</td>
</tr>
<tr>
<td>II</td>
<td>-1.300 to -0.440</td>
<td>-1.300 to -0.100</td>
<td>1.257</td>
<td>645</td>
<td>258*</td>
</tr>
<tr>
<td>III</td>
<td>-0.750 to -0.360</td>
<td>-0.230 to -0.100</td>
<td>1.257</td>
<td>736</td>
<td>294*</td>
</tr>
<tr>
<td>IV</td>
<td>-0.850 to -0.190</td>
<td>-0.390 to -0.100</td>
<td>1.256</td>
<td>672</td>
<td>269*</td>
</tr>
<tr>
<td>V</td>
<td>-1.260 to 0.000</td>
<td>-1.300 to -0.320</td>
<td>1.259</td>
<td>343</td>
<td>137*</td>
</tr>
<tr>
<td>Paul (Least squares)</td>
<td>-0.468</td>
<td>-0.122</td>
<td>1.251</td>
<td>835</td>
<td>344†</td>
</tr>
<tr>
<td>(Least cost)</td>
<td>-0.478</td>
<td>-0.092</td>
<td>1.250</td>
<td>808</td>
<td>330†</td>
</tr>
<tr>
<td>(Double centroid)</td>
<td>-0.472</td>
<td>-0.110</td>
<td>1.250</td>
<td>822</td>
<td>334†</td>
</tr>
<tr>
<td>(Average slope)</td>
<td>-0.472</td>
<td>-0.146</td>
<td>1.251</td>
<td>865</td>
<td>361†</td>
</tr>
</tbody>
</table>

\(^\gamma\)Original field elevations are shown in Figure 43 (Appendix D).

*Cost is based upon $0.40/cu yd.

†Cost is based upon a Load Factor of $82.96/ft and a Distance Factor of $12.62/ft/100 ft.
Land grading design affects the final slope of the graded surface which in turn influences furrow stream size, advance function, *Distribution Uniformity*, crop yield, and therefore, MNP. Each time some new land slope is considered, a comprehensive optimization procedure is required. This should not be the case if an optimum design is already being obtained for a given land slope. In other words, if an optimum design and associated land grading costs are known, then by just knowing a land grading cost a quick prediction can be made for the expected MNP. In other words, the MNP of alternate designs can be estimated from the MNP predicted for a given grading program plus or minus the difference in the cost of land grading predicted by any alternate program and amortized over the life of the system. This is because the MNP is relatively insensitive to slight changes in slopes resulting in nearly the same furrow stream size and only small differences in the time of advance as was discussed in the section of *Effect of Water Advance Phase on Maximum Net Farm Profit*.

To illustrate this argument, Table 24 shows four options of land grading. The last three have the same design slope resulting in the same furrow stream size and advance function, but different grading costs. The upper half of the table shows the predicted MNP for the four options using detailed optimization techniques which take into account the differences in the time of advance (there was a difference of 50 minutes in the predicted advance time between the first and the last three design alternatives). The
Table 24. Effect of land grading design on the predicted Maximum Net Farm Profit.

<table>
<thead>
<tr>
<th>Description</th>
<th>Design trial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Land grading cost - $/acre</td>
<td>162</td>
</tr>
<tr>
<td>Time of advance - minutes</td>
<td>720</td>
</tr>
<tr>
<td><em>MNFP</em> (based upon detailed analysis) - $/acre*</td>
<td>803</td>
</tr>
<tr>
<td>Estimated <em>MNFP</em> (based upon CRF method) - $/acre</td>
<td>803</td>
</tr>
</tbody>
</table>

estimated *MNFP* (lower half of Table 24) was obtained from the *MNFP* of the first design trial minus the differences in land grading costs amortized over the life of the system. The differences in the two sets of *MNFP* are negligible. The minor variations are mainly due to the 9 percent difference in the predicted time of advance.

**Effect of Furrow Length on Overall System Design and Performance**

Furrow length is a significant element which affects the design and management of furrow irrigation systems. Long furrows are desired by many farmers for they facilitate cultivation practices. Furrow length affects furrow stream size, water application patterns, amount of runoff water, and time of application which results in the *MNFP*. In order to select an optimum furrow length for a given
field the MNFP associated with several trial lengths should be evaluated. The length which yields the highest MNFP should be selected, provided that it is practical and acceptable by the farmer.

Table 25 shows one such analysis for a field design using three different furrow lengths. For each length a complete optimization process was conducted to determine an optimum furrow stream size and a corresponding system design and management program. The important design and operation data for each MNFP are presented in Table 25. It was assumed in the analysis that shorter furrows require more management efforts than longer runs and thus the operational cost associated with them would be higher. Since no easy estimation for this extra cost could be made, a 10 percent increase in the initial system cost was included in the design associated with the 700-foot runs and 15 percent for that associated with the 460-foot runs as compared to the initial cost of 1400-foot runs.

The results in Table 25 indicate that the MNFP does not vary significantly as furrow length changes even though it tends to reach the highest values at a furrow length of 1400 feet. Total system cost varies inversely with furrow length. The reason for this variation in total system cost can be explained by comparing the \( R_f \)'s which are lower for longer runs and require a smaller IRRS. As \( R_f \) increases, larger IRRS's are needed and therefore, higher unit costs are required. As \( R_f \)'s continue to increase, the
Table 25. Effect of furrow length on overall system design and performance for a furrow irrigation system with an IRRS.

<table>
<thead>
<tr>
<th>Description</th>
<th>1400</th>
<th>700</th>
<th>460</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNFP -$/acre-</td>
<td>414</td>
<td>403</td>
<td>404</td>
</tr>
<tr>
<td>System cost -$/acre-</td>
<td>75</td>
<td>88</td>
<td>87</td>
</tr>
<tr>
<td>q -gpm-</td>
<td>13.47</td>
<td>14.65</td>
<td>16.83</td>
</tr>
<tr>
<td>R&lt;sub&gt;f&lt;/sub&gt;-%</td>
<td>33.4</td>
<td>44.7</td>
<td>66.2</td>
</tr>
<tr>
<td>T&lt;sub&gt;s&lt;/sub&gt; -hours-</td>
<td>34</td>
<td>20</td>
<td>19</td>
</tr>
<tr>
<td>t&lt;sub&gt;a&lt;/sub&gt; -minutes-</td>
<td>960</td>
<td>375</td>
<td>135</td>
</tr>
<tr>
<td>N&lt;sub&gt;s&lt;/sub&gt;</td>
<td>3</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>d&lt;sub&gt;u&lt;/sub&gt; -inches-</td>
<td>3.76</td>
<td>3.88</td>
<td>3.74</td>
</tr>
<tr>
<td>d&lt;sub&gt;i&lt;/sub&gt; -inches-</td>
<td>2.87</td>
<td>3.31</td>
<td>3.53</td>
</tr>
<tr>
<td>d&lt;sub&gt;a&lt;/sub&gt; -inches-</td>
<td>5.16</td>
<td>6.64</td>
<td>10.81</td>
</tr>
<tr>
<td>Vol. of unused runoff water -ac ft-</td>
<td>-0.73</td>
<td>1.02</td>
<td>-0.06</td>
</tr>
</tbody>
</table>

The time of application for the total field is reduced which cuts labor and total system unit costs.

From the results shown in Table 25, it seems to be more profitable to use long furrows and small streams. No further conclusions can be made, however, until more analyses are done on different soils and with different crops to verify the variation of system
design and operational elements. More accurate means to estimate the increase in managerial costs as furrow length decreases are also necessary.

**Effect of Water Lift, Water Cost, and Crop Value on System Design and Management**

The interaction among water lift, water cost, crop value, and system design and performance is of an important consideration. In Table 26 the MNFP simply decreases as water cost and/or lift increases. Moreover, optimum system design as expressed by the depths of application changes appreciably with both water cost and lift.

In Table 26, as water cost increases, the optimum design and management program calls for more uniform applications with total depths of applied irrigation water. This is because increasing water cost can be looked at either as an increase in the value of the water supply resource or as an increase in the cost of obtaining the water, i.e., pumping and conveying it, which is another way of stating increased water lift. It is interesting that at a water lift of 200 feet no alterations in system designs are suggested as water cost increases. This could be the case because a DU of 82.4 percent is needed at a water cost of $3/ac-ft. This DU value is already high and any more improvements beyond this value may demand extremely large costs that cannot be offset by improved production. This phenomenon was discussed in detail in an earlier section.
Table 26. Interaction of water lift, water cost, sugar-cane value, and optimum system design and performance for a furrow irrigation system with an IRRS.

<table>
<thead>
<tr>
<th>Water cost $/ac-ft</th>
<th>Water lift -feet-</th>
<th>MNFP</th>
<th>DU-%</th>
<th>Depth of Applic.</th>
<th>MNFP</th>
<th>DU-%</th>
<th>Depth of applic.</th>
</tr>
</thead>
<tbody>
<tr>
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<td>469</td>
<td>60.7</td>
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<td>407</td>
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<td></td>
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<td>407</td>
<td>82.4</td>
<td>61.25</td>
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<td>326</td>
<td>82.4</td>
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<tr>
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<td>50</td>
<td>242</td>
<td>82.4</td>
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<td>195</td>
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<td>379</td>
<td>82.4</td>
<td>58.00</td>
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<td>326</td>
<td>82.4</td>
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<td>0</td>
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<td>0</td>
<td>195</td>
<td>82.4</td>
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<tr>
<td></td>
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<td>195</td>
<td>82.4</td>
<td>49.00</td>
<td>200</td>
<td>195</td>
<td>82.4</td>
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</tbody>
</table>

Crop value = $10.90/ton for sugar-cane

<table>
<thead>
<tr>
<th>Water cost $/ac-ft</th>
<th>Water lift -feet-</th>
<th>MNFP</th>
<th>DU-%</th>
<th>Depth of Applic.</th>
<th>MNFP</th>
<th>DU-%</th>
<th>Depth of applic.</th>
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</thead>
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<tr>
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<td>0</td>
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<td>61.25</td>
<td>200</td>
<td>741</td>
<td>82.4</td>
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<td></td>
<td>50</td>
<td>649</td>
<td>84.4</td>
<td>54.50</td>
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<td>599</td>
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<tr>
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<td>84.4</td>
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<td>599</td>
<td>82.4</td>
<td>52.00</td>
<td>200</td>
<td>599</td>
<td>82.4</td>
</tr>
</tbody>
</table>

Crop value = $16.35/ton for sugar-cane

* Crop is sugar-cane with an estimated crop production cost of $245/acre. *Crop Production Function is shown in Appendix D.

γ*Maximum Net Farm Profit in $/acre

†Seasonal depth of irrigation water in inches
Effect of Runoff Water Prediction on System Design and Performance

The amount of runoff water, $R_f$, plays an important role in the design of IRRS and in evaluating the MNFP. Therefore, a careful estimation of runoff percentage, $R_f$, is needed in designing and evaluating furrow irrigation systems.

Several options for predicting the amounts of runoff water are available and applicable for a given set of conditions, and the designer must select one of them. In this section the two major methods are used for estimating the quantities of runoff water and analyzing system design, capacity, and operation associated with each one of them. The two methods compared are the traditional inflow-outflow method (explained in Chapter IV) and the three approaches of the runoff hydrograph method (presented and discussed in Appendix C).

Table 27 shows the results of an analysis where the four alternatives were used to design furrow irrigation systems for a given set of field conditions. The inflow-outflow method gave very high runoff percentages and a much larger storage reservoir as compared to the runoff hydrograph methods. It should be stated, however, that the results shown represent an analysis where the furrow stream size, $q$, the time of application per set, $T_s$, and the intake advance functions were fixed. Therefore, nearly the same $R_f$ values should be expected from all four options.
Table 27. Effect of the method of predicting the amounts of runoff water on system design and performance.

<table>
<thead>
<tr>
<th>Description</th>
<th>Inflow-Outflow</th>
<th>Runoff Hydrograph</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inflow EWF*</td>
<td>Runoff TIM†</td>
</tr>
<tr>
<td>q -gpm</td>
<td>10.10</td>
<td>10.10</td>
</tr>
<tr>
<td>( R_p )-%</td>
<td>35.4</td>
<td>11.1</td>
</tr>
<tr>
<td>Vol of storage reserv. -ac-ft-</td>
<td>4.16</td>
<td>0.56</td>
</tr>
<tr>
<td>Recirculating-pump flow rate -gpm-</td>
<td>162</td>
<td>161</td>
</tr>
<tr>
<td>Pump-back pipe size -inches-</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Vol. of unused runoff water -ac-ft-</td>
<td>3.58</td>
<td>-0.53</td>
</tr>
<tr>
<td>Recession time -minutes-</td>
<td>--</td>
<td>25</td>
</tr>
<tr>
<td>( N_s )</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>System cost -$/acre-</td>
<td>62.7</td>
<td>51.7</td>
</tr>
<tr>
<td>MNFP -$/acre-</td>
<td>302</td>
<td>313</td>
</tr>
</tbody>
</table>

* Elliptical-wetting front method (see Appendix C)
† Integrated-intake method (see Appendix C)
‡ Integrated-infiltration volume method (see Appendix C)
The large difference between the $R_f$ values may be attributed to the fact that the inflow-outflow method does not account for small factors which may affect the amount of runoff water, like surface storage and/or time of recession. Furthermore, small errors in measuring intake function (or functions) significantly affect the results obtained by the inflow-outflow method. Such errors are minimized by using the runoff hydrograph methods because this approach is based upon a finite integration process along the length of the run. On the other hand, the integration process included in the runoff hydrograph methods may minimize the errors introduced by inaccurate intake measurements but may accumulate more computational errors during the integration operations because such operations are based upon the approximate trapezoidal rule.

In Table 27 there is little difference between the predicted MNFP values from the four options. The maximum difference was only $11/acre which can be introduced by small errors in measuring the intake function. For the inflow-outflow method more runoff water was left in the storage reservoir at the end of irrigation which contributed to high irrigation costs, thus less net farm profits.

One conclusion could be made at this stage and that is the method of predicting the amounts of runoff bears little difference on the expected MNFP but it may affect the capacity of some of the design elements of IRRS because of under- or over-estimating the percentages of runoff water.
Modeling of furrow irrigation proved to be very effective in optimizing system design. The procedure developed in this research provides the engineer with a valuable tool to optimally allocate the resources and maximize net farm profit from the system.

The optimization process developed herein begins with land grading design by which the slope of the irrigated land is chosen. The land slope and soil type are used to predict a maximum non-erosive furrow stream size and water advance function down the furrow channel. An average depth of infiltration per irrigation is then assumed and used to predict the wetting profile along the furrow and the amount of runoff water. Then a design of an Irrigation Runoff Recovery System, IRRS, is executed, when needed, and total irrigation cost is calculated using the available cost data. The gross return and the net farm profit for that particular design are estimated by using the predicted wetting profile and the appropriate Crop Production Function, CPP. This procedure is repeated by changing the average depth of application per irrigation and evaluating the net farm profit until an application depth and an associated system design and management strategy which yield the highest net farm profit are found.

At the present time the model presented is subjected to some limitations, the first of which is that a uniform irrigation water
application program is assumed during the whole irrigation season. In other words, the same irrigation with the same depth of application is repeated at uniform time intervals during the season. In reality, light applications are needed only in the early stages of crop growth and heavier applications should be used as the roots develop and extend deeper. Another limitation is that the design and optimization processes are based upon an average furrow stream size and furrow advance and intake functions, i.e., variations of stream size and intake characteristics from furrow to furrow or between irrigations are not included. Such variations in furrow stream size and intake characteristics are unavoidable under real field conditions and must be considered in the analysis. The third major limitation to the model is that for a given optimization process the external design factors are held constant. For example, available supply stream discharge and all costs and values of system constituents are held constant. When some change is introduced on any one of these factors, a new optimization process is needed to execute optimal design and management strategy that fit the new set of conditions.

The model presented was also used in conducting sensitivity analyses to study the effect of major design elements on overall system performance. From the analysis presented earlier it was concluded that furrow intake function, \( I \), significantly affects system design, cost, and Maximum Net Farm Profit, MNFP. It was pointed out that in searching for an optimum furrow stream size, \( q \), the accompanying variation in intake function should be considered; otherwise erroneous values will be obtained. An empirical method of
relating \( I \) and \( q \) was suggested, used in this research, and found to
give adequate results. However, currently it seems necessary to
investigate the relationship between \( I \) and \( q \) in more general terms.

Furrow stream size, \( q \), greatly influences system cost and \( MNFP \)
because \( q \) influences furrow intake characteristics, time of appli-
cation per irrigation, and amounts of runoff water. An optimum \( q \) can
be obtained by investigating \( MNFP \)'s associated with several \( q \) values
then the stream size which yields the highest \( MNFP \) should be selected,
provided it gives a practical design and management strategy. It
was found, for instance, that when no \( IRRS \) is utilized \( MNFP \) can be
continually increased as \( q \) is decreased up to a point where \( q \) will be
limited because of very long times of advance required. However,
when an \( IRRS \) is used, the influence of \( q \) on \( MNFP \) and system performance
is small due to balancing \( IRRS \) capacity and time required to apply the
desired average depth of application on the entire field.

Water advance-phase exhibited minor effects on the calculated
\( MNFP \), especially on medium- or heavy-textured soils. No appreciable
difference was noticed among the \( MNFP \)'s evaluated by using several
advance prediction techniques which suggests that the method of
estimating advance function is insignificant. This is true for two
reasons, first is the fact that the advance time constitutes a small
part in the irrigation water application cycle, and second, is that
all the advance prediction techniques yield almost the same results and
therefore lead to nearly the same system design and \( MNFP \).

The predicted sub-surface wetting profile along the furrow
varies from a linear to a curvilinear pattern depending on the method
of analysis used. The variation between the two extreme patterns diminishes as the time of application increases because the intake function is assumed to be a decay function and the rate of infiltration decreases as time of opportunity increases. The wetting pattern showed no significant effect on MNFP which points out that no sophisticated prediction is needed to get the exact shape of the wetting front.

The variation of MNFP and system cost as a function of uniformity of infiltration was also analyzed for several soil and crop types. It was found that water application with extremely low Distribution Uniformity, DU, values result in very poor yield and high values are expensive to obtain, and thus may not be justified by the crops grown. An optimum range of DU's seems to exist over which no gain or loss in MNFP is obtained. Thus, the choice of a desired DU in that optimum range depends on personal preference.

*Irrigation Runoff Recovery Systems, IRRS's* play important roles in the design of furrow irrigation systems. It was found that for a given set of conditions, a break-even point can be located where there will be no difference between furrow irrigation systems with and without IRRS's. Such break-even points depend on the variables considered and the function being evaluated. Several cases were presented to demonstrate the variation of MNFP and system cost with runoff percentages, $R_f$'s, and system capacity.

Methods of performing land grading designs affect overall system design by placing two main constraints, the first of which is the calculated land slope and the second is the cost of land grading
operations. Land slope, in turn, affects water advance down the furrow channel but recalling that the water advance phase has a negligible effect on MNFP which implies that land slope does not affect overall system performance. The land grading cost varied depending on field topography, but when the cost is amortized over the entire life of the system, taking into account current Compound Interest Rate, i, then the net effect of the variation of land grading costs became negligible.

Based upon the soil type and field conditions considered in the analysis it was found that longer furrows and smaller stream sizes are recommended since the increased uniformity contributes to higher yields and MNFP's. Furthermore, long runs facilitate cultivation operations since they reduce the number of turns needed at the ends of the runs. More investigation is required on other soils and for other field conditions to study the effect of shortening furrow lengths on the cost increase associated with cultivation practices.

It was found that increasing either water cost, water lift, and/or crop value requires more uniform water applications and less total depth of applied water. In some cases increasing any one of the above factors may not change system design because such change depends on the magnitude of the increase.

The method of predicting the amount of runoff water seems to affect the expected volumes of runoff water and the capacity of some parts of the IRRS used. However, no significant effect was exerted on the predicted MNFP by the method of predicting runoff water. Further analysis is encouraged to explore the net effect of estimating runoff
water on system performance for various soils, furrow stream sizes, crops, and furrow lengths.

Based upon the results of the sensitivity analysis presented in Chapter VI, the land grading and the system design models can be combined together to eliminate the existing man-machine interface and to consolidate the two models. The flow charts shown in Figures 6 through 8 are reconstructed and shown in Figure 25, where the design routes are limited to the most efficient ones. A new computer model should now be developed following the flow chart given in Figure 25.
Figure 25. Consolidated flow chart of furrow irrigation system design and optimization model.
CHAPTER VIII
SUGGESTIONS AND RECOMMENDATIONS FOR IMPROVEMENTS AND FURTHER STUDY

The foregoing analyses lead to the following suggestions and recommendations to improve the current status of the model:

1. Using the flow chart given in Figure 25 to construct a new consolidated computerized model of furrow irrigation system design.

2. Reconstructing some parts of the model to be applicable to the design and optimization of border and basin irrigation methods.

3. Including in the optimization process a rationale to account for cross-row variation in the intake function in addition to the row-wise variation. This can be done in several ways, one of which seems to be easy and promising, and that is to assume the variation in the intake characteristics across the field follows a normal distribution. The crop yield is thence predicted by integrating the double-level wetting pattern vs. Crop Production Function, CPF. Some work is already being attempted by the writer to verify this procedure, but still more analysis is needed.

4. Studying the variation of intake function with furrow stream size since this forms an essential piece of data for the developed optimization process. No such study or analysis could be located at the present time which emphasizes the need for more investigations and field trials to enable the designer to predict
intake functions for other stream sizes from two or three trials. An empirical method was suggested and used in this report and was found to give very good results. Some work has already been done by Powell (62) but still more investigations are needed.

5. Modifying the rationale of *Irrigation Runoff Recovery Systems*, IRRS, design first developed by Stringham and Hamad (81) to obtain more flexible system design and account for variations in intake function during the irrigation season which may affect the amount of runoff water predicted hence system capacity. Furthermore, some form of intermittent pumping-back could be included to reduce the size of the storage reservoir required to hold runoff water.
<table>
<thead>
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<th>References</th>
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<th>Year</th>
<th>Title</th>
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<tbody>
<tr>
<td>1</td>
<td>Al-abdulla, T. I.</td>
<td>1965</td>
<td>Effect of some physical parameters on soil intake rates.</td>
<td>Ph.D. Dissertation, Department of Agricultural and Irrigation Engineering, Utah State University, Logan, Utah 84322.</td>
</tr>
</tbody>
</table>


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<table>
<thead>
<tr>
<th>No.</th>
<th>Author(s)</th>
<th>Year</th>
<th>Title and Details</th>
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<tr>
<td>41</td>
<td>Lim, Lam Kheng</td>
<td>1966</td>
<td>Analysis of application efficiency as related to intake function and recession function for surface irrigation. M.S. Thesis, Department of Agricultural and Irrigation Engineering, Utah State University, Logan, Utah.</td>
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<tr>
<td>43</td>
<td>Marr, J. C.</td>
<td>1967</td>
<td>Furrow irrigation. California Agricultural Experiment Station, Manual No. 37, Davis, California.</td>
</tr>
<tr>
<td>44</td>
<td>Marr, J. C. n.d.</td>
<td></td>
<td>The border method of irrigation. California Agricultural Experiment Station, Circular 408., Davis, California.</td>
</tr>
<tr>
<td>47</td>
<td>Merriam, J. L. and J. Keller</td>
<td>1973</td>
<td>Irrigation system evaluation and improvement. CUSUSWASH 211(d)-4, Department of Agricultural and Irrigation Engineering, Utah State University, Logan, Utah.</td>
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<tr>
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<td>1941</td>
<td>The influence of slope on erosion in small irrigation furrows. M.S. Thesis, Department of Civil Engineering, Utah State University, Logan, Utah.</td>
</tr>
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Appendix A.

Maximum Non-erosive Surface Irrigation Stream Size
for Graded Furrows and Borders

Introduction

The analysis presented herein is a refinement of a previously-developed empirical method for predicting non-erosive surface irrigation stream sizes using slope and soil characteristics. The method was first suggested by Gardner and Lauritzen (27) where they used the continuity concept to predict the rate of erosion for a given stream as follows

\[
\frac{\partial G_d}{\partial t} = \frac{\partial \sigma}{\partial t} + \frac{\partial \nu \sigma}{\partial x}
\]  

where

- \(G_d\) = depth to which the soil has worn down at time, \(t\)
- \(t\) = time since the water has reached point \(x\), or time of opportunity
- \(x\) = distance down the slope
- \(\nu\) = mean velocity of flow at point \(x\) and time \(t\)
- \(\sigma\) = silt content per unit area of the eroding surface.

Since the silt content per unit area, \(\sigma\), is difficult to determine, they assumed the following empirical relationship

\[
\sigma = \sigma_0 e^{-f't} = \sigma_0 (1 - e^{\alpha'x}) e^{-f't}
\]
where

\[ f' = \text{a function of } a \text{ to be determined} \]
\[ \sigma_o = \text{silt content at the water front} \]
\[ \sigma_w = \text{silt content of the stream when loaded to capacity which} \]
\[ \text{is a function of stream size, bed slope, and soil} \]
\[ \text{characteristics} \]
\[ a' = \text{a coefficient} \]

Equations 86 and 87 were then combined and integrated using the boundary conditions that \( G_o = 0 \) @ \( t = 0 \), to find the functions \( f' \) as follows

\[ f' = \frac{\beta}{x} \left( 1 - e^{-\alpha s} \right) \]  \[ \text{[88]} \]

where

\[ e = \text{base of natural logarithm} \]
\[ \alpha_s \text{ and } \beta_s \text{ are functions of stream size, bed slope, and soil characteristics.} \]

To illustrate the use of the developed analysis, they assumed the function \( \beta_s \), critical stream size, and bed slope can be empirically related by

\[ q_c = \alpha_s \beta_s \]  \[ \text{[89]} \]

where
\[ q_c = \text{a critical non-erosive furrow stream size, lps (gpm)} \]
\[ \alpha_S = \text{a soil parameter} \]
\[ S_o = \text{slope of the channel bottom expressed as a percentage} \]
\[ \beta_S = \text{an exponent} \]

Their experiment showed a very good agreement between calculated and measured rates of erosion which implied that the empirical relationships given by Equations 87, 88, and 89 were adequate for their test conditions.

No attempt has been done since then to find the values of the coefficients \( \alpha_S \) and \( \beta_S \) in Equation 89 for different soil types. However, the refinement made on the method presented above was to find the values for the coefficients in Equation 89 for six major soil types, both for furrow and border irrigation methods.

**Analysis and results**

The values of the coefficients in Equation 89 can be evaluated by statistically correlating non-erosive stream size and bed slope. Data of measured non-erosive furrow and border stream sizes in different soil types, locations, and initial moisture conditions, gathered by Criddle, et al. (17) in seventeen Western United States, were statistically analyzed.

The coefficients in Equation 89 were evaluated by applying a simple linear regression analysis to the logarithmic expression of Equation 89 as follows
\[ \log q_c = \log a_s + \beta_s \log S_o \]  \hspace{1cm} [90]

or

\[ G_v = A_s + \beta_s U \]  \hspace{1cm} [91]

where

- \( G_v \) = a variable representing \( \log q \)
- \( U \) = a variable representing \( \log S_o \)
- \( A_s \) = a coefficient representing \( \log a_s \).

Figure 26 is a plot of \( q \) vs. \( S_o \) for soil type III showing the correlation between the two variables. Table 28 gives the values of the coefficients \( a_s \) and \( \beta_s \) for six major categories of soils using furrow and border methods of irrigation.

**Summary**

The above analysis indicates that non-erosive surface irrigation stream size can be predicted by knowing the soil type and bed slope. Equation 89 and the values of the coefficients given in Table 28 can be used in the design of surface irrigation systems to eliminate the hazard of erosion, reduction of soil fertility, and downstream contamination.
Figure 26. Relationship between furrow slope and maximum non-erosive furrow stream size for soil type III.
Table 28. Values of the coefficients $\alpha$ and $\beta$ for different soil types using furrow and border methods of irrigation.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>Furrow Irrigation</th>
<th>Border Irrigation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha$ -gpm-</td>
<td>$\beta$</td>
</tr>
<tr>
<td>I</td>
<td>14.144</td>
<td>-0.937</td>
</tr>
<tr>
<td>II</td>
<td>15.666</td>
<td>-0.550</td>
</tr>
<tr>
<td>III</td>
<td>9.712</td>
<td>-0.733</td>
</tr>
<tr>
<td>IV</td>
<td>10.216</td>
<td>-0.704</td>
</tr>
<tr>
<td>V</td>
<td>17.605</td>
<td>-0.615</td>
</tr>
<tr>
<td>VI</td>
<td>10.543</td>
<td>-0.548</td>
</tr>
</tbody>
</table>

* I Very heavy-textured soil with very slow permeable subsoil and substratum. Depth to the impermeable layer is more than 36 inches.

II Moderately heavy-textured soil with slow permeable subsoil and substratum. Depth to the impermeable layer is 20 to 36 inches.

III Medium-textured soil with moderately slow permeable subsoil and substratum. Depth to the impermeable layer is 20 to 36 inches.

IV Medium-textured soil with moderately slow permeable subsoil and substratum. Depth to the impermeable layer is 10 to 20 inches.

V Light-textured soil with moderately permeable subsoil and substratum. Depth to the impermeable layer is 10 to 20 inches.

VI Very light-textured soil with moderately rapid permeable subsoil and substratum. Depth to the impermeable layer is less than 10 inches.
Appendix B.

An Approach to Predict Water Advance

In Furrow Irrigation

Theory and analysis

The analysis presented herein shows the development and comparison of two procedures to predict the advance of water in furrow irrigation. Both methods are based upon the continuity concept where part of the applied water is infiltrated below the ground surface and the other part is stored in the furrow channel. The two main assumptions in the analysis are: (a) constant furrow stream size at furrow inlet; and (b) prismatic furrow channel with uniform slope along the furrow.

The first procedure is depicted in Figure 27 where the water profile above and below the ground surface during the time of advance is shown at a given instant of time. An exact calculation of the advance distances can be obtained if the equations describing the shapes of the water and wetting fronts are known. Both fronts may take any shape depending on soil and furrow characteristics. The possible shapes of the two fronts are bounded by a triangular and a rectangular shape as shown by the dotted lines in Figure 27 and may take any shape within those bounds. Since actual field measurements of the profiles are extremely difficult, the shape of either front, for a given soil, can be assumed, the prediction process performed,
the results matched with actual field data, and the shape of the front which best-approximates the field trial chosen.

The second procedure uses the same method of calculating the surface storage volume but uses an integration process to find the accumulated volume of infiltrated water. The furrow is divided into small segments and at any given instant, the average intake rates for each length segment are summed to get the total volume of infiltrated water at that instant.
The two procedures are discussed in more details in the following sections. To conserve clarity in this paper, water stored on the surface and infiltrated will be analyzed separately, and later combined.

**Surface storage**

Surface storage is a function of the water surface profile and the geometry of the furrow. To study the effect of the water surface profile on the advance distance, an elliptical, a parabolic, and a linear profile were each superimposed on a trapezoidal and a parabolic furrow channel. For brevity, only the analysis of the elliptical profile is presented in detail. The analysis for the other two are similar.

I. If the furrow is of prismatic trapezoidal cross-section as shown in perspective in Figure 28, the total volume is the sum of the rectangular center section and the two triangular side wedges. At any given time instant, the equation of the ellipse describing the water surface profile is

\[ \frac{d^2}{d_0^2} + \frac{x^2}{X_1^2} = 1 \]  \[ [92] \]

where

\[ d = \text{depth of water in the furrow at any given distance } x, \text{ ft (m)} \]
\[ d_0 = \text{depth of water in the furrow at the head, ft (m)} \]
\[ x = \text{any given distance down the furrow measured from the head, ft (m)} \]
\[ X_1 = \text{length of advance at time } t, \text{ ft (m)}. \]

Thus

\[ d = d_0 \sqrt{1 - \frac{x^2}{X_1^2}} \tag{93} \]

and the volume of the central part in Figure 28 would be

\[ V'_c = \frac{X_1}{2} B_t d \, dx = 0.785 B_t d_0 X_1 \tag{94} \]

where

- \( V'_c \) = volume of the central part of storage, cu ft (cu m)
- \( B_t \) = bottom width of a prismatic, trapezoidal furrow channel, ft (m).

The volume of the two side edges will be given by

\[ V_w = 2 \int_0^{X_1} \frac{a'd}{2} \, dx = \int_0^{X_1} Z d \, d_0 \sqrt{1 - \frac{x^2}{X_1^2}} \]

\[ = 0.667 Z d_0^2 X_1 \tag{95} \]

where

- \( V_w \) = volume of wedge storage, cu ft (cu m)
- \( Z \) = side slopes of a prismatic, trapezoidal furrow channel.

Therefore, the total volume of storage is

\[ V_{et} = 0.785 B_t d_0 X_1 + 0.667 Z d_0^2 X_1 \]

\[ = (0.785 B_t + 0.667 Z d_0) X_1 d_0 \tag{96} \]
Figure 28. Perspective and projections of a prismatic trapezoidal furrow channel.
where

\[ V_{et} = \text{volume of surface storage using elliptical water front and trapezoidal furrow cross-section, cu ft (cu m)} \]

A similar analogy can be followed but assuming the shape of the water profile is described by an \( r \)-th-degree parabola with the vertex at the tip of the front, as shown below

\[
\hat{d} = (1 - \frac{x}{X_1})^{1/r}
\]

where

\[ r = \text{degree of the parabola considered.} \]

Therefore, the volume of storage will be given by

\[
V_{et} = \left( \frac{n}{r + 1} B_t + \frac{n}{r + 2} Z d_o \right) X_1 d_o
\]

If the shape of the water front were assumed to be linear, the volume of surface storage would then be given by

\[
V_{et} = (0.500 B_t + 0.333 Z d_o) X_1 d_o
\]

II. If the furrow is of a prismatic, \( sth \)-degree parabolic cross-section as shown in Figure 29, the furrow channel cross-section at any distance, \( x \), can be considered by

\[
d = h' b_x^s
\]

where

\[ b_x = \text{top width of the water way at any distance } x, \text{ ft (m)} \]
Figure 29. Cross-section of a furrow channel described by a second-degree parabola.

$h' = a$ coefficient which is equal to $d / B_p^s$

$B_p = \text{top width of a parabolic water way at the head of the furrow, ft (m)}$

$s = \text{degree of the parabola considered.}$

Therefore, Equations 93 and 100 can be combined and integrated from 0 to $X_1$ to get the volume of surface storage at any time $t$, as follows
\[ V_{ep} = \left[ 0.88623 \frac{B}{p} \frac{s}{s + 1} \frac{\Gamma(\frac{1+3s}{2})}{\Gamma(\frac{1+4s}{2})} \right] X_1 d_o \]  

where

\[ V_{ep} = \text{volume of surface storage using elliptical water front and}\]

\[ s^{th}\text{-degree furrow cross-section, cu ft (cu m)} \]

\[ \Gamma = \text{the gamma function}. \]

Similarly, by using an \( n^{th}\)-degree parabolic water front with the vertex at its tip, the volume of surface storage will be given by

\[ V_{ep} = \left[ \frac{n s^2}{(s+1)(s+1+nr)} \right] X_1 d_o \]  

and, for a linear water front, the storage volume is obtained by

\[ V_{er} = \left[ \frac{s^2}{(s+1)(2s+1)} \right] X_1 d_o \]

As can be seen from the above analysis that for any cross-sectional geometry and water front shape, the volume of surface storage can be written as follows

\[ V_{st} = \lambda d_o X_1 \]

where

\[ V_{st} = \text{volume of surface storage at any time } t, \text{ cu ft (cu m)} \]

\[ \lambda = \text{surface storage coefficient which depends on the water way cross-section and water front shape, ft (m)}. \]
Infiltrated water

If an elliptical wetting front shape is assumed, the volume of infiltrated water at any time \( t \), will be

\[
V_{i\theta} = \frac{0.785}{K_1} \cdot \frac{d_u}{x_1} \cdot \omega_b
\]  

[105]

where

- \( V_{i\theta} \) = volume of infiltrated water at any given time \( t \), cu ft (cu m)
- \( d_u \) = accumulated depth of infiltrated water at the head of the furrow, inches (mm)
- \( \omega_b \) = an imaginary width of the wetted bulb, ft (m).

From furrow inflow-outflow measurements, an intake function can be developed and assumed to be of the following exponential order

\[
I = K \cdot t^n
\]  

[106]

where

- \( I \) = intake rate at any time \( t \), gpm/ft (lps/m)
- \( K \) = coefficient of Kostakov intake function
- \( n \) = exponent of Kostakov intake function, always less than zero
- \( t \) = time of opportunity, minutes.

and integrating Equation 106 gives the accumulated volume of infiltrated water at any time \( t \), as follows
\[ V_{ai} = \frac{K}{K_{19} \ (n+1)} \ t^{n+1} \]  

where

\[ V_{ai} \] = accumulated volume of infiltration at any time \( t \), cu ft/ft (cu m/m)

\( K_{19} \) = a constant which is equal to 7.48 for the English units and 16.667 for the metric units.

Furthermore, \( V_{ai} \) can be expressed by

\[ V_{ai} = \frac{d_i}{K_1} \ w_b \ (1 \text{ unit length}) \]  

and combining Equations 107 and 108 yields

\[ d_i = \frac{K \cdot K}{K_{19} \ w_b \ (n+1)} \ t^{n+1} \]  

where

\[ d_i \] = accumulated depth of infiltrated water at any time \( t \), inches (mm).

The accumulated depth of infiltration at the head of the furrow, \( d_u \), can be obtained from Equation 109 by substituting the proper time of opportunity.

Combining Equations 105 and 109 gives

\[ V_{ie} = \frac{0.785 \ K}{K_{19} \ (n+1)} \ x_1 \ t^{n+1} \]  

[110]
For an \( r \)th-degree parabolic front, the accumulated volume of infiltration will be given by

\[
V_{ie} = \left[ \frac{r}{r+1} \frac{K}{K_{19} (n+1)} \right] X_{1} t^{n+1}
\]

[111]

and for a linear wetting front the accumulated volume of infiltration

\[
V_{ie} = \left[ \frac{0.500 K}{K_{19} (n+1)} \right] X_{1} t^{n+1}
\]

[112]

More generally, for any wetting front shape, the accumulated volume of infiltration at any time \( t \), is given by

\[
V_{i} = \phi X_{1} t^{n+1}
\]

[113]

where

\( V_{i} \) = accumulated volume of infiltration, for any front shape, at time \( t \), cu ft (cu m)

\( \phi \) = infiltration coefficient which depends on the intake characteristics of the soil.

Advance distance

By knowing furrow stream size, time of application, volume of storage, and volume of infiltration, the advance distance, \( X_{1} \), at any time \( t \), can be obtained by equating the total volume of application to the accumulated volume of infiltration and the volume of surface storage. Thus, utilizing Equations 104 and 113 gives
or

\[ X_1 = \frac{q \ t}{K_{19} \ (\lambda \ \ddot{d} \ + \ \phi \ t^{n+1})} \]  

Equation 115 is similar to the prediction equation presented by Fok and Bishop (24) except that Equation 115 does not involve any empirical advance parameters.

Very often an empirical advance relationship is used in the design of furrow irrigation systems (24) which is expressed as follows

\[ x = a \ t^b \]  

or

\[ X_1 = a \ t^b \]  

Equation 72 has been found to closely-fit field data, but, when no field data are available, it is difficult to estimate the coefficients \(a\) and \(b\). However, since Equation 72 follows a straight line when plotted on a log-log paper, and for relatively high values of \(t\), Equation 115 also approaches a straight line, then the two equations can be analytically related to estimate the coefficients \(a\) and \(b\) in terms of furrow cross-section geometry and intake characteristics.

**Integrated intake method**

Another method of calculating the accumulated volume of infiltrated water would be by dividing the length of the furrow into small length segments and summing-up the average intake rate
over the individual segments to obtain the volume of infiltrated water. This method was originally proposed by Patterson (55). But, to estimate the volume of surface storage he assumed that it can be approximated by small segments as shown by the cross-hatched shapes in Figure 30, then he predicted the flow rate at the beginning of each segment and used Manning's Equation to find the flow depth at that location. This method can be very much simplified by using Equation 104 to estimate the volume of surface storage at any time $t$. Therefore, the accumulated volume of infiltrated water at any time will be given by

$$v(t) = \sum_{i=1}^{n} \left( \frac{2}{3} \frac{L_i}{X_i} d_i \right)$$

Figure 30. Longitudinal section through furrow surface storage showing the configuration of the water front.
\[ \Delta V_m = \frac{\Delta t}{K_{19}} \sum_{j=1}^{m} I_{i \Delta t} \Delta X_{m-j+1} \]  

[116]

where

- \( \Delta V_m \) = accumulated volume of infiltration when predicting the advance over the \( m_{1+1} \) length segment, cu ft (cu m)
- \( I_{i \Delta t} \) = intake rate evaluated at time \( i \Delta t \), gpm/ft (lps/m)
- \( \Delta X \) = incremental distance advanced in time \( \Delta t \), ft (m)
- \( m_1 \) = an index indicating the \( m \)th incremental distance
- \( j \) = a distance-summation index.

Furthermore, the volume of storage added when the distance \( \Delta X_{m+1} \) is advanced will be given by

\[
\Delta V_s = \lambda \, d_o \, \left[ \sum_{j=1}^{m+1} \Delta X_{j} - \sum_{j=1}^{m} \Delta X_{j} \right]
\]

[117]

or

\[
\Delta V_s = \lambda \, d_o \, \Delta X_{m_{1+1}}
\]

[118]

Thus

\[
q \, \Delta t = \lambda \, d_o \, \Delta X_{m_{1+1}} + \Delta V_{m_{1+1}} + I_{\Delta t} + \Delta V_m
\]

[119]

or

\[
\Delta X_{m_{1+1}} = \frac{q \, \Delta t - \Delta V_m}{\lambda \, d_o + I_{\Delta t}}
\]

[120]
The above analysis may seem very complicated to use, while if the incremental time, $\Delta t$, is kept constant, then the above iterative procedure will be greatly simplified especially with the use of computers.

Experiment and application

The above analyses have been tested using field data for two soils, a heavy clay and a medium-textured silt loam soils, and trapezoidal and rectangular furrow channels. Figures 31 and 32 show two trials one on each soil where several combinations of water and wetting front shapes, and integrated intake methods have been tested.

The shape of the surface storage seems to have a minor or negligible effect on the advance of water. For example, in Figure 31 the curve labeled $E$ was obtained by using an elliptical wetting front combined with an elliptical and a parabolic water fronts. The maximum difference between the two predictions was about 6.0 feet. Similar analysis was done on the curve labeled $S$ where a second-degree parabolic wetting front was combined with an elliptical and parabolic water fronts and no significant difference was found between the two results. Figure 32 depicts a similar phenomenon.

However, the shape of the infiltration pattern does give appreciable difference in the prediction accuracy. For example, the trial shown in Figure 31, which was done on a heavy clay, indicates that the second-degree parabolic wetting front bestfits that soil; while the trial shown in Figure 32, which was done on a
Figure 31. Actual and predicted advance functions on a clay loam soil (USDA Research Center at Kimberly, Idaho).
$E = \text{Elliptical front pattern}$

$S = \text{Second-degree-parabola front pattern}$

$I = \text{Intake Method}$

$\bullet = \text{Measured}$

$q = 7.61 \text{ gpm}$

Figure 32. Actual and predicted advance function on medium-textured silt loam soil (Idaho State Experiment Station).
medium-textured silt loam, indicates that the elliptical wetting front best fits that soil. Similar results were obtained from other trials, from which it is concluded that for heavy soils, a flat infiltration pattern would closely describe the actual shape, and for medium-textured soils, an elliptical or similar shape may be used to approximate field conditions.

The integrated intake method gives very close results on both soils since it depends mainly on intake measurements. The curves labeled \( I \) in Figure 31 and Figure 32 were obtained by using integrated intake combined with elliptical, parabolic, and linear water fronts. Again several runs indicate that the difference among the three water fronts was very small and hard to be depicted.

Comparison with other techniques

The two methods developed herein were compared with previously developed procedures. Figure 33 shows a comparison between the procedures developed by Fok and Bishop (24) and by the writer using data from Furrow 4 presented by Fok and Bishop (24) in their article. Figure 34 shows a comparison between the procedures developed by Fok and Bishop (24), Davis (20), Patterson (55), and the writer, together with actual field data from experiment on a clay loam soil.

As can be seen in Figures 33 and 34 that Fok and Bishop's approach (24) is the same as assuming an elliptical wetting front and elliptical, parabolic, and linear water fronts. The function predicted by using Davis' procedure (20) was very close to the actual field measurements at the beginning of the irrigation, then
Figure 33. Actual and predicted advance functions using previously developed and the presented techniques [data from Furrow #4, Fok and Bishop (24)].
Figure 34. Actual and predicted advance functions on a clay loam soil using various prediction techniques (USDA Research Center at Kimberly, Idaho).
it under-estimated the advance distance. This is because of assuming the values of the parameters in his equation and because the furrow channel was almost rectangular, thus the cross-sectional area cannot be expressed as a function of the square of the flow depth. The values predicted by using Patterson's procedure (55) were higher than the actual values, mainly because of under-estimating surface storage as was discussed earlier. On this particular clay loam soil, a parabolic wetting front seems to describe the actual wetting pattern and give a good estimation of the advance function, while the elliptical wetting front under-estimates the advance distance.

Summary and conclusions

Water advance in furrow irrigation can be predicted by knowing furrow and intake characteristics. Two procedures are presented which are based upon the continuity concept and assumed shapes of the water and wetting fronts. Several trails on a heavy clay and a medium-textured silt loam soil showed that the shape of the water front has very small effect on the accuracy of the predicted distances. Increasing the actual measured depth of flow at the head of the furrow by 50 percent reduced the predicted distance by a maximum of 4.5 percent from the predicted values using the actual normal depth of flow. Doubling the depth, i.e., 100 percent error caused a maximum of 7.0 percent error in the predicted distances using actual measured depth of flow. This indicates that for design purposes only an estimation of the normal depth of flow at the head of the furrow is necessary.
From the conducted field experiments it was indicated that for a heavy soil, a flat shape of the wetting front tends to give better results than deep, bulky shapes. For a light-textured soil, an elliptical wetting front or similar shape describes the shape of the wetting pattern. More research at this point should be done on other soil types to verify the shapes of the wetting fronts that fit a given soil type, thereafter, just knowing the soil texture and intake function would make a prediction of the advance function possible.
Appendix C.

Predicting Runoff Hydrographs From Furrow Irrigations

Theory and analysis

The prediction procedure presented herein is based on the continuity concept where part of the water applied is assumed to be infiltrated into the soil and the remainder appears as runoff at the end of the furrow. The method is based upon four assumptions:

1. Prismatic furrow channel with constant surface storage during the runoff time period.

2. Constant furrow stream size throughout the irrigation.

3. Intake rate can be expressed as an exponential function of the intake opportunity time.

4. The intake rate is constant during the time of recession and the receding runoff rate varies linearly with time.

In general, the runoff hydrograph rises very rapidly during the short time following the beginning of the runoff, then it keeps rising but at a small rate and reaches the maximum just when the water is turned-off. In most of the literature, it has been assumed that the runoff reaches a constant rate shortly after the water has reached the lower end. However, field measurements show that with constant furrow stream size, the runoff rate never becomes constant since the intake rate diminishes with the time. Toward the end of the irrigation, however, the variation in the intake rate is very small so the assumption of a constant flow rate may be justified.
Therefore, in this study, the runoff hydrograph is divided into two zones; a rising portion with rapidly rising and slowly rising parts and a recession portion.

In order to calculate the volume of infiltrated water at any time, during the rising portion of the runoff hydrograph, five techniques were developed, analyzed, and compared. These techniques are, at any time during the rising runoff hydrograph limb

1. The wetting front is assumed to be described by
   a. an ellipse;
   b. a second-degree parabola;
   c. a linear function of the distance along the furrow.

2. The inflow rate is equal to the intake rate integrated over the furrow length plus the runoff rate.

3. The inflow volume is equal to the accumulated volume of infiltration integrated over the furrow length plus the runoff volume.

Rising hydrograph portion

As was mentioned above, three assumed shapes of the wetting fronts are investigated. However, for brevity, the analysis of an elliptical front is presented here and only the results of the second-degree parabola and the linear functions are given.

Elliptical wetting front. A longitudinal section along the furrow which shows the wetting fronts at several instants of time is depicted in Figure 35. In order to find the accumulated volume of infiltration per unit length of furrow for any time increment,
Figure 35. Longitudinal section along the furrow showing the wetting front at several time instances.
Kostakov intake function

\[ I = K t^n \]  \[106\]

can be obtained from inflow-outflow measurements which, when integrated over time yields

\[ V_{ai} = \frac{K}{K_{19} (n+1)} t^{n+1} \]  \[107\]

Therefore, if the wetted area below the furrow has an imaginary width \( w_b \), then

\[ V_{ai} = \frac{d_i}{w_b} (1 \text{ unit length}) \]  \[108\]

or

\[ d_i = \frac{K_{19} V_{ai}}{w_b} = \frac{K_{19} K}{K_{19} w_b (n+1)} t^{n+1} \]  \[109\]

Furthermore, from Figure 35 the depth of infiltrated water and the distance along the furrow can be expressed as follows

\[ \frac{(d_{x1} - d_{x1}')^2}{(d_{u1} - d_{u1}')^2} + \frac{x^2}{L^2} = 1 \]  \[121\]

where

\( d_{x1} = \) accumulated depth of infiltrated water at the lower end of the furrow, inches (mm)
\( \dot{d}_{u1} \) = accumulated depth of infiltrated water at the upper end of the furrow, inches (mm)

\( \dot{d}_{x1} \) = accumulated depth of infiltrated water at station \( x \) down the furrow, inches (mm)

\( L \) = length of the furrow, feet (m)

\( x \) = a given distance down the furrow measured from the upper end, feet (m).

Simplifying Equation 121 yields

\[
\dot{d}_{x1} = \dot{d}_{l1} + (\dot{d}_{u1} - \dot{d}_{l1}) \sqrt{1 - \frac{x^2}{L^2}} \tag{122}
\]

and if a constant time increment, \( \Delta t \), is used then

\[
\dot{d}_{x2} = \dot{d}_{l2} + (\dot{d}_{u2} - \dot{d}_{l2}) \sqrt{1 - \frac{x^2}{L^2}} \tag{123}
\]

where

\( \dot{d}_{l2} \) = accumulated depth of infiltrated water at the lower end of the furrow \( \Delta t \) minutes after \( \dot{d}_{l1} \) had occurred, inches (mm).

\( \dot{d}_{u2} \) and \( \dot{d}_{x2} \) also occur \( \Delta t \) minutes after \( \dot{d}_{u1} \) and \( \dot{d}_{x1} \), respectively.

Thus, the volume of infiltration during \( \Delta t \) minutes is

\[
\Delta V = \frac{1}{K_1} \int_0^L (\dot{d}_{x2} - \dot{d}_{x1}) \, dx \tag{124}
\]
where

\[ \Delta V = \text{volume of infiltrated water during an increment of time } \Delta t, \text{ cu ft/ft width (cu m/m width)} \]

\[ \Delta t = \text{time increment, minutes.} \]

Combining Equations 122, 123, and 124 and integrating give

\[ \Delta V = 0.785 (d_{u2} - d_{u1}) + 0.215 (d_{l2} - d_{l1}) \quad [125] \]

Thus, if it is assumed that \( d_{l1} \) and \( d_{u1} \) occur \( i\Delta t \) after the water has reached the lower end, i.e., \( d_{l2} \) occurred in time \( i\Delta t \) and \( d_{u2} \) occurred in time \( t_a + i\Delta t \), then the accumulated volume of infiltrated water per unit width in time \( \Delta t \) will be obtained by combining Equations 109 and 125 as follows

\[ \Delta V = 0.785 \frac{KL}{K_{19} \omega_b (n+1)} \left[ (t_a + (i+1) \Delta t)^{n+1} - (t_a + i\Delta t)^{n+1} \right] + 0.215 \frac{KL}{K_{19} \omega_b (n+1)} \]

\[ \{ (i+1) \Delta t^{n+1} - (i \Delta t)^{n+1} \} \quad [126] \]

and the total accumulated volume of infiltration in the wetted area will be

\[ \Delta V_i = \Delta V \omega_b \]

\[ = a_e' \{(\beta_i + \Delta t)^{n+1} - (\beta_i)^{n+1}\} + (1 - a_e') \gamma_i \Delta t^{n+1} \quad [127] \]
where
\[ a' = \text{an elliptical front coefficient} \]

\[ = 0.785 \frac{K}{L/K^{19}} (n+1) \]  \[\text{[128]}\]

\[ \beta = \text{a parameter which is equal to } t_a + i \Delta t, \text{ minutes} \]

\[ \gamma_i = \text{a coefficient which is equal to } (i+1)^{n+1} - i^{n+1} \]

\[ i = \text{a time index} \]

\[ t_a = \text{time required for the water to reach the end of the furrow or time of advance, minutes.} \]

Therefore, the average runoff rate will be

\[ q_{ir} = q - \frac{\Delta V_i}{\Delta t} \]  \[\text{[129]}\]

where

\[ q_{ir} = \text{runoff stream size at any time } t, \text{ gpm (lps).} \]

and combining Equations 128 and 129 gives

\[ q_{ir} = q - \frac{a'}{\Delta t} \left\{ (\beta + \Delta t)^{n+1} - (\beta)^{n+1} \right\} \]

\[ - (1 - a') \gamma_i (\Delta t)^n \]  \[\text{[130]}\]

Therefore, the runoff rate \( q_{ir} \) can be estimated at various time periods by changing the index, \( i \).

Parabolic wetting front. When the wetting front is assumed to be described by a second-degree parabola, then a similar analysis given in Equations 121 through 129 can be used to calculate \( q_{ir} \). The
resulting relationship is similar to Equation 130 with $a'_e$ replaced by $a'_p$, where

$$a'_p = \text{a parabolic front coefficient}$$

$$= 0.667 \frac{K L}{K_{19} (n+1)} \quad [131]$$

**Linear wetting front.** If during the time of rising runoff hydrograph limb, the depth of infiltration is assumed to vary linearly with the distance along the furrow, then a similar analogy can be followed to develop a relationship similar to Equation 130 with $a'_e$ replaced by $a'_l$ where

$$a'_l = \text{a linear front coefficient}$$

$$= 0.500 \frac{K L}{K_{19} (n+1)} \quad [132]$$

The choice of the proper wetting front for prediction purposes depends mainly on the soil type. However, application of the above three shapes to two soils and several replications showed that the shape of the wetting front does not affect the predicted runoff rates significantly.

**Integrated intake method**

The volume of infiltrated water during any given time increment, $\Delta t$, can be estimated by dividing the total length of the furrow into small segments and summing-up the average intake rate over individual length segments as shown below
\[ \Delta V_i = \frac{\Delta t}{K_{19}} \sum_{j=1}^{m_2} I_{ij} \Delta X_{m_2-j+1} \]  

where

\( \Delta V_i \) = accumulated volume of infiltrated water along the furrow length at \( i \Delta t \) minutes after runoff began, cu ft (cu m)

\( I_{ij} \) = intake rate evaluated on a given length segment, \( j \), \( i \Delta t \) minutes after runoff began, gpm/ft (lps/m)

\( \Delta X_{ij} \) = length segment, ft (m)

\( m_2 \) = number of length segments.

The intake rate on a given length segments, \( I_{ij} \), should be evaluated at the proper time of opportunity. Therefore, for length segment, \( j \), at any time \( t \) since the beginning of irrigation, the time of opportunity will be

\[ t_{ij} = t - t_{a_j} \]

where

\( t_{ij} \) = time of opportunity \( i \Delta t \) minutes after the runoff began, minutes

\( t \) = time since the beginning of irrigation, minutes

= time of application, minutes

\( t_{a_j} \) = time required for the water to reach length segment \( j \), minutes.

Since a constant time increment is assumed, then after runoff began the time since the beginning of irrigation can be written as follows
\[ t = t_a + i \Delta t \]  

[135]

and if the empirical advance function

\[ x = a t^b \]  

[72]

is used to estimate the time of advance, then, the time of opportunity on any length segment, \( j \), \( i \Delta t \) minutes after runoff began can be obtained by combining Equations 134, 135 and 72 as follows

\[
t_{ij} = \left( \frac{L}{a} \right)^{1/b} + i \Delta t - \left( \frac{\sum_{k=1}^{\Delta X} k}{a} \right)^{1/b}
\]  

[136]

Therefore, the average runoff rate at time \( i \Delta t \) after the beginning of runoff can be obtained by combining Equations 108, 133, and 136 as shown below

\[
q_{ir} = q - \frac{1}{K_{19}} \sum_{j=1}^{m_2} I(t_{ij}) \frac{\Delta X}{m_0 - j + 1}
\]  

[137]

where

\[ I(t_{ij}) = \text{intake rate evaluated at } i \Delta t \text{ minutes after the runoff began, gpm/ft (lps/m).} \]

Equations 136 and 137 give a good estimation of the runoff rate, \( q_{ir} \), at any time \( i \Delta t \) after the beginning of the runoff.

**Integrated depth method**

The accumulated depth or volume of infiltrated water during any time increment can be calculated by summing-up the depth of
infiltrated water over individual length segments as was done in the integrated intake method. Thus using Equations 107 and 136, the accumulated volume of infiltrated water would be

$$\Delta V_t = \frac{K}{K_{19} (n+1)} \sum_{j=1}^{m_2} (t_{i,j}^{n+1}) \Delta X_{m_2-j+1}$$ \[138\]

and the average runoff rate at time $i \Delta t$ after the beginning of the runoff would be

$$q_{ir} = q - \frac{K}{K_{19} (n+1)} \frac{m_2}{\Delta t} \sum_{j=1}^{m_2} (t_{i,j}^{n+1}) \Delta X_{m_2-j+1}$$ \[139\]

as can be seen that Equations 137 and 139 are analytically similar but Equation 139 is based upon the concept of average depth of infiltration while Equation 137 is based upon the average rate of infiltration over a length segment.

Receding hydrograph section

Recession of water in furrow irrigation usually takes a short time period and in most cases is not as important as it is in border irrigation. However, a close estimation of the recession time can be made if the receding runoff rate is assumed to vary linearly with the time of recession and that the intake rate is at its basic value and varies linearly with the time. In graded furrows, the water first recedes at the head of the furrow and the recession proceeds downstream. Thus, using the above assumptions and Figure 36, the time of recession can be estimated as follows
Figure 36. Schematic diagram showing the rising and the receding limbs of a typical runoff hydrograph from furrow irrigation.
\[ V_s = \left( \frac{q_p}{2} + \frac{L I_t}{2} \right) \frac{t'_r}{K_{19}} \]

or

\[ t'_r = \frac{2 K_{19} V_s}{q_p + L I_t} \] \[140\]

where

- \( t'_r \) = time of recession after the water has been turned-off, minutes
- \( V_s \) = volume of surface storage which is equal to furrow channel cross-sectional area times furrow length, cu ft (cu m)
- \( q_p \) = peak runoff rate, gpm (lps)
- \( I_t \) = intake rate evaluated at the time when the water is turned-off, gpm/ft (lps/m).

Field experiments showed that recession does not start instantaneously as the water is turned-off, but usually stays for a few minutes at \( q_p \) then decreases. However, this should not cause too big an error in the total runoff time period since for full irrigations the total runoff period may be in the order of a few hours rather than a few minutes.

**Experiment and application**

Field experiments on silt loam and heavy clay loam soils showed good agreement between predicted and measured runoff rates. Figures 37 and 38 are two trials on silt loam soil from which it
Figure 37. Measured and predicted runoff hydrographs for furrow stream size of 7.61 gpm on a silt loam soil.
Figure 38. Measured and predicted runoff hydrographs for furrow stream size of 8.88 gpm on a silt loam soil.
can be seen that no significant difference exists between the various techniques of predicting the runoff hydrograph. Assuming a given shape of the wetting front made a small difference only in the first few minutes after runoff began, thereafter, the three techniques depicted by Equations 130, 131, and 132 gave the same results as shown in Figures 37 and 38 by one single curve. The predicted hydrographs plotted in Figure 39 are results from actual field trial on a heavy clay loam soil and confirms that there is no significant difference between the predicted hydrographs using the various techniques presented in the text.

Furthermore, it can be seen from Figures 37, 38, and 39 that the predicted hydrographs first under-estimate then over-estimate runoff rates, hence the total predicted volume of runoff almost the same as the actual volume.

Another interesting phenomenon is depicted in Figure 37 through Figure 39 and that is the actual recession limb of the hydrograph is very close to a straight line which verifies the assumption made in the text.

A detailed Fortran IV computer program has been developed to perform the interactive procedure, predicts the recession time, and calculates the percentage of runoff water.

Summary

Runoff water prediction from furrow irrigation is a necessary element in the design of Irrigation Runoff Recovery Systems, IRRS's. Five techniques are presented to estimate the hydrographs and
Figure 39. Measured and predicted runoff hydrographs for a furrow stream size of 7.11 gpm on a heavy clay loam soil.
volumes of runoff water using furrow intake and advance functions. The developed procedures give a good approximation of the runoff hydrographs and there is no significant difference among the predicted volumes using the various approaches.
Appendix D.

Input Data and SI Conversions

Table 29 gives a list of the soil types used in the sensitivity analysis and the advance and intake characteristics of each soil. Table 30 provides some SI conversion factors for the measurement units used in the text.

Figure 40 shows the Crop Production Functions for sugar-cane and corn crops used in the sensitivity analysis and Figures 41 through 43 give the original ground elevations for the fields used in the study.

Table 29. Intake functions for various soil types used in the sensitivity analysis.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>I-gpm/ft-</th>
<th>K</th>
<th>x-feet-*</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$K t^{-0.510}$</td>
<td>0.0900 $q^{0.000}$</td>
<td>80.20 $t^{0.674}$</td>
</tr>
<tr>
<td>B</td>
<td>$K t^{-0.550}$</td>
<td>0.0195 $q^{0.785}$</td>
<td>76.70 $t^{0.430}$</td>
</tr>
<tr>
<td>C</td>
<td>$K t^{-0.220}$</td>
<td>0.0110 $q^{0.995}$</td>
<td>43.84 $t^{0.622}$</td>
</tr>
<tr>
<td>D</td>
<td>$K t^{-0.555}$</td>
<td>0.0125 $q^{1.090}$</td>
<td>45.00 $t^{0.280}$</td>
</tr>
<tr>
<td>E</td>
<td>$K t^{-0.333}$</td>
<td>0.0230 $q^{0.225}$</td>
<td>45.23 $t^{0.668}$</td>
</tr>
<tr>
<td>F</td>
<td>$K t^{-0.372}$</td>
<td>0.1410 $q^{0.000}$</td>
<td>30.23 $t^{0.810}$</td>
</tr>
</tbody>
</table>

* Empirical advance function obtained from field trials.
Table 30. SI conversions for the measurement units used in this report.

<table>
<thead>
<tr>
<th>To convert</th>
<th>From</th>
<th>To</th>
<th>Multiply by</th>
</tr>
</thead>
<tbody>
<tr>
<td>inches</td>
<td>mm</td>
<td></td>
<td>25.40</td>
</tr>
<tr>
<td>feet</td>
<td>meters</td>
<td></td>
<td>0.3048</td>
</tr>
<tr>
<td>acres</td>
<td>hectares</td>
<td></td>
<td>0.4049</td>
</tr>
<tr>
<td>cu ft</td>
<td>cu m</td>
<td></td>
<td>0.0283</td>
</tr>
<tr>
<td>cu yd</td>
<td>cu m</td>
<td></td>
<td>0.7646</td>
</tr>
<tr>
<td>ac-in</td>
<td>ha-mm</td>
<td></td>
<td>10.273</td>
</tr>
<tr>
<td>ac-ft</td>
<td>ha-mm</td>
<td></td>
<td>123.275</td>
</tr>
<tr>
<td>gallons</td>
<td>liters</td>
<td></td>
<td>3.7879</td>
</tr>
<tr>
<td>cfs</td>
<td>lps</td>
<td></td>
<td>28.317</td>
</tr>
<tr>
<td>cfs/ft</td>
<td>lps/m</td>
<td></td>
<td>92.908</td>
</tr>
<tr>
<td>gpm</td>
<td>lps</td>
<td></td>
<td>0.0631</td>
</tr>
<tr>
<td>gpm/ft</td>
<td>lps/m</td>
<td></td>
<td>0.2071</td>
</tr>
<tr>
<td>in/hr</td>
<td>mm/hr</td>
<td></td>
<td>25.40</td>
</tr>
<tr>
<td>in/ft</td>
<td>mm/m</td>
<td></td>
<td>83.337</td>
</tr>
</tbody>
</table>
Figure 40. *Crop Production Functions* for sugar-cane and corn crops used in the study.
Figure 41. Original ground surface elevations in feet at a 100- by a 100-foot grid for a 41-acre field.
Figure 42. Original ground surface elevations in feet by a 100-by-a 100-foot grid for a 45-acre field.
Figure 43. Original ground surface elevations in feet at a 100- by a 100-foot grid for a 61-acre field.
Appendix E.

Computer Programs for Land Grading Design
Table 31. List, formats, and descriptions of the input information used in the land grading model.

<table>
<thead>
<tr>
<th>Card No.</th>
<th>Name</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NM</td>
<td>I2</td>
<td>Number of fields to be graded</td>
</tr>
<tr>
<td>2</td>
<td>LAND</td>
<td>I2</td>
<td>An index to select the desired land grading method</td>
</tr>
<tr>
<td>3</td>
<td>COTY(I)</td>
<td>20A4</td>
<td>Field identification</td>
</tr>
<tr>
<td>4</td>
<td>COTY2(I)</td>
<td>20A4</td>
<td>Field identification</td>
</tr>
<tr>
<td></td>
<td>N</td>
<td>I2</td>
<td>Number of stations in the row direction</td>
</tr>
<tr>
<td></td>
<td>M</td>
<td>I2</td>
<td>Number of stations in the cross-row direction</td>
</tr>
<tr>
<td></td>
<td>AMAXX</td>
<td>F7.3</td>
<td>Maximum allowable slope in the row direction expressed as a percentage</td>
</tr>
<tr>
<td></td>
<td>AMINX</td>
<td>F7.3</td>
<td>Minimum allowable slope in the row direction expressed as a percentage</td>
</tr>
<tr>
<td></td>
<td>AMAXY</td>
<td>F7.3</td>
<td>Maximum allowable slope in the cross-row direction expressed as a percentage</td>
</tr>
<tr>
<td></td>
<td>AMINY</td>
<td>F7.3</td>
<td>Minimum allowable slope in the cross-row direction expressed as a percentage</td>
</tr>
<tr>
<td></td>
<td>ECF</td>
<td>F6.3</td>
<td>Expected cut-fill ratio, C/F</td>
</tr>
<tr>
<td></td>
<td>DECF</td>
<td>F6.3</td>
<td>Allowable deviation from the expected cut-fill ratio, C/F</td>
</tr>
<tr>
<td></td>
<td>COST</td>
<td>F6.3</td>
<td>Cost of moving the soil in dollars per cubic yard</td>
</tr>
</tbody>
</table>
Table 31. Continued.

<table>
<thead>
<tr>
<th>Card No.</th>
<th>Name</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>EXVC</td>
<td>F7.0</td>
<td>Extra volume of cut needed on the field in cubic yards</td>
</tr>
<tr>
<td></td>
<td>EXVF</td>
<td>F7.0</td>
<td>Extra volume of fill needed on the field in cubic yards</td>
</tr>
<tr>
<td></td>
<td>TOL</td>
<td>F6.3</td>
<td>Tolerance for the summation of the absolute differences between consecutive surface adjustments at each station for Kriz's methods types II, III, IV, and V</td>
</tr>
<tr>
<td></td>
<td>DSC</td>
<td>F5.2</td>
<td>Depth of cut for which the number of stations exceeding that depth will be counted</td>
</tr>
<tr>
<td></td>
<td>DSF</td>
<td>F5.2</td>
<td>Depth of fill for which the number of stations exceeding that depth will be counted</td>
</tr>
<tr>
<td>6</td>
<td>GGG</td>
<td>F6.2</td>
<td>Square grid spacing in feet</td>
</tr>
<tr>
<td>7</td>
<td>KKK</td>
<td>I2</td>
<td>An index to select the desired design of Kriz's methods</td>
</tr>
<tr>
<td></td>
<td>KKP</td>
<td>I2</td>
<td>An index to select the desired design of Paul's methods</td>
</tr>
<tr>
<td>8*</td>
<td>R1(I)</td>
<td>F6.2</td>
<td>Distances in feet from the first row to the field boundaries at consecutive stations</td>
</tr>
<tr>
<td>9*</td>
<td>R2(I)</td>
<td>F6.2</td>
<td>Distances in feet from the last row to the field boundaries at consecutive stations</td>
</tr>
<tr>
<td>10*</td>
<td>R3(I)</td>
<td>F6.2</td>
<td>Distances in feet from the first cross-row to the field boundaries at consecutive stations</td>
</tr>
</tbody>
</table>
Table 31. Continued.

<table>
<thead>
<tr>
<th>Card No.</th>
<th>Name</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11*</td>
<td>$R_4(I)$</td>
<td>F6.2</td>
<td>Distances in feet from the last cross-row to the field boundaries at consecutive stations</td>
</tr>
<tr>
<td>†</td>
<td>$H(I, J)$</td>
<td>F6.2</td>
<td>Original ground surface elevations in feet at the stakes</td>
</tr>
<tr>
<td></td>
<td>$LF$</td>
<td>F10.5</td>
<td>Load Factor in dollars per foot of cut</td>
</tr>
<tr>
<td></td>
<td>$DF$</td>
<td>F10.5</td>
<td>Distance Factor in dollars per foot of cut per 100 feet of haul distance</td>
</tr>
</tbody>
</table>

* More than one card might be needed
† The number of cards depends on the size of the field
γ Last card
ACOST = AVERAGE COST OF LAND GRAZING, $ / ACRE
AMAXX = MAXIMUM ALLOWABLE SLOPE IN THE ROW DIRECTION EXPRESSED AS A PERCENTAGE
AMAXY = MAXIMUM ALLOWABLE SLOPE IN THE CROSS-ROW DIRECTION EXPRESSED AS A PERCENTAGE
AMINX = MINIMUM ALLOWABLE SLOPE IN THE ROW DIRECTION EXPRESSED AS A PERCENTAGE
AMINY = MINIMUM ALLOWABLE SLOPE IN THE CROSS-ROW DIRECTION EXPRESSED AS A PERCENTAGE
AVGC = CENTROID ELEVATION OF THE FIELD = CEN
CF = DESIRED RATIO OF CUT TO FILL BY DEPTH
COST = COST OF MOVING THE SOIL, $ / CUBIC YARD
COTY = IDENTIFICATION HEADINGS FOR OUTPUT
COTY2 = IDENTIFICATION HEADINGS FOR OUTPUT
CUYP = AVERAGE VOLUME OF EARTH WORK, CU YD / ACRE
CUYN = TOTAL DEPTH OF FILL OVER THE WHOLE FIELD, FEET
CUTP = TOTAL DEPTH OF CUT OVER THE WHOLE FIELD, FEET
DAF = ALLOWABLE DEVIATION OF RATIO OF CUT TO FILL
DF = DISTANCE FACTOR, $ / FT OF CUT / 100 FEET HAUL DISTANCE
DSC = DEPTH OF CUT FOR WHICH THE NUMBER OF STATIONS EXCEEDING THAT DEPTH WILL BE COUNTED
DSF = DEPTH OF FILL FOR WHICH THE NUMBER OF STATIONS EXCEEDING THAT DEPTH WILL BE COUNTED
ECF = EXPECTED RATIO OF CUT TO FILL
EXVC = EXTRA VOLUME OF CUT NEEDED ON THE FIELD, CU YD
EXVF = EXTRA VOLUME OF FILL NEEDED ON THE FIELD, CU YD
HF = LOAD FACOTR, $ / FT OF CUT BASED ON BANK YARDS
H(I,J) = ORIGINAL GROUND SURFACE ELEVATION AT STATIONS ON 100 FT X 100 FT GRID = A(I,J)
ICF = TOTAL NUMBER OF STATIONS HAVING CUT
IFL = TOTAL NUMBER OF STATIONS HAVING FILL
IOCT = TOTAL NUMBER OF STATIONS WITH CUT OVER THE SPECIFIED DEPTH
IOFL = TOTAL NUMBER OF STATIONS WITH FILL OVER THE SPECIFIED DEPTH
WHEN USING KRIZ SUBROUTINE AND KKP IS
   1 PERFORM DESIGN TYPE I
   2 PERFORM DESIGN TYPES I AND II
   3 PERFORM DESIGN TYPES I, II, AND III
   4 PERFORM DESIGN TYPES I, II, III, AND IV
   5 PERFORM DESIGN TYPES I, II, III, IV, AND V
WHEN USING PAUL'S SUBROUTINE AND KKP = 1 USE LEAST COST METHOD
   KKP = 2 USE LEAST SQUARES METHOD, KKP = 3 USE DOUBLE CENTROID METHOD, KKP = 4 USE AVERAGE SLOPE METHOD
LF = LOAD FACOTR, $ / FT OF CUT BASED ON BANK YARDS
WHEN LAND IS

= 1 CALL SOIL CONSERVATION SERVICE, SCS, SUBROUTINE
= 2 CALL KRIZ SUBROUTINE
= 3 CALL PAUL SUBROUTINE

NM = NUMBER OF SETS OF DATA TO BE EVALUATED
NX OR M = NUMBER OF STATIONS IN THE CROSS-ROW DIRECTION OR X-DIRECTION
NY OR N = NUMBER OF STATIONS IN THE ROW DIRECTION OR Y-DIRECTION

R1(I) = DISTANCES FROM THE FIRST ROW TO FIELD BOUNDARY, FEET
R2(I) = DISTANCES FROM THE LAST ROW TO FIELD BOUNDARY, FEET
R3(J) = DISTANCES FROM FIRST CROSS-ROW TO FIELD BOUNDARY, FEET
R4(J) = DISTANCES FROM LAST CROSS-ROW TO FIELD BOUNDARY, FEET

SACRE = AREA OF THE GRADED FIELD, ACRES
SLOPEX = SLOPE OF THE GRADED PLANE IN THE X-DIRECTION
SLOPEY = SLOPE OF THE GRADED PLANE IN THE Y-DIRECTION

TCMS = TOTAL COST OF MOVING SOIL, $
TCMSLS = TOTAL COST OF MOVING SOIL USING LEAST SQUARES DESIGN, $
TCOST = TOTAL COST OF EARTH WORK, $
TOL = TOLERANCE FOR THE SUMMATION OF THE ABSOLUTE DIFFERENCES BETWEEN CONSECUTIVE SURFACE ADJUSTMENTS AT EACH STATION FOR TYPES II, III, IV, AND V OF SHIM AND KRIZ DESIGNS

VCTT = TOTAL VOLUME OF EARTH WORK IN CUT, CU YARDS
VFIT = TOTAL VOLUME OF EARTH WORK IN FILL, CU YARDS
VRCF = RATIO OF CUT TO FILL BY VOLUME

DIMENSION H(SO, 50), A(50, 50), B(50, 50), C(SO, 50), R1(SO),
R2(50), R3(50), R4(50), R1(I), R1(J), R2(I), R2(J), R3(J), R4(J),
CHEC(50, 50), CUTE(50, 50), HH(50, 50)
REAL LF

FORMAT STATEMENTS FOR READING INPUT DATA

1 FORMAT(2F7.3, 3F6.3, 2F7.0, F6.3, 2F5.2)
2 FORMAT(20A4)
3 FORMAT(13F6.2)
4 FORMAT(I10, F10, 3)
5 FORMAT(2F10.5)

READING THE NUMBER OF FIELDS TO BE GRADED
READ(5,1) NM
DO 50 KG = 1, NM

CHOOSING THE PROPER LAND GRADING METHOD
READ(5,1) LAND

READING FIELD IDENTIFICATION
READ(5,2) (CUTY(I), I=1, 20)
READ(5,2) (CUTY2(I), I=1, 20)

READING DESIGN LIMITATIONS AND UNIT COST
READ(5,1) N, M, AMAXX, AMINX, AMAXY, AMINY, ECF, DECF, COST, EXVC,
1 EXVF, TOL, DSC, DSE

READING DIMENSIONS OF A SQUARE GRID

DIMENSION M(50, 50), A(50, 50), B(50, 50), C(50, 50), R1(50),
R2(50), R3(50), R4(50), COTY(50), COTY2(50), ACHE(50, 50),
F(50, 50), CI(50, 50), AA(50, 50), BI(50, 50), AVGX(50),
AVGY(50), SLPX(50), SLPY(50), SLPN(50), VC(51, 51), VF(51, 51),
C2(50, 50), AVGNO(50), CALHCSO, 50), CUT(50, 50), HM(50, 50)
REAL LF
READ(5,3) GGG

CHOOSING THE PROPER ALTERNATIVE OF A GIVEN LAND GRADING METHOD
READ(5,1) KKK, KKP
GO TO (8, 9, 8), LAND

READING DISTANCES FROM THE LAST STATION TO THE FIELD BOUNDARIES
READ(5,3) (RI(I), I=1, N)
READ(5,3) (R2(I), I=1, N)
READ(5,3) (R3(I), I=1, M)
READ(5,3) (R4(I), I=1, M)

READING ORIGINAL GROUND SURFACE ELEVATIONS AT STAKES (ROW WISE)
DO 10 I=1, N
10 READ(5,3) (RI(I, J), J=1, M)

READING THE LOAD AND DISTANCE FACTORS FOR PAUL'S METHODS
READ(5,5) LF, DF
GO TO (20, 40, 20), LAND

RENUMBERING STAKES POSITIONS TO FIT PAUL'S AND THE SCS METHODS
DO 11 I=1, N
11 MH(J, I) = H(I, J)
DO 11 J=1, M

CALLING THE PROPER SUBROUTINE TO PERFORM THE DESIRED LAND GRADING
GO TO (21, 40, 30), LAND

CALL SCS(MH, SLOPEX, SLOPEY, M, N, CEN, ICT, IFL, ECF, VRCF, VCTT, 1 VFFT, IOCT, IOFL, AVCTT, ACUST, AREA, TCUST, R1, R2, R3, R4, 2 DECF, COST, EXVC, EXVF, DSC, DSF, COTY, COTY2, GGG)
GO TO 50

CALL KRIZ(KKK, M, N, AVGC, ICT, IFL, ECF, VRCF, VCTT, IOCT, IOFL, 1 AVCTT, ACOST, SACRE, TCOST, H, AMAX, AMINX, AMAXY, AMINY, DECF, 2 COST, EXVC, EXVF, TOL, DSC, DSF, R1, R2, R3, R4, COTY, COTY2, GGG)
GO TO 50

CALL PAUL(KKP, M, N, CEN, CUTP, CUTN, LF, DF, GRADL, SLOPEX, 1 SLOPEY, RC, ECF, TCMSPA, TCM, CUPA, HH, COTY, COTY2, GGG)

CONTINUE
STOP
END
SUBROUTINE KRIZ(KPK, M, N, AVGC, ICT, IFL, ECF, VRPF, VCTT, IOCT)

1 IFIL, AVCST, SачE, TCST, A, AMAXX, AMINX, AMAXY, AMINY, C

2 DECF, COST, EXVC, EXVF, TOL, DSC, DSF, R1, R2, R3, R4, COTY, C

3 COTY2, GG)

SUBROUTINE FOR PERFORMING LAND GRADING DESIGNS USING SHIH AND

KRIZ'S METHODS

DIMENSION A(SO, 50), B(SO, 50), C(SO, 50), AA(50, 50), B1(50, 50), C

AVGX(50), AVGY(SO), SLPX(SO), COTY(20), SLPY(20), R1(50), R2(50), R3(50), R4(50), SLPN(SO)

VC(51, 51), VF(51, 51), C2(50, 50), ACOST(50, 50), COTY2(20)

FORMAT STATEMENTS FOR PRINTING INPUTS AND OUTPUTS

5 FORMAT(14,3X,15F8.2)

6 FORMAT(7X,15F8.2)

46 FORMAT('//10X,'ORIGINAL FIELD ELEVATION')

50 FORMAT('//10X,'DEPTHS OF CUTS AND FILLS')

51 FORMAT('//10X,'FINAL DESIGN ELEVATIONS')

52 FORMAT('//10X,'FINAL DESIGN SLOPES IN ROW DIRECTION')

65 FORMAT(10X,'---------- CROSS ROW DIRECTION')

166 FORMAT('//2X,'TYPE I - UNIFORM SLOPE (PLANE SURFACE) WITH ROW AND

1CROSS ROW DIRECTION')

167 FORMAT('//2X,'TYPE II - VARIABLE SLOPE WITH ROW AND CROSS ROW DRAINAGE')

202 FORMAT('//2X,'TYPE III - UNIFORM SLOPE IN INDIVIDUAL ROWS IN THE ROW

1DIRECTION AND VARIABLE')

54 FORMAT('//14X,'SLOPE IN THE CROSS ROW DIRECTION WITH ROW AND CROSS ROW

1DRAINAGE')

173 FORMAT('//2X,'TYPE IV - UNIFORM SLOPE IN INDIVIDUAL ROWS WITH ROW

1DRAINAGE AND A MINIMUM')

55 FORMAT('//13X,'AND MAXIMUM ALLOWABLE CROSS ROW SLOPE (NO CROSS ROW DR

1AINAGE)')

186 FORMAT('//2X,'TYPE V - VARIABLE SLOPE IN INDIVIDUAL ROWS WITH ROW D

RAINAGE AND A MINIMUM')

56 FORMAT('//12X,'AND MAXIMUM ALLOWABLE CROSS ROW SLOPE (NO CROSS ROW DR

1AINAGE)')

22 FORMAT('//2X,'TOTAL AREA=',F7.3,' ACRES')

20 FORMAT('//5X,'******************************************************************************

1******************************************************************************')

4 FORMAT('5X,'F20.4, '*)

28 FORMAT('5X,'******************************************************************************

1******************************************************************************')

29 FORMAT('//30X,'DESIGN REQUIREMENTS')

49 FORMAT('//12X,'******************************************************************************

1******************************************************************************')

58 FORMAT('12X,'+}

1 ALLOWABLE SLOPES IN PERCENT +

1)

23 FORMAT('12X,'******************************************************************************

1)

27 FORMAT('12X,'******************************************************************************

1)

700 FORMAT('12X,'******************************************************************************

1)

25 FORMAT('12X,'+ MINIMUM SLOPE',F9.3,12X,F9.3, ')

701 FORMAT('12X,'+ MAXIMUM SLOPE',F9.3,12X,F9.3, ')

702 FORMAT('//2X,'EXPECTED CUT/FILL RATIO BY VOLUME=',F5.3, ' TOLERAN

209
ICE='1',FS,3)

703 FORMAT(2X,'EXTRA VOLUME OF CUT=',FB,1,' CY, EXTRA VOLUME OF FILL
1=',FB,1,' CY')

704 FORMAT(2X,'DEVIATION OF EXPECTED CUT/FILL RATIO=',FS,3,', COST=3
1=',FS,3,') PER CUBIC YARD')

705 FORMAT(2X,'NUMBER OF STATIONS IN ROW=',I2,', PROPOSED MAXIMUM DE
1PTH OF CUT=',F6,2,' FT')

706 FORMAT(2X,'NUMBER OF STATIONS IN CROSS ROW=',I2,', PROPOSED MAXI
1MUM DEPTH OF FILL=',F6,2,' FT')

707 FORMAT(2X,'DISTANCES TO FIELD BOUNDARIES FROM:')

708 FORMAT(5X,'FIRST ROW ------- R1(I)= ',1F6.2)

709 FORMAT(5X,'LAST ROW ------- R2(I)= ',1F6.2)

710 FORMAT(5X,'FIRST CROSS ROW ------- R3(J)= ',1F6.2)

711 FORMAT(5X,'LAST CROSS ROW ------- R4(J)= ',1F6.2)

722 FORMAT(2X,'(NOTE: CUTS ARE SHOWN AS POSITIVE AND FILLS AS NEGATI
1VE)')

723 FORMAT(2X,'TOTAL VOLUME OF CUT=',F10.3,' CY, FINAL CUT/FILL RA
1TIO BY VOLUME=',FS,3)

724 FORMAT(2X,'NUMBER OF STATIONS WITH CUT=',I4,', NUMBER OF STATION
1S WITH FILL=',I4)

725 FORMAT(2X,'NUMBER OF STATIONS WITH CUT OVER THE PROPOSED MAXIMUM DE
1PTH=',I4)

726 FORMAT(2X,'NUMBER OF STATIONS WITH FILL OVER THE PROPOSED MAXIMUM DE
1PTH=',I4)

727 FORMAT(2X,'AVERAGE VOLUME=',FB,3,' CY/ACRE, AVERAGE COST=',F6,2
1,' PER ACRE')

728 FORMAT(2X,'TOTAL COSTS=',F8.2)

729 FORMAT(2X,'(NOTE: MINUS SIGN INDICATES A DROP IN ELEVATION AWAY F
1ROM THE FIRST CROSS ROW)')

NUM=1

C WRITING INPUT DATA

WRITE(6,20)

WRITE(6,4) (COTY(I), I=1, 20)

WRITE(6,4) (COTY2(I), I=1, 20)

WRITE(6,26)

WRITE(6,29)

WRITE(6,49)

WRITE(6,58)

WRITE(6,23)

WRITE(6,27)

WRITE(6,700)

WRITE(6,25) AMINX, AMINY

WRITE(6,701) AMAXX, AMAXY

WRITE(6,49)

WRITE(6,702) ECF, TOL

WRITE(6,703) EXVC, EXVF

WRITE(6,704) DECF, COST

WRITE(6,705) N, DSC

WRITE(6,706) M, DSF

WRITE(6,707)

WRITE(6,708) (R1(I), I=1, N)

WRITE(6,709) (R2(I), I=1, N)

WRITE(6,710) (R3(I), I=1, M)

WRITE(6,711) (R4(I), I=1, M)

AMAXX=AMAXX

AMINX=AMINX

AMAXY=AMAXY

AMINY=AMINY

WRITE(6,46)
WRITE(6,65)
C
CONTROL FOR FIELD DATA PRINT OUT
IF(M=15) 620, 620, 621
620 DO 45 I=1, N
45 WRITE(6,5) I, (A(I, J), J=1, M)
GO TO 622
621 DO 623 I=1, N
623 WRITE(6,5) I, (A(I, J), J=1, 15)
C
NUMBER OF FIELDS THAT HAVE BEEN DESIGNED
622 NUM=NUM+1
C
CALCULATE INDIVIDUAL AND FIELD ROW SLOPES, CENTROIDS AND
C
CENTROID LOCATIONS
CALL SRAB(A,N,M,AVGC,SLXX,ASX,AVGX,SLPX, GGG)
C
TRANSPOSE MATRIX (CROSS ROWS BECOME ROWS)
DO 10 I=1, N
10 00 10 J=1, M
M(J, I)=A(I, J)
MAKE FIELD A UNIT MATRIX FOR LATER AREA CALCULATIONS
ACRE(I, J)=1.0
CALCULATE INDIVIDUAL AND FIELD CROSS ROW SLOPES, CENTROID
C
AND CENTROID LOCATIONS
CALL SRAB(AA, M, N, AVGC, SLYY, ASY, AVGY, SLPY, GGG)
C
CALCULATE AREA OF THE FIELD
SACRE=0.0
DO 21 J=1, M
21 SACRE=SACRE+ACRE(I, J)
CALCULATE AREA IN ACRES
SACRE=SACRE*GGG*GGG/43560.0
WRITE(6,22) SACRE

C
START TYPE I DESIGN ******************************************
WRITE(6,166)
C
CHOOSE CALCULATED OR ALLOWABLE SLOPES
C
CALL HMGB(A,N,H,SLXX,SLYY,AVGC,SLXY,ASY,ASY,AMAAX,AMAXY,AMINX,AMINY,C2,
C
1 GGG)
DO 57 I=1, N
57 00 57 J=1, M
C(J, J)=C(I, J)
C
BALANCE RATIO OF CUT TO FILL BY DEPTH
CALL Balc(CF1,N,M,C1,R1,R2,R3,R4,DSC,DSF,IOCT,IOFL,ICT,IFL, GGG)
C
CALCULATE EARTHWORK QUANTITIES
CALL VlNC(C,R1,R2,R3,R4,N,M,VC,VF,VCTT,VFTT, GGG)
C
ADJUST FOR ADDITIONAL VOLUMES OF CUT OR FILL
VCTT=VCTT+EXVC
VFTT=VFTT+EXVF
IF(VFTT, EQ. 0.0) GO TO 209
C
Determine ratio of cut to fill by volume
VRCF=VCTT/VFTT
COMPARE CALCULATED AND EXPECTED RATIOS OF CUT TO FILL BY VOLUME

ERR2=ERR - VRCP

COUNT NUMBER OF TIME VOLUMES WERE CALCULATED

NMEH=ERR + 1

COMPARE DIFFERENCE BETWEEN SUCCESSIVE VOLUME CALCULATIONS WITH

ALLOWABLE DIFFERENCES

IF(ABS(ERR) = DECIF) 209, 209, 210

CHECK NUMBER OF TIMES THE VOLUME HAS BEEN CALCULATED

210 IF(NMEH = 1) 301, 301, 302

301 ERR=ERR

CHECK THE SIGN OF THE ERR VALUE

305 IF(ERR) 303, 209, 304

WHEN ERR IS NEGATIVE

303 CF1=CF1 + 0.01

GO TO 211

WHEN ERR IS POSITIVE

304 CF1=CF1 + 0.01

GO TO 211

302 ERR2=ERR

CHECK IF CONSECUTIVE ERR VALUES HAVE CHANGED SIGN

IF(ERR1=ERR2) 209, 209, 305

PRINT DEPTH OF CUT OR FILL AT EACH STATION

209 WRITE(b,50)

WRITE(b,722)

WRITE(b,65)

CONTROL FOR FIELD DATA PRINT OUT

IF(M=15) 624, 624, 625

624 DO 164 I=1, N

164 WRITE(b,5) I, (C(I, J), J=1, M)

GO TO 626

625 DO 627 I=1, N

627 WRITE(b,65) I, (C(I, J), J=1, 15)

WRITE(b,65) (C(I, J), J=16, M)

CALCULATE FINAL DESIGN ELEVATIONS

626 DO 169 I=1, N

DO 169 J=1, M

169 B(I, J)= A(I, J)-C(I, J)

PRINT FINAL DESIGN ELEVATIONS

WRITE(b,51)

WRITE(b,65)

CONTROL FOR FIELD DATA PRINT OUT

IF(M=15) 628, 628, 629

628 DO 170 I=1, N

170 WRITE(b,5) I, (B(I, J), J=1, M)

GO TO 630

629 DO 631 I=1, N

631 WRITE(b,5) I, (B(I, J), J=1, 15)

WRITE(b,65) (B(I, J), J=16, M)

CALCULATE AVERAGE VOLUME PER ACRE

630 AVCTT1=VCTT/SACRE

CALCULATE TOTAL COST

TCOST1=VCTT1*COST

CALCULATE AVERAGE COST

ACOST1=AVCTT1*COST

VCTT1 = VCTT

VRCP = VRCP

PRINT TOTAL VOLUME OF CUT, RATIO OF CUT TO FILL

WRITE(b,723) VCTT1,VRCP

PRINT TOTAL NUMBER OF STATIONS WITH CUT AND WITH FILL

WRITE(b,724) ICT, IFL

PRINT NUMBER OF STATIONS WITH CUT OVER THE PROPOSED MAXIMUM DEPTH
WRITE(b,725) IUCT
WRITE(b,72b) IOFL
WRITE(b,727) AVCCT1, ACOST1
WRITE(b,72m) TCOST1
IF(KKK . EQ. 1) GO TO 900
C
C START TYPE II DESIGN
WRITE(b,167)
NABB = 0
NERR = 0
CF1 = ECF
GO TO 171
C BALANCE RATIO OF CUT TO FILL BY DEPTH
168 CALL BALC(CF1,N,M,C2,R1,R2,R3,R4,USC,DSF,IOCT,IOFL,ICT,IFL,GGG)
C CALCULATE DESIGN ELEVATIONS
171 DO 172 J=1, N
DO 172 J=1, M
172 B(I, J) = A(I, J)-C2(I, J)
C DESIGN VARIABLE SLOPES FOR TYPE II DESIGN
CALL WARP(A,b,C2,N,M,AMXX,AMINX,AMAXY,AMINY,ABB,GGG)
C COUNT NUMBER OF TIMES WARP WAS USED
NABB = NABH + 1
IF(NABB . EQ. 1) GO TO 168
C COMPARE DIFFERENCE BETWEEN SUCCESSIVE DESIGN WITH ALLOWABLE
C TOLERANCE
IF(ABB = TOL) 175, 175, 400
C CHECK FOR CONVERGENCE ONLY AFTER 4 SUCCESSIVE DESIGNS
400 IF(NABB = 5) 168, 401, 402
C CHECK FOR CONVERGENCE IN DESIGN
401 ABB1 = ABB
GO TO 168
402 ABB2 = ABB
IF(ABB2 = ABB1) 610, 610, 175
610 ABB1 = ABB2
GO TO 168
C SAME COMMENTS APPLY FOR THE FOLLOWING AS IN TYPE I DESIGN
175 CALL VLNC(C2,R1,R2,R3,R4,N,M,VC,VF,VCTT,VFTT,GGG)
NABB = 0
VCTT = VCTT + EXVC
VFTT = VFTT + EXVF
IF(VFTT . EQ. 0.0) GO TO 212
VRCF = VCTT/ VFTT
ERR = ECF = VRCF
NERR = NERR + 1
IF(ABS(ERR) = DECF) 212, 212, 213
213 IF(NERR = 1) 311, 311, 312
311 ERR1 = ERR
315 IF(ERR) 313, 212, 314
313 CF1 = CF1 = 0.01.
GO TO 168
314 CF1 = CF1 + 0.01
GO TO 168
312 ERR2 = ERR
IF(ERR1*ERRH2) 212, 212, 315
212 WRITE(b,50)
WRITE(b,722)
WRITE(b,65)
IF(M = 15) 632, 632, 633
632 DO 182 I=1, N
182 WRITE(a,5) I, (C2(I, J), J=1, M)
GO TO 634
633 DO 635 I=1, N
635 WRITE(a,5) I, (C2(I, J), J=1, 15)
634 WRITE(a,51)
WRITE(a,65)
IF(M=15) 636, 636, 637
636 DO 194 I=1, N
194 WRITE(a,5) I, (B(I, J), J=1, M)
GO TO 638
637 DO 639 I=1, N
639 WRITE(a,5) I, (B(I, J), J=1, 15)
638 AVCTT2=VCTT/SACRE
TCOST2=VCTT*COST
ACOST2=AVCTT2*COST
VRCF2 = VRCF
WRITE(a,723) VCTT2, VRCF
WRITE(a,724) IOT, IFL
WRITE(a,725) IOT
WRITE(a,726) IOT
WRITE(a,727) AVCTT2, ACOST2
WRITE(a,728) TCOST2
IF(KKK .EQ. 2) GO TO 900

C
C START TYPE III DESIGN **********************************************
C WRITE(a,202)
WRITE(a,54)
NERR = 0
CF1 = ECF
NAVY = 0
DO 508 I=1, N
508 B1(I, J) = B1(I, J)
DO 508 J=1, M
C CALCULATE INDIVIDUAL ROW SLOPES
C CALL SRAB(ij1,N,H,4VGC,SLXX,ASX,AVGN,SLPN,GGG)
C DESIGN TYPE III DESIGN
C CALL RNACN,M,AVGN,SLPN,ASX,AHXX,AMXX,AMYY,Bl,AVY,GGG)
C COUNT NUMBER OF TIMES BRNA WAS USED
NAVY = NAVY + 1
C COMPARE DIFFERENCE BETWEEN SUCCESSIVE DESIGNS WITH ALLOWABLE
C TOLERANCE
C IF(AVY = TOL) 507, 507, 509
C CHECK FOR CONVERGENCE ONLY AFTER 4 SUCCESSIVE DESIGNS
C IF(NAVY = 5) 506, 510, 511
C CHECK FOR CONVERGENCE IN DESIGN
510 AVY1 = AVY
GO TO 506
511 AVY2 = AVY
IF(AVY2 - AVY1) 195, 195, 507
195 AVY1 = AVY2
GO TO 506
C PRINT FINAL DESIGN SLOPE FOR EACH ROW
C WRITE(a,52)
WRITE(a,729)
WRITE(a,6,6) (SLPN(J), J=1, M)
C   CALCULATE DEPTH OF CUT OR FILL
      DO 206 I=1, N
      DO 206 J=1, M
206   C(I, J) = A(I, J) - B(I, J)
C   BALANCE RATIO OF CUT TO FILL BY DEPTH
      CALL HALL(C, M, N, R1, R2, R3, R4, DSC, DSF, IDCT, IFL, IFL, GGG)
      CALL VNC(C, R1, R2, R3, R4, N, M, VC, VF, VCTT, VFFT, GGG)
      VCTT = VCTT + EXVC
      VFFT = VFFT + EXVF
      IF(VFFT, EQ, 0.0) GO TO 214
      VRCF = VCTT/VFFT
      ERR = ECF - VRCF
      NERR = NERR + 1
      IF(ABS(ERR) = DEC) 214, 214, 215
215   IF(NERR = 1) 321, 321, 322
      ERR1 = ERR
      ERR2 = ERR
      IF(ERR1=ERR2) 214, 214, 325
      WRITE(b, 50)
      WRITE(b, 722)
      WRITE(b, 65)
      IF(M=15) 640, 640, 641
      DO 203 I=1, N
      DO 203 J=1, M
203   WRITE(b, 5), (C(I, J), J=1, M)
      WRITE(b, 65)
      WRITE(b, 5)
      WRITE(b, 6)
      (C(I, J), J=1, 15)
      DO 204 I=1, N
      DO 204 J=1, M
204   B(I, J) = A(I, J) - C(I, J)
      WRITE(b, 51)
      WRITE(b, 65)
      IF(M=15) 644, 644, 645
      DO 205 I=1, N
      DO 205 J=1, M
205   WRITE(b, 5), (B(I, J), J=1, M)
      WRITE(b, 65)
      WRITE(b, 5)
      WRITE(b, 6)
      (B(I, J), J=1, 15)
      DO 206 I=1, N
      DO 206 J=1, M
206   WRITE(b, 723) VCTT, VRCF
      WRITE(b, 724) ICT, IFL
      WRITE(b, 725) IDCT, IFL
      WRITE(b, 726) IFL
      WRITE(b, 727) AVCCT3, ACOST3
      WRITE(b, 728) TCOST3
      IF(KKK . EQ . 3) GO TO 900
C   C   START TYPE IV DESIGN  **************************************
WRITE(b, 173)  # 576
WRITE(b, 55)   # 577
Navy = 0       # 578
Nerr = 0       # 579
Cf1 = Ecf     # 580
Go To 174     # 581
C
176 CALL SRAH(I1, N, M, Avgc, Slxx, Asx, Avgx, Slpx, Ggg) # 582
174 CALL BRKN(N, M, Avgx, SLpx, ASX, AMAXX, AMinX, AMAXy, B1, AVY, GGG) # 583
C
COUNT NUMBER OF TIMES BRKN WAS USED # 584
NAVY = NAVY + 1 # 585
C
177 CALL SKAB(B1, N, M, Avgc, Slxx, Asx, Avgx, Slpx, Ggg) # 586
179 CALL BRKN(N, M, Avgx, Slpx, Asx, Amaxx, Amint, Amaxy, B1, Avy, GGG) # 587
C
COMPUTE DIFFERENCE BETWEEN SUCCESSIVE DESIGNS WITH ALLOWABLE # 588
TOLERANCE # 589
IF(Avy = Tol) 177, 177, 247 # 590
C
CHECK FOR CONVERGENCE ONLY AFTER 4 SUCCESSIVE DESIGNS # 591
247 IF(Navy = 5) 17b, 248, 249 # 592
C
CHECK FOR CONVERGENCE IN DESIGN # 593
248 Avy1 = Avy # 594
Go To 176 # 595
249 Avy2 = Avy # 596
IF(Avy2 - Avy1) 19b, 19b, 177 # 597
19b Avy1 = Avy2 # 598
Go To 176 # 599
C
PRINT FINAL DESIGN SLOPE FOR EACH ROW # 600
177 WRITE(b, 52) # 601
WRITE(b, 724) # 602
WRITE(b, b6) (Slpx(j), J=1, M) # 603
C
CALCULATE DEPTH OF CUT OR FILL # 604
DO 179 I=1, N # 605
DO 179 J=1, M # 606
179 C(I, J) = A(I, J) - B1(I, J) # 607
DO 59 I=1, N # 608
DO 59 J=1, M # 609
59 C2(I, J) = C(I, J) # 610
C
BALANCE RATIO OF CUT TO FILL BY DEPTH # 611
219 CALL DALCCCF1, N, M, C, R1, R2, R3, R4, Dsc, Dsf, IocT, IofL, Ict, IfL, GGG) # 612
C
SAME COMMENTS APPLY FOR THE FOLLOWING AS IN TYPE I DESIGN # 613
CALL VLNC(C, R1, R2, R3, R4, N, M, Vc, Vf, VcTt, VfTt, GGG) # 614
VcTt = VcTt + Exvc # 615
VfTt = VfTt + Exvf # 616
IF(VfTt . EQ. 0.0) Go To 217 # 617
Vrcf = VcTt / VfTt # 618
Err = Ecf - Vrcf # 619
Nerr = Nerr + 1 # 620
IF(ABS(Err) = Decf) 217, 217, 218 # 621
218 IF(Nerr = 1) 331, 331, 332 # 622
331 Er1 = Err # 623
335 IF(Err) 333, 217, 334 # 624
333 Cf1 = Cf1 - 0.01 # 625
Go To 219 # 626
334 Cf1 = Cf1 + 0.01 # 627
Go To 219 # 628
332 Err2 = Err # 629
IF(Err1 . EQ. Err2) 217, 217, 335 # 630
217 WRITE(b,70) # 631
WRITE(b,722) # 632
WRITE(b,65) # 633
IF(M = 15) 648, 648, 649 # 634
648 Do 184 I=1, N # 635
184 WRITE(b, 5) I, (C(I, J), J=1, M) # 636
GO TO 650
649 DO 651 I=1, N
       WRITE(b,5) I, (C(I, J), J=1, 15)
650 DO 180 I=1, N
651 WRITE(b,6) (C(I, J), J=16, M)
DO 180 J=1, M
180 B(I, J) = A(I, J) - C(I, J)
WRITE(b,51)
WRITE(b,65)
IF(M .LT. 15) GO TO 652, 652, 653
652 DO 181 I=1, N
181 WRITE(b,5) I, (B(I, J), J=1, 15)
GO TO 654
653 DO 655 I=1, N
654 WRITE(b,5) I, (B(I, J), J=1, 15)
AVCTT4 = VCTT / SACRE
TCOST4 = VCTT * COST
ACOST4 = AVCTT4 * COST
VCTT4 = VCTT
VRCF4 = VRCF
WRITE(b,723) VCTT4, VRCF
WRITE(b,724) ICT, IFL
WRITE(b,725) ICT
WRITE(b,727) AVCTT4, ACOST4
WRITE(b,728) TCOST4
IF(KKK .NE. 4) GO TO 900
START TYPE V DESIGN
WRITE(180)
WRITE(5b)
START TYPE V DESIGN
WRITE(b,196)
WRITE(b,56)
NABB = 0
NERR = 0
CF1 = ECF
GO TO 187
CALCULATE THE DESIGN ELEVATION
186 CALL BALCCF1(N,M,C2,R1,R2,R3,R4,DSC,DSF,IOCT,IOFL,ICT,IFL,GG)
187 DO 189 I=1, N
DO 189 J=1, M
188 B1(I, J) = A1(I, J) - C2(I, J)
188 C DESIGN TYPE V
C CALL MAMP8(A, B1,C2,N,M,AMAXX,AMINX,AMAXY,AMAXY,AABB,GG)
C COUNT NUMBER OF TIMES MAMP8 WAS USED
NABB = NABB + 1
IF(NABB .EQ. 1) GO TO 188
C COMPARE DIFFERENCE BETWEEN SUCCESSIVE DESIGNS WITH ALLOWABLE
C TOLERANCE
C IF(NABB .LT. 190) 190, 190, 403
C CHECK FOR CONVERGENCE ONLY AFTER 4 SUCCESSIVE DESIGNS
190 IF(NABB .LT. 5) 190, 404, 405
C CHECK FOR CONVERGENCE IN DESIGN
403 IF(NABB .LT. 5) 190, 404, 405
404 AABB = AABB
GO TO 188
405 AABB = AABB
IF(AABB = AABB) 611, 611, 190
611 AABB = AABB
GO TO 188
SAME COMMENTS APPLY FOR THE FOLLOWING AS IN TYPE I DESIGN
CALL VLNC(C2,R1,R2,R3,R4,N,M,VC,VF,VCTT,VFTT,GGG)
NABB = 0
VCTT = VCTT + EXVC
VFTT = VFTT + EXVF
IF(VFTT • EU, 0,0) GO TO 220
VRCF = VCTT / VFTT
ERK = ECF = VMCF
NERR = NERR + 1
IF(ABS(ERR) = DECF) 220, 220, 221
221 IF(NERR = 1) 341, 341, 342
341 ERR1 = ERR
345 IF(ERR) 343, 220, 344
343 CF1 = CF1 = 0, 01
GO TO 188
344 CF1 = CF1 + 0, 01
GO TO 188
342 ERR2 = ERR
IF(ERR1 = ERR2) 220, 220, 345
220 WRITE(b,50)
WRITE(b,722)
WRITE(b,65)
IF(M = 15) 656, 656, 657
656 DO 191 I=1, N
191 WRITE(b,5) I, (C2(I, J), J=1, M)
GO TO 658
657 DO 659 I=1, N
659 WRITE(b,6) (C2(I, J), J=1, 15)
658 WRITE(b,51)
WRITE(b,65)
IF(M = 15) 660, 660, 661
660 DO 193 I=1, N
193 WRITE(b,5) I, (B1(I, J), J=1, M)
GO TO 662
661 DO 663 I=1, N
663 WRITE(b,5) I, (B1(I, J), J=1, 15)
662 AVCTTS = VCTT / SACRE
TCOSTS = VCTT * COST
ACOSTS = AVCTTS * COST
VCTTS = VCTT
VRCFS = VMCF
WRITE(b,723) VCTTS, VRCF
WRITE(b,724) ICT, IFL
WRITE(b,725) I0CT
WRITE(b,726) I0FL
WRITE(b,727) AVCTTS, ACOSTS
WRITE(b,728) TCOSTS
GO TO 900
RETURN
END
SUBROUTINE SHAB(HM,K,L,AVC,SP,AS,AV,SLP,GGG)

THE SYMMETRICAL RESIDUALS METHOD, AND CALCULATING CENTROID

DIMENSION HM(50, 50), T(50), T1(50), T2(50), SLP(50), AV(50)

SET FIELD SLOPE EQUAL TO ZERO
SP=0.0

SET ELEVATIONS EQUAL TO ZERO
ST=0.0

CHANGE FROM INTEGER TO REAL VARIABLE
FN=K
FM=L

DETERMINE DENOMINATOR FROM EQUATION (1), OR (2)
D = FN * FN

CHECK IF NUMBER OF STATIONS IS ODD OR EVEN
N2=K/2
N3=N2
N22=(K+1)/2
IF(N2, EQ, N22) GO TO 10

WHEN STATION IS ODD
N2=N2+1
D=D+1.0

CALCULATE VALUES FROM EQUATIONS (1), (2), (3), OR (4)

DO 15 J=1, L
SET TOTAL OF ROW ELEVATIONS EQUAL TO ZERO
T(J)=0.0

SET LOCATION OF CENTROID EQUAL TO ZERO
ST=0.0

SUM ELEVATIONS AND LOCATIONS IN EACH ROW
00 11
11

CALCULATE INDIVIDUAL ROW SLOPES
SLP(J) = ((11.0 * (T2(J) - T1(J))) / D) * (100.0 / GGG)

SUM THE ROW SLOPES
SP = SP + SLP(J)

CALCULATE BEST SLOPE
SP = SP / FM

CALCULATE CENTROID ELEVATION
AVC=ST/(FN*FM)

CALCULATE CENTROID LOCATION
AS = SU / FN
RETURN
SUBROUTINE HMGb(BB,K,L,SLX,SLY,AV,SX,SY,AMAX,AMIY,C,GGG)
SUBROUTINE FOR CHECKING ROW AND CROSS ROW SLOPES, CALCULATING DESIGN ELEVATIONS, AND CALCULATING DEPTHS OF CUTS AND FILLS
DIMENSION BB(50, 50), B(50, 50), C(50, 50)

712 FORMAT(11X, '+++++++++++++++++++++++++++++++++++++++++++++++++++++
1++')
713 FORMAT(11X, 'DESI~ ELEVATIONS SLOPES IN PERCENT
1+++')
714 FORMAT(11X, 'NOTE: A MINUS SLOPE INDICATES A DROP IN ELEVATION
1+++')
715 FORMAT(11X, 'AWAY FROM STATION ALL, A POSITIVE SLOPE
1+++')
716 FORMAT(11X, 'INDICATES A RISE IN ELEVATION AWAY FROM
1+++')
717 FORMAT(11X, 'STATION ALL.)
1+++')
718 FORMAT(11X, '----------------------------------------
1+++')
719 FORMAT(11X, '----------------------------------------
1+++')
720 FORMAT(11X, 'CALCULATED SLOPE, F9.3, 12X, F9.3, 1+++')
721 FORMAT(11X, 'FINAL SLOPE, F9.3, 12X, F9.3, 1+++')
722 PRINT DESIGN SLOPES IN PERCENT
WRITE(b,712)
WRITE(b,713)
WRITE(b,714)
WRITE(b,715)
WRITE(b,716)
WRITE(b,717)
WRITE(b,718)
WRITE(b,719)
WRITE(b,720)
SLX, SLY
CHECK AND ADJUST TO BE WITHIN ALLOWABLE ROW SLOPES
IF(SLX, GT, AMIX) GO TO 51
IF(SLX, LT, AMAX) SLX=AMAX
GO TO 52
SLX=AMIY
CHECK AND ADJUST TO BE WITHIN ALLOWABLE CROSS ROW SLOPES
IF(SLY, GT, AMIY) GO TO 53
IF(SLY, LT, AMAY) SLY=AMAY
GO TO 50
CALCULATE CONSTANT A IN EQUATION (8)
S = AV = (SLX * SX + SLY * SY) * GGG / 100.0
PRINT FINAL ROW AND CROSS ROW SLOPES
WRITE(b,721)
WRITE(b,722)
CALCULATE DESIGN ELEVATIONS
DO 20 I=1, K
DO 20 J=1, L
FI=1
FJ=1
20 B(I, J) = S + (SLX * FI + SLY * FJ) * GGG / 100.0
CALCULATE DEPTH OF CUT OR FILL
DO 21 I=1, K
DO 21 J=1, L
21 C(I, J) = B(I, J) - B(I, J)
RETURN
END
SUBROUTINE BALCCECF,K,L,C1,R2,R3,R4,DSC,DSF,IOCT,IOFL,ICT,IFL,
  IGGG)
C SUBROUTINE FOR BALANCING AND CHECKING THE MAXIMUM ALLOWABLE LIMITS
C OF THE DEPTHS OF CUTS AND FILLS
C DIMENSION C(50, 50), C1(50, 50), R1(50), R2(50), R3(50), R4(50)
C SET NUMBER OF TIMES THE RATIO OF CUT TO FILL WAS COMPUTED EQUAL
C TO ZERO
C FORM A MATRIX FOR COMPUTING NEXT RATIO OF CUT TO FILL BY DEPTH
  9 DO 20 I=1, K
    DO 20 J=1, L
   20 CI(I, J)= C1(I, J)
  FL=0.0
  CT=0.0
  IFL=0
  ICT=0
C ADJUST CUTS OR FILLS FOR VARIABLE BOUNDARIES IN FIRST AND
C LAST CROSS ROWS
  DO 41 J=1, L
    CI(I, J)=CI(I, J)*((R1(J)+0.50 * IGGG) / IGGG)
   41
C ADJUST CUTS OR FILLS FOR VARIABLE BOUNDARIES IN FIRST AND
C LAST ROWS
  DO 42 I=1, K
    CI(I, J)=CI(I, J)*((R1(I)+0.50 * IGGG) / IGGG)
   42
C START TO SUM CUTS AND FILLS AND NUMBER OF STATIONS WITH EACH
C IN EACH ROW
  DO 23 J=1, L
    FILL=0.0
    IFILL=0
    CUT=0.0
    ICUT=0
    IF (CI(I1, J)) 24, 24, 25
C CHECK IF STATION HAS CUT OR FILL
  DO 26 I=1, K
    IF (CI(I1, J)) 24, 24, 25
C SUM DEPTH OF FILLS AND NUMBER OF STATIONS WITH FILL
   24 FILL=FILL + CI(I, J)
   IFILL=IFILL + 1
C SUM DEPTH OF CUTS AND NUMBER OF STATIONS WITH CUT
   GO TO 26
   25 CUT=CUT+CI(I, J)
   ICUT=ICUT + 1
C CONTINUE
  CONTINUE
C CALCULATE TOTAL SUM OF DEPTH OF FILLS AND NUMBER OF STATIONS
C WITH FILL
   FL=FL + FILL
   IFL = IFL + IFILL
C CALCULATE TOTAL SUM OF DEPTH OF CUTS AND NUMBER OF STATIONS
C WITH CUT
   CT = CT + CUT
C IF NO CUT OR FILL, RETURN TO MAIN PROGRAM
   IF (FL .EQ. 0.0) GO TO 43
C CALCULATE RATIO OF CUT TO FILL BY DEPTH
   RCF=CT / FL
C COMPARE EXPECTED AND CALCULATED RATIOS OF CUT TO FILL
Eh=ECF / HCF
C COUNT NUMBER OF TIMES THE RATIO OF CUT TO FILL WAS COMPUTED
NCF = NCF + 1
C CHECK IF ER VALUE IS WITHIN ALLOWABLE TOLERANCE
IF(ABS(EH) > 0.0001) 32, 32, 30
C CHECK FOR CONVERGENCE
30 IF(NCF = 1) 34, 34, 35
34 ER1 = EH
C CALCULATE EQUATION (12)
36 CCT = ICT
FFL = IFL
E=((CT/CCT)+(FL/FFL))xERx0.25
C CALCULATE EQUATION (13)
DO 31 I=1, K
DO 31 J=1, L
31 C(I, J) = C(I, J) + E
GO TO 9
C CHECK FOR CONVERGENCE
35 ER2 = EH
C CHECK FOR CONVERGENCE
37 ER1 = ER2
GO TO 36
C COUNT THE NUMBER OF STATIONS OVER A SPECIFIED CUT OR FILL
32 IOCT = 0
IOFL = 0
DO 40 I=1, K
DO 40 J=1, L
IF(C(I, J), GE, DSC) IOCT=IOCT+1
IF(C(I, J), LE, DSC) IOFL=IOFL+1
40 CONTINUE
43 RETURN
END
SUBROUTINE VLNC(C,R1,R2,R3,R4,K,L,VC,VF,VCTT,VFTT,GGG)  
SUBROUTINE FOR CALCULATING THE VOLUMES OF EARTH WORK USING THE  
END GROUND AREA METHOD  
DIMENSION C(50, 50), R1(50), R2(50), R3(50), R4(50), S1(51),  
S2(51), S3(51), S4(51), C2(51, 51), C3(51, 51), C4(51, 51),  
VC(51, 51), VF(51, 51), VCTT(51), VFTT(51), 102(51, 51), D(52, 52),  
F(52, 52), Id(52, 52), 0(52, 52), F(52, 52),  
N1= K + 1  
N2= K + 2  
M1= L + 1  
M2= L + 2  
T1 = GGG / GGG / 108.0  
T2 = 1 / 2.0  
T3 = 1 / 3.0  
C CALCULATE DISTANCES TO CROSS ROW BOUNDARIES AS A RATIO TO 50 FEET  
S3(I) = 2.0 * R3(I) / GGG  
S4(I) = 2.0 * R4(I) / GGG  
S3(M) = 2.0 * R3(L) / GGG  
S4(M) = 2.0 * R4(L) / GGG  
C CALCULATE AVERAGE DISTANCE TO CROSS ROW BOUNDARIES BETWEEN 2  
STATIONS AS A RATIO TO 50 FEET  
DO 31 I=2, K  
S3(J)=(R3(J-1)+R3(J))/GGG  
30 S4(J)=(R4(J-1)+R4(J))/GGG  
C CALCULATE DISTANCES TO ROW BOUNDARIES AS A RATIO TO 50 FEET  
S1(I) = 2.0 * R1(I) / GGG  
S2(I) = 2.0 * R2(I) / GGG  
S1(M) = 2.0 * R1(K) / GGG  
S2(M) = 2.0 * R2(K) / GGG  
C CALCULATE AVERAGE DISTANCE TO ROW BOUNDARIES BETWEEN 2 STATIONS  
AS A RATIO TO 50 FEET  
DO 31 I=2, K  
S1(I)=(R1(I-1)+R1(I))/GGG  
31 S2(I)=(R2(I-1)+R2(I))/GGG  
C FORM ZERO MATRICES FOR CUT, FILL AND NUMBER OF STATIONS WITH  
CUT OR FILL  
DO 8 I=1, N2  
DO 8 J=1, M2  
F(I, J)= 0.0  
ID(I, J)= 0.0  
8 D(I, J)=0.0  
C FORM MATRICES FOR DEPTHS OF CUTS OR FILLS  
DO 41 J = 2, M1  
DO 41 I=2, N1  
F(I, J) = C(I-1, J-1)  
C CHECK IF STATION IS CUT OR FILL  
IF(F(I, J)) 40, 41, 41  
C CHANGE FILL FROM NEGATIVE TO POSITIVE VALUE  
40 D(I, J)=F(I, J)  
C IF FILL, PUT INTEGER 1 IN THAT STATION LOCATION  
IF(D(I, J) .GT. 0.0) ID(I, J) = 1  
F(I, J) =0.0  
41 CONTINUE  
C START CALCULATION OF VOLUMES OF CUT OR FILL  
VCTT = 0.0  
VFTT = 0.0  
DO 43 J=1, M1  
C SET VOLUME OF CUT AND FILL EQUAL TO ZERO IN JTH ROW  
VCT(J) = 0.0
VFT(J) = 0.0
DO 42 I=1, N

C SUM DEPTH OF CUT IN EACH GRID
C2(I, J) = F(I, J) + F(I+1, J) + F(I+1, J+1)

C SUM DEPTH OF FILL IN EACH GRID
VFC(I, J) = VFC(I, J) + VFC(I, J+1) + VFC(I+1, J+1)

C CHECK IF SUM OF DEPTH OF CUT AND FILL IS ZERO IN EACH GRID
IF(C2(I, J) + VFC(I, J)) 46, 45, 46

45 VC(I, J) = 0.0
VFC(I, J) = 0.0
GO TO 244

C CALCULATE TOTAL NUMBER OF INTEGERS IN EACH GRID
46 ID2(I, J) = ID(I, J) + ID(I, J+1) + ID(I+1, J) + ID(I+1, J+1)

C SELECT WHICH OF EQUATIONS (14) TO (23) APPLY
IF(ID2(I, J) = 1) 109, 104, 120
120 IF(ID2(I, J) = 3) 121, 112, 109

C DETERMINE IF STATIONS WID AN CUT ARE ADJACENT OR OPPOSITE
121 IF2(I, J) = 3*I(U(I, J) + 2*ID(I, J+1) + ID(I+1, J)
IF(IF2(I, J) = 3) 107, 109, 107

C CALCULATE EQUATION (15)
104 VC(I, J) = T3*C2(I, J) * (2.0 + (C2(I, J)/3.0*02(I, J) = C2(I, J)))

C CALCULATE EQUATION (16)
105 VFC(I, J) = T1*(D2(I, J) + D2(I, J)) * (3.0*(C2(I, J) + 3.0*D2(I, J)))
GO TO 44

C CALCULATE EQUATION (17)

C CALCULATE EQUATION (18)
108 VFC(I, J) = T2*(D2(I, J) + (D2(I, J) + D2(I, J))/D2(I, J) + C2(I, J)))
GO TO 44

C CALCULATE EQUATION (19)

C CALCULATE EQUATION (20)
110 VFC(I, J) = T1*(D2(I, J) + D2(I, J)) / (C2(I, J) + D2(I, J))
GO TO 44

C CALCULATE EQUATION (21)
112 VC(I, J) = T1*(C2(I, J) + C2(I, J)) * (3.0/(D2(I, J) + 3.0*C2(I, J)))

C CALCULATE EQUATION (22)
113 VFC(I, J) = T3*D2(I, J) * (2.0 + (D2(I, J) + 3.0*C2(I, J) + D2(I, J))

C ADJUST VOLUME OF CUT OR FILL FOR VARIABLE FIRST CROSS ROW BOUNDARY
44 IF(I=1) 200, 250, 200
250 VC(I, J) = VC(I, J) + S3(J)
VFC(I, J) = VFC(I, J) + S3(J)
GO TO 274

C ADJUST VOLUME OF CUT OR FILL FOR VARIABLE LAST CROSS ROW BOUNDARY
200 IF(I=N1) 274, 251, 274
251 VC(I, J) = VC(I, J) + S4(J)
VFC(I, J) = VFC(I, J) + S4(J)

C ADJUST VOLUME OF CUT OR FILL FOR VARIABLE FIRST ROW BOUNDARY
274 IF(J=1) 264, 252, 264
252 VC(I, J) = VC(I, J) + S1(I)
VFC(I, J) = VFC(I, J) + S1(I)
GO TO 244

C ADJUST VOLUME OF CUT OR FILL FOR VARIABLE LAST ROW BOUNDARY
264 IF(J=M1) 244, 253, 244
253 VC(I, J) = VC(I, J) + S2(I)
VFC(I, J) = VFC(I, J) + S2(I)

C SUM VOLUMES OF CUT OR FILL IN EACH ROW
244 VCT(J) = VCT(J) + VC(I, J)
VFT(J) = VFT(J) + VFC(I, J)

42 CONTINUE
43 VT = VCT + VCT(J)

RETURN
END
C
SUBROUTINE WARPB(BB,B,C,K,L,AMAX,AMIX,AMAY,AMIY,ABB,GGG)
C
SUBROUTINE FOR CALCULATING, ADJUSTING, AND CHECKING THE DESIGN
SLOPES IN THE ROW AND CROSS-DIRECTION FOR NON-UNIFORMLY
DIMENSION BB(50, 50), B1(50, 50), B1(50, 50), C(50, 50)
FORM MATRIX FOR NEXT TYPE II DESIGN
DO 14 I=1, K
DO 14 J=1, L
14 B1(I, J) = R(I, J)
C
START ADJUSTMENT OF ELEVATIONS
DO 15 J=1, L
DO 15 I=1, K
Z1 = 9.0
Z2 = 9.0
Z3 = 10.0
Z4 = 10.0
AMA = AMAX * GGG / 100.0
AMI = AMIX * GGG / 100.0
AMAA = AMAY * GGG / 100.0
AMIA = AMIY * GGG / 100.0
C
CHECK FOR ADJUSTMENT AT STATIONS IN FIRST CROSS ROW (I, J)
IF(I, EQ. I) GO TO 30
C
CHECK THAT SLOPE BETWEEN I AND I+1 IS WITHIN ALLOWABLE LIMITS
C
CALCULATE NEW CUT OR FILL
C(I, J) = BB(I, J) - B1(I, J)
C
CHECK IF STATION IS CUT OR FILL
IF(C(I, J),LT,0.0) GO TO 27
C
IF CUT, CALCULATE POSSIBLE ADJUSTMENT Z1
Z1 = ABS(B1(I, J)-B1(I-1, J))=ABS(AMI)
GO TO 26
C
IF FILL, CALCULATE POSSIBLE ADJUSTMENT Z1
27 Z1 = ABS(AMA) =ABS(B1(I, J)-B1(I-1, J))
C
CHECK IF POSSIBLE ADJUSTMENT IS LESS THAN ZERO
28 IF(Z1, LT, 0.0) Z1 = 0.0
C
CHECK FOR ADJUSTMENT AT STATIONS IN LAST CROSS ROW (K, J)
IF(I, EQ. K) GO TO 31
C
CHECK THAT SLOPE BETWEEN I AND I+1 IS WITHIN ALLOWABLE LIMITS
C
CALCULATE NEW CUT OR FILL
C(I+1, J) = BB(I+1, J)-B1(I+1, J)
C
CHECK IF STATION IS CUT OR FILL
IF(C(I, J), LT, 0.0) GO TO 29
C
IF CUT, CALCULATE POSSIBLE ADJUSTMENT Z2
Z2 = ABS(AMI) = ABS(B1(I+1, J)-B1(I, J))
GO TO 32
C
IF FILL, CALCULATE POSSIBLE ADJUSTMENT Z2
29 Z2 = ABS(B1(I+1, J)-B1(I, J)) = ABS(AMIX)
C
CHECK IF POSSIBLE ADJUSTMENT IS LESS THAN ZERO
32 IF(Z2, LT, 0.0) Z2 = 0.0
C
CHECK FOR ADJUSTMENT AT STATIONS IN FIRST ROW (I, 1)
31 IF(J, EQ. 1) GO TO 10
C
CHECK THAT SLOPE BETWEEN J AND J-1 IS WITHIN ALLOWABLE LIMITS
C
CALCULATE NEW CUT OR FILL
C(I, J) = BB(I, J) - B1(I, J)
C CHECK IF STATION IS CUT OR FILL
IF(C(I, J) . LT . 0.0) GO TO 37
C IF CUT, CALCULATE POSSIBLE ADJUSTMENT Z3
Z3 = ABS(B1(I, J) - B1(I, J-1)) - ABS(AMIA)
GO TO 38
C IF FILL, CALCULATE POSSIBLE ADJUSTMENT Z3
Z3 = ABS(AMAA) - ABS(B1(I, J) - B1(I, J-1))
C CHECK IF POSSIBLE ADJUSTMENT IS LESS THAN ZERO
37 IF(Z3 . LT . 0.0) Z3 = 0.0
C CHECK FOR ADJUSTMENT AT STATIONS IN LAST ROW (I, L)
IF(J . EQ. L) GO TO 11
C CHECK THAT SLOPE BETWEEN J AND J+1 IS WITHIN ALLOWABLE LIMITS
C CALCULATE NEW CUT OR FILL
C(I, J+1) = B1(I, J+1) - B1(I, J)
C CHECK IF STATION IS CUT OR FILL
IF(C(I, J) . LT . 0.0) GO TO 39
C IF CUT, CALCULATE POSSIBLE ADJUSTMENT Z4
Z4 = ABS(AMAA) - ABS(B1(I, J+1) - B1(I, J))
GO TO 42
C IF FILL, CALCULATE POSSIBLE ADJUSTMENT Z4
39 Z4 = ABS(B1(I, J+1) - B1(I, J)) - ABS(AMIA)
C CHECK IF POSSIBLE ADJUSTMENT IS LESS THAN ZERO
42 IF(Z4 . LT . 0.0) Z4 = 0.0
C CHOOSE THE MINIMUM VALUE OF Z1, Z2, Z3, AND Z4
11 Z8 = AMIN1(Z1, Z2, Z3, Z4)
Z7 = Z8
C SET CUT OR FILL EQUAL TO ZERO IF ALREADY WITHIN SLOPE LIMITATIONS
IF(ABS(C(I, J)) . LT. Z8) C(I, J) = 0.0
C ADJUST THE CUT WHEN CUT IS GREATER THAN OR EQUAL TO Z8
IF(C(I, J) . GE. Z8) C(I, J) = C(I, J) - Z8
C ADJUST THE FILL WHEN FILL IS GREATER THAN OR EQUAL TO Z8
IF(C(I, J) . LE. Z7) C(I, J) = C(I, J) + Z8
C CALCULATE NEW ELEVATION
15 B1(I, J) = B1(I, J) - C(I, J)
C CALCULATE ABSOLUTE VALUE OF DIFFERENCE IN ELEVATION BETWEEN
C CONSECUTIVE ADJUSTMENTS
ABB = 0.0
DO 24 I = 1, K
DO 24 J = 1, L
24 ABB = ABB + ABS(B1(I, J) - B(I, J))
RETURN
END
SUBROUTINE BHNA(K, L, AV, SLP, AF, AMAX, AMIX, AMAY, AMIY, 61, AVY, GGG)

SUBROUTINE FOR CALCULATING AND ADJUSTING DESIGN ELEVATIONS FOR

SHIH AND KHI'S DESIGN TYPE IV

DIMENSION AV(SO), SLP(SO), B(SO, 50), B1(50, SO), S(SO)

CHECK AND ADJUST TO BE WITHIN ALLOWABLE ROW SLOPES

AMIA = AMIY * GGG / 100.0
AMAA = AMAY * GGG / 100.0
DO 64 J=1, L
IF(SLP(J), GT, AMIX) GO TO 51
IF(SLP(J), LT, AMAX) SLP(J) = AMAX
GO TO 64

51 SLP(J) = AMIX
64 CONTINUE

CALCULATE CONSTANT A IN EACH ROW

DO 12 J=1, L
12 S(J) = AV(J) - SLP(J) * AF * GGG / 100.0

CALCULATE DESIGN ELEVATION

DO 19 J=1, L
DO 19 I=1, K
FI = I
19 B1(I, J) = S(J) + SLP(J) * FI * GGG / 100.0

FORM MATRIX FOR NEXT TYPE III DESIGN

DO 82 J=1, L
DO 82 I=1, K
82 B1(I, J) = B(I, J)

START ADJUSTMENT PROCEDURE

M3 = L = 1
DO 66 J=1, M3
DO 66 I=1, K

CALCULATE EQUATION (34)

AY = B1(I, J) - B1(I, J+1) + AMIA

CHECK IF AY IS POSITIVE OR NEGATIVE

IF(AY) 68, 66, 69

IF NEGATIVE, CALCULATE NEW ELEVATION AT J+1

68 B1(I, J+1) = B1(I, J) + AMIA

GO TO 66

IF POSITIVE, CALCULATE NEW ELEVATION AT J+1

69 IF(AY, GT, ABS(AMAA-AMIA)) B1(I, J+1) = B1(I, J) + AMAA
66 CONTINUE

CALCULATE ABSOLUTE VALUE OF DIFFERENCE IN ELEVATION BETWEEN

CONSECUTIVE ADJUSTMENTS

AVY = 0.0
DO 85 J=1, L
DO 85 I=1, K
85 AVY = AVY + ABS(B1(I, J) - B(I, J))

RETURN
END
SUBROUTINE BRKN(K,L,AV,SLP,AS,AMAX,AMIX,AMAY,Bl,AVY,GGG)

SUBROUTINE FOR CALCULATING AND ADJUSTING DESIGN ELEVATIONS FOR SHIH AND KkIZ'S DESIGN TYPE III

DIMENSION AV(SOl, SLPCSO), 6(50, 50), S(SO)

CHECK AND ADJUST TO BE WITHIN ALLOWABLE ROW SLOPES

AMAA = AMAY * GGG / 100.0
AMIA = AMIY * GGG / 100.0
DO 64 J=1, L
IF(SLPCJ) > AMIX) GO TO 51
IF(SLP(J), LT, AMAX) SLP(J) = AMAX
GO TO 64

51 SLP(J) = AMIX
CONTINUE

C CHECK AND ADJUST TO BE WITHIN ALLOWABLE ROW SLOPES

AMAA = AMAY * GGG / 100.0
AMIA = AMIY * GGG / 100.0
DO 64 J=1, L
IF(SLPCJ) > AMIX) GO TO 51
IF(SLP(J), LT, AMAX) SLP(J) = AMAX
GO TO 64

51 SLP(J) = AMIX
CONTINUE

C CALCULATE CONSTANT A IN EACH ROW
DO 12 J=1, L
12 S(J) = AV(J) - SLP(J) * AS * GGG / 100.0

C CALCULATE DESIGN ELEVATION
DO 19 J=1, L
DO 19 I=1, K

19 BI(I, J) = S(J) + SLP(J) * FI * GGG / 100.0

C FORM MATRIX FOR NEXT TYPE IV DESIGN
DO 82 J=1, L
DO 82 I=1, K

82 BI(I, J) = BI(I, J)

C START ADJUSTMENT PROCEDURE
M3 = L - 1
DO 66 J=1, M3
DO 66 I=1, K

C CALCULATE ELEVATION DIFFERENCE BETWEEN STATIONS J AND J+1
AY = BI(I, J) - BI(I, J+1)

C CHECK THAT SLOPE BETWEEN J AND J+1 IS WITHIN ALLOWABLE LIMITS
IF(ABS(AY) = ABS(AMAA)) 6b, 6b, 67

C CHECK IF AY IS POSITIVE OR NEGATIVE
IF(AY) = 6b, 6b, 69

C IF NEGATIVE, CALCULATE NEW ELEVATION AT J+1
68 BI(I, J+1) = BI(I, J) - AMAX
GO TO 66

C IF POSITIVE, CALCULATE NEW ELEVATION AT J+1
69 BI(I, J+1) = BI(I, J) + AMAX
GO TO 66

CONTINUE

C CALCULATE ABSOLUTE VALUE OF DIFFERENCE IN ELEVATION BETWEEN CONSECUTIVE ADJUSTMENTS
AVY = 0.0
DO 85 J=1, L
DO 85 I=1, K

85 AVY = AVY + ABS(BI(I, J) - BI(I, J))
RETURN
END
SUBROUTINE WRAP(BB,B1,C,K,L,AMAX,AMIX,AMAY,ABB,GGG)

C SUBROUTINE FOR CALCULATING, ADJUSTING, AND CHECKING THE DESIGN
C SLOPES IN THE ROW AND CROSS-DIRECTION FOR NGN=UNIFORMLY
C GRADED SURFACES
C DIMENSION BB(50, 50), B2(50, 50), B1(50, 50), C(50, 50)
C FORM MATH FOR NEXT TYPE V DESIGN

C DIMENSION B(50, 50), B2(50, 50), B1(50, 50), C(50, 50)
C FORM MATH FOR NEXT TYPE V DESIGN

AMIX = AMIX * GGG / 100.0
AMAY = AMAY * GGG / 100.0
AMAX = AMAX * GGG / 100.0

C CHECK THAT SLOPE BETWEEN I AND I-1 IS WITHIN ALLOWABLE LIMITS

GO TO 15

C CHECK FOR ADJUSTMENT AT STATIONS IN FIRST CROSS ROW (I, J)
C IF(1.EQ.1) GO TO 30
C CHECK THAT SLOPE BETWEEN I AND I-1 IS WITHIN ALLOWABLE LIMITS
C CALCULATE NEW CUT OR FILL
C(C(I, J))=B(I, J)-B2(I, J)
C CHECK IF STATION IS CUT OR FILL
C(C(I, J),LT,0.0) GO TO 27
C IF CUT, CALCULATE POSSIBLE ADJUSTMENT Z1
Z1 =ABS(B2(I, J)-B2(I-1, J)) -ABS(AMI)
GO TO 26
C IF FILL, CALCULATE POSSIBLE ADJUSTMENT Z1
Z1 = ABS(AMI) -ABS(B2(I, J)-B2(I-1, J))
C CHECK IF POSSIBLE ADJUSTMENT IS LESS THAN ZERO
C IF(Z1 LT,0.0) Z1 0.0
C CHECK FOR ADJUSTMENT AT STATIONS IN LAST ROW (K, J)
C IF(1.EQ.K) GO TO 31
C CHECK THAT SLOPE BETWEEN I AND I+1 IS WITHIN ALLOWABLE LIMITS
C CALCULATE NEW CUT OR FILL
C(C(I, J))=B(I+1, J)-B2(I+1, J)
C CHECK IF STATION IS CUT OR FILL
C(C(I, J), LT, 0.0) GO TO 29
C IF CUT, CALCULATE POSSIBLE ADJUSTMENT Z2
Z2 = ABS(AMI) -ABS(B2(I+1, J)) -B2(I, J))
GO TO 32
C IF FILL, CALCULATE POSSIBLE ADJUSTMENT Z2
Z2 = ABS(B2(I+1, J)) -B2(I, J)) -ABS(AMI)
C CHECK IF POSSIBLE ADJUSTMENT IS LESS THAN ZERO
C IF(Z2 LT,0.0) Z2 = 0.0
C CHECK FOR ADJUSTMENT AT STATIONS IF FIRST ROW (I, 1)
C IF(J .EQ 1) GO TO 10
C CALCULATE POSSIBLE ADJUSTMENT Z3
Z3 =ABS(AMI) -ABS(B2(I, J)-B2(I, J))
C CHECK IF POSSIBLE ADJUSTMENT IS LESS THAN ZERO
C IF(Z3 LT,0.0) Z3 = 0.0
C CHECK FOR ADJUSTMENT AT STATIONS IN LAST ROW (I, L)
C IF(J .EQ L) GO TO 11
C CALCULATE POSSIBLE ADJUSTMENT Z4
Z4 = ABS(AMI) -ABS(B2(I, J)+B2(I, J))
C CHECK IF POSSIBLE ADJUSTMENT IS LESS THAN ZERO
C IF(Z4 LT,0.0) Z4 = 0.0
C MOUSE THE MINIMUM VALUE OF Z1, Z2, Z3, AND Z4
Z8 = MIN(Z1, Z2, Z3, Z4)
Z7 = Z8
C SET CUT OR FILL EQUAL TO ZERO IF ALREADY WITHIN SLOPE LIMITATIONS
C IF(ABS(C(I, J)) LT, Z8) C(I, J) = 0.0
C ADJUST THE CUT WHEN CUT IS GREATER THAN OR EQUAL TO Z8
C IF(C(I, J), GE, Z8) C(I, J) -C(I, J) = Z8

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# 1364
SUBROUTINE PAUL(KKP, NX, NY, CEN, CUTP, CUTH, LF, DF, GRADL, # 1384
1 SLOPEX, SLOPEY, RC, RU, TCMSPA, TCMX, CUYPA, H, COTY, CUTY2, # 1385
1 GGG) # 1386
C SUBROUTINE FOR PERFORMING LAND GRADING DESIGNS USING PAUL'S # 1387
C METHODS # 1388
DIMENSION H(SO, SO) , CALHCSO, 50), CUTCSO, # 1389
1 COTY2(20) # 1390
INTEGER X, Y, D, F, B, # 1391
1 REAL LF, NSLOX, NSLOY, LMYC, LMXC, LMY, LNX, NY # 1392
C DEPTHS OF CUTS AND FILLS MUST BE LESS THAN 10 FEET # 1393
C GROUND SURFACE ELEVATION MUST BE GREATER THAN ZERO AND LESS THAN # 1394
1 100 FEET # 1395
C MAXIMUM SUM OF CUTS OR FILLS MUST BE LESS THAN 1000 FEET # 1396
C ALL DEPTHS OF CUTS AND FILLS AND ELEVATIONS ARE IN FEET # 1397
C ALL INPUT DATA AND RESULTS ARE IN FEET EXCEPT THE VOLUMES OF EARTH # 1398
C WORK WHICH ARE IN CUBIC YARDS # 1399
C FORMAT STATEMENTS FOR PRINTING INPUTS AND OUTPUTS # 1400
4 FORMAT(SX,' 15F8.2') # 1401
5 FORMAT(14,3X,15F8.2) # 1402
6 FORMAT(7X,15F8.2) # 1403
100 FORMAT(1H1,30X,'COMPUTER MINIMIZED COST METHOD FOR A PLANE') # 1404
108 FORMAT(1H0'ELEVATIONS AT STAKES') # 1405
113 FORMAT(1H1,30X,'LEAST SQUARES METHOD FOR A PLANE') # 1406
114 FORMAT(1H1,30X,'DOUBLCENTROID METHOD FOR A PLANE') # 1407
115 FORMAT(1H1,30X,'AVERAGE SLOPE METHOD FOR A PLANE') # 1408
142 FORMAT(1H0'CUTS (POSITIVE) FILLS (NEGATIVE)') # 1409
149 FORMAT(1H0'CALH (CALCULATED ELEVATIONS)') # 1410
700 FORMAT(1H0'NUMBER OF STATIONS IN THE X-DIRECTION =',I5,' AND N # 1411
1 NUMBER OF STATIONS IN THE Y-DIRECTION =',I5) # 1412
701 FORMAT(1H0'NUMBER OF STATIONS IN THE X-DIRECTION =',I5'] # 1413
702 FORMAT(1H0'NUMBER OF STATION IN THE Y-DIRECTION =',I5,1H0'TOTAL DEPTH OF # 1414
1 CUT =',F8.2,1H0' FT') # 1415
703 FORMAT(1H0'EXPECTED CUT-FILL RATIO =',F8.3',' AND CALCULATED CU # 1416
1T =FILL RATIO =',F8.3) # 1417
704 FORMAT(1H0'LOAD FACTOR =',F8.3,' $/FT AND DISTANCE FACTOR =', # 1418
1F8.3,' $/FT/100 FT') # 1419
705 FORMAT(1H0'TOTAL COST =',F9.2,' $ AND UNIT COST =',F9.2,' $/A # 1420
1CRE') # 1421
706 FORMAT(1H0'SLOPE IN THE X-DIRECTION =',F10.3,' AND SLOPE IN THE # 1422
1Y-DIRECTION =',F10.3) # 1423
707 FORMAT(1H0'EXCAVATION VOLUME =',F10.3,' Cu YD/ ACRE') # 1424
708 FORMAT(1H0'TOTAL AREA OF THE FIELD =',F10.3,' ACRE') # 1425
WRITE(6,4) (COTY(I), I=1, 20) # 1426
WRITE(6,4) (COTY2(I), I=1, 20) # 1427
1 NY = NUMBER OF ELEVATIONS IN THE Y-DIRECTION # 1428
WRITE(6,108) # 1429
IF(NX = 15) 1, 1, 2 # 1430
1 DO 3 Y=1, NY # 1431
3 WRITE(6,5) Y, (H(X, Y), X=1, NX) # 1432
GO TO 103 # 1433
2 DO 7 Y=1, NY # 1434
WRITE(6,5) Y, (H(X, Y), X=1, 15) # 1435
READ(b,b1) (H(X, Y), X=1, 5, Y=1, 5)

N = NUMBER OF ELEVATIONS IN THE ARRAY
N = NX * NY
CALCULATING THE ELEVATION OF THE CENTROID
SUMH = SUM OF ELEVATIONS
SUMH=0, 0
DO 160 X=1, NX
DO 160 Y=1, NY
SUMH=SUMH+H(X,Y)
160 CONTINUE

CONTINUE
CEN=SUMH/N
GRADL
GRADL=(1.0+K0)/(2.0*RO*N)•(RO•ABS(CUTN)•CUTP)
DETERMINE CUTS AND FILLS AFTER LOWERING THE GRADE LINE
CALL CNF(CEN,H,SLOPEX,SLOPEY,NX,NY,CUTP,CUTN,CUYPA,CALH,CUT,GRADL,
1 N, GGG)
GRADL=(1.0+RO)/(2.0•RO•N)•(RO•ABS(CUTN)•CUTP)
DETERMINE CUTS AND FILLS AFTER LOWERING THE GRADE LINE
CALL CNF(CEN,H,SLOPEX,SLOPEY,NX,NY,CUTP,CUTN,CUYPA,CALH,CUT,GRADL,
1 N, GGG)
RC=ABS(CUTP/CUTN)
TCMS = TOTAL COST OF MOVING SOIL IN DOLLARS
K IS SET EQUAL TO 1 BEFORE ENTERING THE SUBPROGRAM SPTCMS
K=1
TCMS=0, 0
CALL SPTCMS (NX,NY,LF,DF,TCMS,K,CUT,RC)
GO TO (901, 340, 340, 340), KKP
PROCEED WITH THE COMPUTER MINIMIZED COST METHOD
SLOPEX = SLOPE MOST RECENTLY CALCULATED IN THE X-DIRECTION
SLOPES = SLOPE IN THE X-DIRECTION BY LEAST SQUARES METHOD
TCMS = MOST RECENTLY CALCULATED TOTAL COST OF MOVING THE SOIL
TCMSLS = TCMS USING LEAST SQUARES SLOPE
SLOPEX=SLOPESLS+0.01
CALL CNF(CEN,H,SLOPEX,SLOPEY,NX,NY,CUTP,CUTN,CUYPA,CALH,CUT,GRADL,
1 N, GGG)
GRADL=(1.0+RO)/(2.0*RO*N)•(RO•ABS(CUTN)•CUTP)
DETERMINE CUTS AND FILLS AFTER LOWERING GRADE LINE
CALL CNF(CEN,H,SLOPEX,SLOPEY,NX,NY,CUTP,CUTN,CUYPA,CALH,CUT,GRADL,
1 N, GGG)
RC=ABS(CUTP/CUTN)
C K IS SET EQUAL TO 1 BEFORE ENTERING THE SUBPROGRAM SPTCMS
K=1
TCMS=0,0
CALL SPTCMS(NX,NY,LF,DF,TCMS,K,CUT,RC)
IF(TCMS .GT. TCMSLS) GO TO 17
A=0.01
GO TO 18
17 A=-0.01
18 TCMS=TCMSLS
DO 393 I=1,20
C TCMS = PREVIOUSLY CALCULATED TOTAL COST OF MOVING SOIL IN DOLLARS
TCMS=TCMS
SLOPEX=SLOXLS+I*A
C SLOYP = SLOPE PREVIOUSLY CALCULATED IN THE X-DIRECTION
SLOYP=SLOPEX=A
C DETERMINE CUTN AND CUTP SO THAT GRADL CAN BE CALCULATED BASED ON R = 0
GRADL=0,0
CALL CNF(CEN,H,SLOPEX,SLOPEY,NX,NY,CUTN,CUYPA,CALH,CUT,GRADL,1 N, GGG)
GRADL=((1.0+R0)/(2.0*R0*M))*(R0*ABS(CUTN)-CUTP)
C DETERMINE CUTS AND FILLS AFTER LOWERING GRADE LINE
CALL CNF(CEN,H,SLOPEX,SLOPEY,NX,NY,CUTN,CUYPA,CALH,CUT,GRADL,1 N, GGG)
RC=ABS(CUTP/CUTN)
C K IS SET EQUAL TO 1 BEFORE ENTERING THE SUBPROGRAM SPTCMS
K=1
TCMS=0,0
CALL SPTCMS(NX,NY,LF,DF,TCMS,K,CUT,RC)
IF(TCMS .GT. TCMSLS) GO TO 17
A=0.01
GO TO 28
393 CONTINUE
C SLOPEX = SLOPE WHICH GIVES THE MINIMUM COST
SLOPEX=SLOXP
TCMS=TCMS
SLOPEY=SLOYS+0.01
C SLOPEY = SLOPE MOST RECENTLY CALCULATED IN THE X-DIRECTION
SLOPEY=SLOPEY
SLOYS=SLOPEY
TCMSLS=TCMS
SLOPEY=SLOYS+0.01
C DETERMINE CUTN AND CUTP SO THAT GRADL CAN BE CALCULATED BASED ON R = 0
GRADL=0,0
CALL CNF(CEN,H,SLOPEX,SLOPEY,NX,NY,CUTN,CUYPA,CALH,CUT,GRADL,1 N, GGG)
GRADL=((1.0+R0)/(2.0*R0*N))*(R0*ABS(CUTN)-CUTP)
C DETERMINE CUTS AND FILLS AFTER LOWERING GRADE LINE
CALL CNF(CEN,H,SLOPEX,SLOPEY,NX,NY,CUTN,CUYPA,CALH,CUT,GRADL,1 N, GGG)
RC=ABS(CUTP/CUTN)
C K IS SET EQUAL TO 1 BEFORE ENTERING THE SUBPROGRAM SPTCMS
K=1
TCMS=0,0
CALL SPTCMS(NX,NY,LF,DF,TCMS,K,CUT,RC)
IF(TCMS .GT. TCMSLS) GO TO 27
A=0.01
GO TO 28
27 A=-0.01
28 TCMS=TCMSLS
DO 392 I=1,20
C TCMS = PREVIOUSLY CALCULATED TOTAL COST OF MOVING SOIL IN DOLLARS
TCMS=TCMS
SLOPEY=SLOYS+I*A
SLOYP=SLOPEY=A
C DETERMINE CUTN AND CUTP SO THAT GRADL CAN BE CALCULATED BASED ON R 0
GRADL=0.0
CALL CNF(CEN,H,SLOPEX,SLOPEY,NX,NY,CUTP,CUTN,CUYPA,CALH,CUT,GRADL,
1 N, GGG)
GRADL=((1.0+R0)/(2.0*R0*N))*(RO*ABS(CUTN)-CUTP)
C DETERMINE CUTS AND FILLS AFTER LOWERING GRADE LINE
CALL CNF(CEN,H,SLOPEX,SLOPEY,NX,NY,CUTP,CUTN,CUYPA,CALH,CUT,GRADL,
1 N, GGG)
RC=ABS(CUTP/CUTN)
C K IS SET EQUAL TO 1 BEFORE ENTERING THE SUBPROGRAM SPTCMS
K=1
TCMS=0.0
CALL SPTCMS(NX,NY,LF,DF,TCMS,K,CUT,RC)
IF(TCMS.GT.TCMS) GO TO 29
CONTINUE
C SLOPEY=SLOPE WHICH GIVES THE MINIMUM COST
SLOPEY=SLOPP
TCMS=TCMS
CONTINUE
C MUST CALL CNF AGAIN BECAUSE CUTS ARE CHANGED IN SPTCMS
CALL CNF(CEN,H,SLOPEX,SLOPEY,NX,NY,CUTP,CUTN,CUYPA,CALH,CUT,GRADL,
1 N, GGG)
C PRINTING FINAL RESULTS
WRITE(b,149)
8 IF(NX=15) 8, 8, 9
10 WRITE(b, S) Y, (CALH(X, Y), X = 1, NX)
GO TO 12
9 DO 11 Y = 1, NY
WRITE(b,5) Y, (CALH(X, Y), X = 1, 15)
11 WRITE(b,6) (CALH(X, Y), X = 16, NX)
12 WRITE(b, 142)
13 DO 15 Y = 1, NY
WRITE(b,6,5) Y, (CUT(X, Y), X = 1, NX)
GO TO 121
14 DO 16 Y = 1, NY
WRITE(b,6,5) Y, (CUT(X, Y), X = 1, NX)
16 WRITE(b,6, 2) (CUT(X, Y), X = 16, NX)
C TCMSPA TOTAL COST OF MOVING SOIL PER ACRE
TCMSPA=TCMS/((GGG*GGG*N)/43560.0)
C CALCULATING THE TOTAL AREA OF THE FIELD
AREA = GGG*GGG * N /43560.0
WRITE(b,700) NX, NY
WRITE(b,704) LF, DF
WRITE(b,705) AREA
WRITE(b,706) SLOPEX, SLOPEY
WRITE(b,701) CEN
WRITE(b,703) RO, RC
WRITE(b,702) CUTP, CUTN
WRITE(b,707) CUYPA
WRITE(b,705) TCMS, TCMSPA
RETURN
END
SUBROUTINE LEAST(CEN, N, NX, NY, H, SLOPEX, SLOPEY, GGG)
SUBROUTINE FOR CALCULATING ROW AND CROSS-ROW DESIGN SLOPES USING
THE LEAST SQUARES TECHNIQUE, AND CALCULATING CENTROID ELEVATION
AND LOCATION

DIMENSION H(50, 50)

DETERMINE STARTING SLOPE WITH THE LEAST SQUARES METHOD

SLOPEX = SLOPE IN THE X-DIRECTION

SHX = SUM OF THE PRODUCT OF THE ELEVATION TIMES THE X-COORDINATE

SHX = 0,00

SXS = SUM OF X

SXS = 0,0

SX = SUM OF X

SX = 0,0

DO 170 X=1,NX

DO 171 Y=1, NY

SHX = SHX + H(X, Y) * X

SXS = SXS + X**2

SX = SX + X

170 CONTINUE

SHX = SHX * N * CEN * ( (NX + 1)/2.0 ) / ( SXS * SX**2/N ) / 100.0 / GGG

SLOPEX = SLOPE IN THE Y-DIRECTION

SHY = SUM OF PRODUCT OF THE ELEVATION TIMES THE Y-COORDINATE

SHY = 0,0

SYS = SUM OF Y

SYS = 0,0

SY = SUM OF Y

SY = 0,0

DO 180 X=1,NX

DO 181 Y=1, NY

SHY = SHY + H(X, Y) * Y

SYS = SYS + Y**2

SY = SY + Y

181 CONTINUE

SLOPEY = SLOPE IN THE Y-DIRECTION

SY = SY * N * CEN * ( (NY + 1)/2.0 ) / ( SYS * SY**2/N ) / 100.0 / GGG

RETURN

END
SUBROUTINE CNF(CE1,E,SLOPX1,SLOPY1,NX1,NY1,CUP1,CUN1,CYP1,A1,CU
11,GRAD1,N1,GGG)
SUBROUTINE FOR CALCULATING DEPTHS AND VOLUMES OF CUTS AND FILLS
USING THE SUMMATION METHOD
DIMENSION E(50, 50), CAL1 (50, 50), CU1 (50, 50)
REAL NX1, NY1
INTEGER X, Y
MULTIPLE REGRESSION FORMULA
IF(MOD(NX1,2),NE,0) GO TO 17
IF(MOD(NY1,2),NE,0) GO TO 18
WHEN X EVEN AND Y EVEN
BEGIN=CE1*(SLOPX1/2.0+(NX1/2.0)*SLOPX1+SLOPY1/2.0+(NY1/2.0)*SLOPY1) * GGG
1 / 100,0
GO TO 23
WHEN X EVEN AND Y ODD
16 BEGIN=CE1*(SLOPX1/2.0+(NX1/2.0)*SLOPX1+(NY1+1)/2.0)*SLOPY1) * GGG
1 / 100,0
GO TO 23
WHEN X ODD AND Y EVEN
BEGIN=CE1-((NX1+1)/2.0)*SLOPX1+(NY1/2.0)*SLOPY1) * GGG
1 / 100,0
GO TO 23
WHEN X ODD AND Y ODD
BEGIN=CE1-((NX1+1)/2.0)*SLOPX1+(NY1+1)/2.0)*SLOPY1) * GGG
1 / 100,0
GO TO 23
CAL1 = CALCULATED ELEVATIONS
DO 210 X=1,NX1
DO 211 Y=1,NY1
CAL1(X,Y)=BEGIN+(SLOPX1*X+SLOPY1*Y) * GGG/100,0 - GRAD1
CONTINUE
CONTINUE
CUTS ARE POSITIVE AND FILLS ARE NEGATIVE
DO 220 X=1,NX1
DO 221 Y=1,NY1
CU1(X,Y)=E(X,Y)-CAL1(X,Y)
CONTINUE
CONTINUE
SUMMATION OF CUTS
CUP1=0,0
DO 222 X=1,NX1
DO 224 Y=1,NY1
IF(CU1(X,Y),LT,0,0) GO TO 224
CUP1=CUP1+CU1(X,Y)
CONTINUE
SUMMATION OF FILLS
CUN1=0,0
DO 240 X=1,NX1
DO 241 Y=1,NY1
IF(CU1(X,Y),GT,0,0) GO TO 241
CUN1=CUN1+CU1(X,Y)
CONTINUE
SUM OF CUTS IN CUBIC YARDS PER ACRE
CYP1=((CUP1*GGG*GGG)/27.0)/((GGG*GGG*N1)/43560.0)
RETURN
END
SUBROUTINE SPTCHS(NX1, NY1, L1, D1, TCM1, K1, CU1, RC1)
SUBROUTINE FOR DETERMINING THE COST OF MOVING THE EARTH USING THE LOAD-DISTANCE FACTOR THEORY
DIMENSION CU1(50,50)
INTEGER V, w, X, Y, A1, A2, A3, A4, A5, A6, A7, A
REAL L1, NX1, NY1

DETERMINE THE COST OF MOVING THE SOIL
LOCATE A CUT
CONTINUE
DO 260 W=1, NY1
DO 261 V=1, NX1
IF(CU1(V, W), LE, 0, 0) GO TO 261
CUM1 = CU1(V, W)
LOCATING A CUT FOR EACH CUT M
DO LOOP FOR ENLARGING THE RADIUS OF THE CIRCLE AROUND A CUT
DO 250 I=1, 20
A1 = V+1
A2 = W+1
A3 = W+1
A4 = V-1
A5 = V-1
A6 = W-1
A7 = W-1

ITERATION ON ONE SIDE OF CUT
DO 270 Y=A7, A7
DO 271 X=A5, A
RESTRICT SEARCH FOR FILL TO THE FIELD
IF(X, LT, 1, OR, X, GT, NX1, OR, Y, LT, 1) GO TO 271
IF(.NOT., (CU1(X, Y), LT, 0, 0)) GO TO 271
CALL FLXFLY(V, W, X, Y, TCM1, CU1, L1, D1, K1, CUM1, RC1)
IT DEPENDS IF CUTS NEED MORE CUTTING OR IF FILLS NEED MORE FILLING
GO TO (10, 51, 201)
K1
CONTINUE
CONTINUE
ITERATIONS ON ONE SIDE OF CUT
DO 272 X=A1, A1
DO 273 Y=A7, A2
RESTRICTS SEARCH FOR FILL TO THE FIELD
IF(Y, LT, 1, OR, Y, GT, NY1, OR, X, GT, NX1) GO TO 273
IF(.NOT., (CU1(X, Y), LT, 0, 0)) GO TO 273
CALL FLXFLY(V, W, X, Y, TCM1, CU1, L1, D1, K1, CUM1, RC1)
IT DEPENDS IF CUTS NEED MORE CUTTING OR IF FILLS NEED MORE FILLING
GO TO (10, 51, 261), K1
275 CONTINUE
272 CONTINUE
C ITEMATIONS ON ONE SIDE OF CUT
DO 274 Y=AS,A3
DO 275 X=AI,A1
C RESTRICTS SEARCH FOR FILL TO THE FIELD
IF(X.LT.0. OR.X.GT.NX1.OR.Y.GT.NY1) GO TO 275
IF(.NOT.(CUI(X,Y).LT.0.0)) GO TO 275
CALL FLXFLY(Vh,XY,TCH1,CUI,L1,D1,K1,CUM1,RC1)
C IT DEPENDS IF CUTS NEED MORE CUTTING OR IF FILLS NEED MORE FILLING
GO TO (10, 51, 261), K1
275 CONTINUE
274 CONTINUE
250 CONTINUE
261 CONTINUE
260 CONTINUE
RETURN
END

SUBROUTINE FLXFLYC8,C,D,E,TCM2,CU2,L2,D2,K2,CUTM,RC2)
SUBROUTINE FOR DETERMINING EARTH-MOVEMENT PATTERN TO MINIMIZE
REAL L2
DIMENSION CU2(S0,50)
HAVE LOCATED A FILL OR NEGATIVE CUT
DEPOSITE SOIL AND DETERMINE IF WE HAVE AN EXCESS OR NEED MORE SOIL
DIFF = DIFFERENCE BETWEEN CUTM AND FILL OR NEGATIVE CUT
DIFF IS NEGATIVE IF ADDITIONAL CUTM IS REQUIRED
THE FILLS MUST BE MULTIPLIED BY THE RATIO SO CUTS AND FILLS WILL
BALANCE
DIFF=CU2(D,E)*RC2+CUTM
IF(DIFF,LT,0) GO TO 46
CUTAM=CUTM+DIFF
DIST=SQRT((C-E)*(C-E)+(D-B)*(D-B))
CMS=CUTAM+L2+CUTAM*DIST*D2
CU2(D,E)=0.0
CU2(B,C)=DIFF
K2=2
GO TO 55
46 CUTAM=CUTM
DIST=SQRT((C-E)*(C-E)+(D-B)*(D-B))
CMS=CU2(D,E)+L2+CU2(D,E)*DIST*D2
CU2(D,E)=0.0
CU2(B,C)=DIFF
K2=3
55 CONTINUE
TCH2=TCH2+CMS
CUL2=CUTM*L2
DIST2=DIST*D2
RETURN
END
SUBROUTINE DOUBLE(CEN, N, NX, NY, H, SLOPEX, SLOPEY, GGG)
DIMENSION H(50, 50)
C SLOPEX (SLOPE IN THE X DIRECTION)
IF(MOD(NX, 2).EQ. 0) GO TO 53
C ODD NUMBER OF STATIONS IN THE X-DIRECTION
C FMXC = SUM OF FIRST HALF OF ELEVATIONS IN THE X-DIRECTION EXCEPT 
REAL LMXC, LMX, LMYC, LMY
C CENTER ROW
FMXC=0.0
B2=(NX+1)/2
DO 181 X=1,B2
DO 182 Y=1,NY
FMXC=FMC+H(X,Y)
CONTINUE
CONTINUE
182 CONTINUE
181 CONTINUE
C LMXC = SUM OF LAST HALF OF ELEVATIONS IN THE X-DIRECTION EXCEPT 
C CENTER ROW
LMXC=0.0
B4=((NX+1)/2)+1
DO 184 X=B4,NX
DO 185 Y=1,NY
LMXC=LMXC+H(X,Y)
CONTINUE
CONTINUE
185 CONTINUE
SLOPEX=((LMXC-FMXC)*4.0*NX)/(N*(NX*2-1)) * 100.0 / GGG
GO TO 5a
C EVEN NUMBER OF STATIONS IN THE X-DIRECTION
C FMX = SUM OF FIRST HALF OF ELEVATIONS IN THE X-DIRECTION
FMX=0.0
B&=NX/2
DO 179 X=1, B
DO 180 Y=1,NY
FMX=FMX+H(X,Y)
CONTINUE
CONTINUE
179 CONTINUE
180 CONTINUE
C LMX = SUM OF LAST HALF OF ELEVATIONS IN THE X-DIRECTION
LMX=0.0
B3=(NX-1)/2
DO 172 X=B3,NX
DO 173 Y=1,NY
LMX=LMX+H(X,Y)
CONTINUE
CONTINUE
172 CONTINUE
SLOPEX=((LMX-FMX)*4.0)/(NX*NY) * 100.0 / GGG
C SLOPEY = SLOPE IN THE Y-DIRECTION
IF(MOD(NY, 2).EQ. 0) GO TO 54
C ODD NUMBER OF STATIONS IN THE Y-DIRECTION
C FHYC = SUM OF FIRST HALF OF ELEVATIONS IN THE Y-DIRECTION EXCEPT 
REAL LHYC, LHY
C CENTER ROW
FHYC=0.0
B5=(NY+1)/2
DO 187 X=1,NX
DO 188 Y=1,B5
FHYC=FHYC+H(X,Y)
CONTINUE
CONTINUE
187 CONTINUE
188 CONTINUE
C LMYC = SUM OF THE LAST HALF OF ELEVATIONS IN THE Y-DIRECTION
SUBROUTINE AVERAGE(CEN, N, NX, NY, H, SLOPEX, SLOPEY, GGG)  
THE AVERAGE SLOPE TECHNIQUE  
DIMENSION H(50, 50)  
SLOPES (SLOPES IN FEET PER 100 FEET BY AVERAGE SLOPE METHOD)  
SUMSLX (SUM OF SLOPES BETWEEN STAKES IN THE X DIRECTION)  
NSLOX (NUMBER OF SLOPES IN THE X DIRECTION)  
REAL NSLOX, NSLOY  
SUMSLX=0.0  
NSLOX=0.0  
DO 171 X=2, NX  
DO 170 Y=1, NY  
D=X-1  
SUMSLX=SUMSLX+(H(X, Y))  
NSLOX=NSLOX+1  
170 CONTINUE  
171 CONTINUE  
SLOPEX = AVERAGE SLOPE IN THE X-DIRECTION  
SLOPEX=(SUMSLX/NSLOX) * 100.0 / GGG  
SLOPEY = SUM OF SLOPES BETWEEN STAKES IN THE Y-DIRECTION  
NSLOY = NUMBER OF SLOPES IN THE Y-DIRECTION  
NSLOY=NSLOY+1  
180 CONTINUE  
181 CONTINUE  
SLOPEY = AVERAGE SLOPE IN THE Y-DIRECTION  
SLOPEY=(SUMSLY/NSLOY) * 100.0 / GGG  
RETURN  
END
SUBROUTINE SCSCH, SLOPEX, SLOPEY, NX, NY, CEN, ICT, IFL, ECF, VRCF, VCTT, VFTT, IOCT, IOFL, AVCTT, ACOST, AREA, TCOST, R1, R2, 2 R3, N4, DECF, COST, EXVC, EXVF, DSC, D5F, COTY, COTY2, GGG)

SUBROUTINE FOR PERFORMING LAND GRADING DESIGNS USING THE SCS METHOD

DIMENSION H(50,50), B(50,50), C(50,50), R1(50), R2(50), R3(50), R4(50), COTY(50), COTY2(50), ACRE(50,50), F(50, 50), C1(50,50)

REAL NX, NY
INTEGER X, Y

FORMAT STATEMENTS FOR WRITING INPUT AND OUTPUT INFORMATION

5 FORMAT(I4,3X,15FH.2)
6 FORMAT(7X,15F8.2)
65 FORMAT(10X,'--------- CROSS ROW DIRECTION')
22 FORMAT(7X,15F8.2, 2)
28 FORMAT(I10X, 1 TOTAL AREA= ',F7,3, ' ACRES')
4 FORMAT(/,2X, 1 CROSS ROW DIRECTION I)
22 FORMAT(/,2X, 1 TOTAL AREA: ',F7,3, ' ACRES')
20 FORMAT(/,10X, 1 *******************************************
4 FORMAT(SX,'* 1 ,20A4 1 1 • 1 )
28 FORMAT(SX,'*******************************************************
110 FORMAT(/,30X, 1 DESIGN REQUIREMENTS 1)
20 FORMAT(/ 10X, 1 DEPTHS OF CUTS AND FILLS)
702 FORMAT(2X,'EXTRA VOLUME OF CUT=',F8,1, ' CY, EXTRA VOLUME OF FILL =',F8,1, ' CY')
704 FORMAT(2X,'DEVIATION OF EXPECTED CUT/FILL RATIO= ',F5,3, ', COST=',F5,3, ', PER CUBIC YARD')
705 FORMAT(2X,'NUMBER OF STATIONS IN ROW=',I2, ', PROPOSED MAXIMUM DEPTH OF CUT=',F6,2, ', FT')
706 FORMAT(2X,'NUMBER OF STATIONS IN CROSS ROW=',I2, ', PROPOSED MAXIMUM DEPTH OF FILL=',F6,2, ', FT')
707 FORMAT(2X,'DISTANCES TO FIELD BOUNDARIES FROM')
708 FORMAT(5X, 'FIRST ROW = ',I10X, 'F6.2, FT')
709 FORMAT(5X, 'LAST ROW = ',R2Y, 'F6.2, FT')
710 FORMAT(5X, 'FIRST CROSS ROW = ',R3X, 'F6.2, FT')
711 FORMAT(5X, 'LAST CROSS ROW = ',R4X, 'F6.2, FT')
722 FORMAT(2X,'NOTE: CUTS ARE SHOWN AS POSITIVE AND FILLS AS NEGATIVE')
723 FORMAT(2X,'TOTAL VOLUME OF CUT=',F10,3, ', CY, FINAL CUT/FILL RATIO BY VOLUME=',F5,3)
724 FORMAT(2X,'NUMBER OF STATIONS WITH CUT=',I4, ', NUMBER OF STATIONS WITH FILL=',I4)
725 FORMAT(2X,'NUMBER OF STATIONS WITH CUT OVER THE PROPOSED MAXIMUM DEPTH=',I4)
726 FORMAT(2X,'NUMBER OF STATIONS WITH FILL OVER THE PROPOSED MAXIMUM DEPTH=',I4)
727 FORMAT(2X,'AVERAGE VOLUME=',F8,3, ', CY/ACRE, AVERAGE COST=',F6,2, ' PER ACRE')
728 FORMAT(2X,'TOTAL COST=',F8,2)
46 FORMAT(/,10X,'ORIGINAL FIELD ELEVATION')

C WRITING THE INPUT DATA
1 WRITE(6,20)
2 WRITE(6,4) (COTY(I), I=1, 20)
WRITE (6, 4) (COT2(I), 1=1, 20)  # 2016
WRITE (6, 28)  # 2017
WRITE (6, 24)  # 2018
WRITE (6, 706) ECF  # 2019
WRITE (6, 705) EXVC, EXVF  # 2020
WRITE (6, 704) DECF, COST  # 2021
WRITE (6, 705) NY, OSC  # 2022
WRITE (6, 706) NX, OSF  # 2023
WRITE (6, 707)  # 2024
WRITE (6, 704) (R1(Y), Y=1, NY)  # 2025
WRITE (6, 705) (R2(Y), Y=1, NY)  # 2026
WRITE (6, 710) (R3(X), X=1, NX)  # 2027
WRITE (6, 711) (R4(X), X=1, NX)  # 2028
WRITE (6, 46)  # 2029
C CONTROL FOR FIELD DATA PRINT OUT  # 2030
IF (NX = 15) 620, 620, 621  # 2031
620 DO 45 Y=1, NY  # 2032
45 WRITE (6, 5) Y, (H(X, Y), X=1, NX)  # 2033
GO TO 622  # 2034
621 DO 623 Y=1, NY  # 2035
WRITE (6, 5) Y, (M(X, Y), X=1, 15)  # 2036
623 WRITE (6, 6) (M(X, Y), X=1b, NY)  # 2037
C CALCULATE THE AREA OF THE FIELD  # 2038
622 DO 11 Y=1, NY  # 2039
11 ACRE(X, Y) = 1.00  # 2040
AREA = 0.00  # 2041
DO 21 X=1, NX  # 2042
C PROPORTIONS FIRST BORDER CROSS HOW TO GRID SPACING  # 2043
ACRE(X, 1) = ACRE(X, 1) * ((R5(X) + 0.50 * GGG) / GGG)  # 2044
C PROPORTIONS LAST BORDER CROSS HOW TO GRID SPACING  # 2045
21 ACRE(X, NY) = ACRE(X, NY) * ((R4(X) + 0.50 * GGG) / GGG)  # 2046
DO 33 Y=1, NY  # 2047
C PROPORTIONS FIRST BORDER ROW TO GRID SPACING  # 2048
ACRE(1, Y) = ACRE(1, Y) * ((R1(Y) + 0.50 * GGG) / GGG)  # 2049
C PROPORTIONS LAST BORDER ROW TO GRID SPACING  # 2050
ACRE(NX, Y) = ACRE(NX, Y) * ((R2(Y) + 0.50 * GGG) / GGG)  # 2051
DO 33 X=1, NX  # 2052
33 AREA = AREA + ACRE(X, Y)  # 2053
C CALCULATE THE AREA IN ACRES  # 2054
AREA = AREA * GGG * GGG / 43560.0  # 2055
WRITE (6, 22) AREA  # 2056
CF = ECF  # 2057
N = NX * NY  # 2058
C CALCULATING THE SLOPES BY THE LEAST SQUARES METHOD  # 2059
CALL SLOPE(H, NX, NY, N, SLOPEX, SLOPEY, CEN, SX, SY, GGG)  # 2060
C CALCULATING THE DEPTHS OF CUT AND FILL  # 2061
211 CALL BAL(H, NX, NY, N, SLOPEX, SLOPEY, CEN, SX, SY, B, DECF, CF, ICT, IFL, IOCT,  # 2062
110FL, OSC, OSF, CGG)  # 2063
C CALCULATING THE VOLUMES OF CUT AND FILL  # 2064
CALL VOL(C, NX, NY, M, R1, R2, R3, R4, VCTT, VFTT, GGG)  # 2065
VCTT = VCTT + EXVC  # 2066
VFTT = VFTT + EXVF  # 2067
IF (VFTT . EQ. 0.0) GO TO 310  # 2068
VRCF = VCTT / VFTT  # 2069
ERR = VRCF - ECF  # 2070
IF (ABS(ERR) . LT . DECF) GO TO 209  # 2071
IF (ERR) 305, 209, 310  # 2072
C ADJUSTING THE CENTROID ELEVATION  # 2073
310 CEN = CEN + 0.010  # 2074
GO TO 211  # 2075
305 CEN = CEN = 0.010
GO TO 211
C
209 PRINT DEPTH OF CUT OR FILL AT EACH STATION
WRITE(b,50)
WRITE(b,722)
WRITE(b,65)
C
210 CONTROL FOR FIELD DATA PRINT OUT
IF(NX = 15) b24, b24, b25
620 DO 164 Y=1, NY
164 WRITE(b,5) Y, (C(X,Y), X=1, NX)
GO TO b26
625 DO 627 Y=1, NY
627 WRITE(b,5) Y, (C(X,Y), X=1, 15)
WRITE(b,6) Y, (C(X,Y), X=1b, NX)
C
211 CONTROL FOR FIELD DATA PRINT OUT
626 DO 169 Y=1, NY
169 B(X, Y) = M(X, Y) - C(X, Y)
C
212 PRINT FINAL DESIGN ELEVATIONS
PRINT FINAL DESIGN ELEVATIONS
WRITE(b,51)
WRITE(b,65)
C
213 CONTINUE FOR FIELD DATA PRINT OUT
WRITE(b,6) Y, (B(X,Y), X=1, NX)
WRITE(b,5) Y, (B(X,Y), X=1, 15)
WRITE(b,6) Y, (B(X,Y), X=1b, NX)
C
214 CALCULATE FINAL DESIGN ELEVATIONS
DO 170 Y=1, NY
170 SEX, Y)
SEX, Y)
= H(X, Y) - C(X, Y)
C
215 CALCULATE FINAL DESIGN ELEVATIONS
PRINT FINAL DESIGN ELEVATIONS
WRITE(b,51)
WRITE(b,65)
C
216 CONTROL FOR FIELD DATA PRINT OUT
WRITE(b,6) Y, (B(X,Y), X=1, NX)
WRITE(b,5) Y, (B(X,Y), X=1, 15)
WRITE(b,6) Y, (B(X,Y), X=1b, NX)
C
217 CALCULATE AVERAGE VOLUME PER ACRE
AVCTT = VCTT/AREA
AVCTT = VCTT/AREA
C
218 CALCULATE TOTAL COST
TCOST = VCTT * COST
TCOST = VCTT * COST
C
219 CALCULATE AVERAGE COST PER ACRE
ACOST = AVCTT * COST
ACOST = AVCTT * COST
C
220 PRINT TOTAL VOLUME OF CUT, RATIO OF CUT TO FILL
WRITE(b,723) VCTT, VRCF
WRITE(b,723) VCTT, VRCF
C
221 PRINT TOTAL NUMBER OF STATIONS WITH CUT AND WITH FILL
WRITE(b,724) ICT, IFL
WRITE(b,724) ICT, IFL
C
222 PRINT NUMBER OF STATIONS WITH CUT OVER THE PROPOSED MAXIMUM DEPTH
WRITE(b,725) ICT
WRITE(b,725) ICT
C
223 PRINT NUMBER OF STATIONS WITH CUT OVER THE PROPOSED MAXIMUM DEPTH
WRITE(b,726) ICT
WRITE(b,726) ICT
C
224 PRINT AVERAGE VOLUME OF CUT AND AVERAGE COST
WRITE(b,727) AVCTT, ACOST
WRITE(b,727) AVCTT, ACOST
C
225 PRINT TOTAL COST
WRITE(b,728) TCOST
WRITE(b,728) TCOST
RETURN
RETURN
END
END
SUBROUTINE SLOPE(H,NX,NY,N,SLOPEX,SLOPEY,CEN,XBAR,YBAR,GGG)
C
SUBROUTINE FOR CALCULATING ROW AND CROSS-HUM DESIGN SLOPES USING
THE LEAST SQUARES TECHNIQUE, AND CALCULATING CENTROID ELEVATION
AND LOCATION
DIMENSION H(50,50)
REAL NX, NY, N
INTEGER X, Y

100 FORMAT(/,10X,'CENTROID ELEVATION =',F7.2,' XBAR =',F7.2,' YBAR =',F7.2,' STATIONS')
110 FORMAT(/,10X,'SLOPE IN THE X-DIRECTION =',F10.5,' FT/100 FT AND SLOPE IN THE Y-DIRECTION =',F10.5,' FT/100 FT')

SUH = 0.00
SHX = 0.00
SHY = 0.00
SXS = 0.00
SYS = 0.00
SX = 0.00
SY = 0.00
GB = 100.0 / GGG
DO 10 X=1, NX
DO 20 Y=1, NY
SUH = SUH + H(X,Y)
20 CONTINUE
10 CONTINUE
CEN = SUH / N
DO 40 X = 1, NX
DO 30 Y = 1, NY
SHX = SHX + H(X,Y) * X
SXS = SXS + X**2
SX = SX + X
30 CONTINUE
40 CONTINUE
C CALCULATING THE SLOPE IN THE X-DIRECTION
SLOPEX = ((SHX = N*CEN*((NX+1.0)/2.0))/(SXS = SXS/N)) * GB
DO 60 X=1, NX
DO 70 Y=1, NY
SHY = SHY + H(X,Y) * Y
SYS = SYS + Y**2
SY = SY + Y
70 CONTINUE
80 CONTINUE
C CALCULATING THE SLOPE IN THE Y-DIRECTION
SLOPEY = ((SHY = N*CEN*((NY+1.0)/2.0))/(SYS = SYS/N)) * GB
C CALCULATING THE LOCATION OF THE CENTROID
XL = 0.00
YL = 0.00
DO 90 Y=1, NY
YBAR = YBAR + Y
90 CONTINUE
C CALCULATING THE LOCATION OF THE CENTROID
XL = X + X
XBAR = XBAR + X
XBAR = XBAR / N
WRITE(6,100) CEN, XBAR, YBAR
C PRINTING DESIGN SLOPES IN THE X- AND Y-DIRECTIONS, RESPECTIVELY
WRITE(6,110) SLOPEX, SLOPEY
RETURN
END
SUBROUTINE BAL(H,NX,NY,N,SLOPEX,SLOPEY,CEN,SX,SY,B,DECF,CF,ICT, 
1 IFL,IOCT,IUFL,DSF,OF,CF,GGG)  
SUBROUTINE FOR BALANCING AND CHECKING THE MAXIMUM ALLOWABLE LIMITS  
OF THE DEPTHS OF CUTS AND FILLS  
DIMENSION H(50,50), B(50,50), C(50,50)  
REAL NX, NY, N  
INTEGER X, Y  
CALCULATING THE ELEVATION OF THE UPPER LEFT-HAND CORNER (ORIGIN OF 
THE AXES)  
26 G = CEN -(SLOPEX * SX + SLOPEY * SY) * GGG / 100.0  
DO 60 X =1, NX  
DO 50 Y =1, NY  
CALCULATING THE GRADE ELEVATION AT INDIVIDUAL STATIONS  
B(X, Y) = G +(SLOPEX * X + SLOPEY * Y) * GGG / 100.0  
CALCULATING THE DEPTH OF CUT OR FILL AT INDIVIDUAL STATIONS  
C(X, Y) = H(X, Y) - B(X, Y)  
50 CONTINUE  
60 CONTINUE  
FL = 0.00  
IFL = 0  
CT = 0.00  
ICT = 0  
DO 40 X =1, NX  
DO 30 Y =1, NY  
IF(C(X, Y)) 21, 21, 22  
CALCULATING THE TOTAL DEPTH OF FILL  
21 FL = FL - C(X, Y)  
IFL = IFL + 1  
GO TO 30  
CALCULATING THE TOTAL DEPTH OF CUT  
22 CT = CT + C(X, Y)  
ICT = ICT + 1  
30 CONTINUE  
40 CONTINUE  
CHECKING THE LIMITS ON CUT OR FILL  
24 IOCT = 0  
IOFL = 0  
DO 32 Y =1, NY  
DO 31 X =1, NX  
IF(C(X, Y) .GE. DSF) IOCT = IOCT + 1  
IF(C(X, Y) .LE. DSF) IUF = IOFL + 1  
33 CONTINUE  
32 CONTINUE  
RETURN  
END  
C
SUBROUTINE VOL(C1,NX,NY,N,M1,R2,R3,R4,VCTT,VFTT,GGG)

SUBROUTINE FOR CALCULATING THE VOLUMES OF EARTH WORK USING THE FOUR-POINT METHOD

DIMENSION C(50, 50), R1(50), R2(50), R3(50), R4(50), F(50, 50),

REAL NX, NY, N
INTEGER X, Y
DO 33 X=1, NX
DO 33 Y=1, NY
33 C(X, Y) = C1(X, Y)
DO 72 Y=1, NY
DO 71 X=1, NX

CHECKING THE DEPTH AT EACH STATION, FILL IS NEGATIVE AND CUT IS POSITIVE

IF(C(X, Y)) 73, 73, 74
73 F(X, Y) = -C(X, Y)
C(X, Y) = 0.00
GO TO 71
74 C(X, Y) = C(X, Y)
F(X, Y) = 0.00
71 CONTINUE
72 CONTINUE
T = GGG * GGG / 108.00
VCTT = 0.00
VFTT = 0.00
VC = 0.00
VF = 0.00

CALCULATING THE VOLUMES FOR THE INTERIOR GRIDS

X = 1.00
Y = 1.00
30 DC = 0.00
DF = 0.00
DO 20 I=X,X+1
DO 10 J=Y,Y+1
DC = DC + C(I, J)
DF = DF + F(I, J)
10 CONTINUE
20 CONTINUE
IF(DC . EQ . 0.0 , AND . DF . EQ . 0.0) GO TO 11
VC = T * (DC * DC)/(UC + DF)
VF = T * (DF * DF)/(DC + DF)
VCTT = VCTT + VC
VFTT = VFTT + VF
11 X = X + 1.00
IF(X . LT . NX) GO TO 30
X = 1.00
Y = Y + 1.00
IF(Y . LT . NY) GO TO 30

CALCULATING THE VOLUMES IN THE FIRST CROSS ROW BORDER

X = 0.00
50 DC = 0.00
DF = 0.00
X = X + 1.0
DO 40 I=X, X+1
DC = DC + 2.0 * C(I, 1)
40 DF = DF + 2.0 * F(I, 1)
IF(DC . EQ . 0.0 , AND . DF . EQ . 0.0) GO TO 61
DO 60 I=X, X
VC=((T*DC+DC)*RH3(I)+H3(I+1))/(DC+DF)*2.0*GGG
VF=((T*DF+DF)*R3(I)+H3(I+1))/(DC+DF)*2.0*GGG
VCTT = VCTT + VC
VFTT = VFTT + VF
IF (X < LT * (NX-1)) GO TO 50
CALCULATING THE VOLUMES IN THE LAST CROSS ROW BORDER
X = 0.0
DC = 0.0
DF = 0.0
DO 75 IMX, X+1
DC = DC + 2.0 * C(I, NY)
DF = DF + 2.0 * F(I, NY)
IF (DC < EQ < 0.0 . AND . DF < EQ < 0.0) GO TO 77
DO 76 IMX, X
VC=((T*DC+DC)*RH4(I)+R4(I+1))/(DC+DF)*2.0*GGG
VF=((T*DF+DF)*R4(I)+R4(I+1))/(DC+DF)*2.0*GGG
VCTT = VCTT + VC
VFTT = VFTT + VF
IF (X < LT * (NX-1)) GO TO 70
CALCULATING THE VOLUMES IN THE FIRST ROW BORDER
Y = 0.0
DC = 0.0
DF = 0.0
DO 81 J=Y, Y+1
DC = DC + 2.0 * C(I, J)
DF = DF + 2.0 * F(I, J)
IF (DC < EQ < 0.0 . AND . DF < EQ < 0.0) GO TO 78
DO 82 J=Y, Y
VC=((T*DC+DC)*RH1(J)+R1(J+1))/(DC+DF)*2.0*GGG
VF=((T*DF+DF)*R1(J)+R1(J+1))/(DC+DF)*2.0*GGG
VCTT = VCTT + VC
VFTT = VFTT + VF
IF (Y < LT * (NY-1)) GO TO 80
CALCULATING THE VOLUMES IN THE LAST ROW BORDER
Y = 0.0
DC = 0.0
DF = 0.0
DO 84 J=Y, Y+1
DC = DC + 2.0 * C(NX, J)
DF = DF + 2.0 * F(NX, J)
IF (DC < EQ < 0.0 . AND . DF < EQ < 0.0) GO TO 79
DO 85 J=Y, Y
VC=((T*DC+DC)*RH2(J)+R2(J+1))/(DC+DF)*2.0*GGG
VF=((T*DF+DF)*R2(J)+R2(J+1))/(DC+DF)*2.0*GGG
VCTT = VCTT + VC
VFTT = VFTT + VF
IF (Y < LT * (NY-1)) GO TO 83
P = 0.25 / 108.00
CALCULATING THE VOLUMES IN THE FIRST UPPER-LEFT-HAND CORNER
IF (C(1,1) < EQ < 0.0 . AND . F(1,1) < EQ < 0.0) GO TO 86
VC = (((4.0*C(1,1))**2)*R1(1)+R3(1))/(C(1,1)+F(1,1)) * P
VF = (((4.0*F(1,1))**2)*R1(1)+R3(1))/(C(1,1)+F(1,1)) * P
VCTT = VCTT + VC
VFTT = VFTT + VF
GO TO 50
CALCULATING THE VOLUMES IN THE UPPER-RIGHT-HAND CORNER

IF(C(NX,1), EQ., 0.0, AND, F(NX, 1), EQ., 0.0) GO TO 87
VC = (((4.0*C(NX,1)**2)*(R3(NX)*R2(1)))/(C(NX,1)+F(NX,1)))*P
VF = (((4.0*F(NX,1)**2)*(R3(NX)*R2(1)))/(C(NX,1)+F(NX,1)))*P
VCTT = VCTT + VC
VFTT = VFTT + VF

CALCULATING THE VOLUMES IN THE LOWER-LEFT-HAND CORNER

IF(C(1,NY), EQ., 0.0, AND, F(1, NY), EQ., 0.0) GO TO 88
VC = (((4.0*C(1,NY)**2)*(R1(NY)*R4(1)))/(C(1,NY)+F(1,NY)))*P
VF = (((4.0*F(1,NY)**2)*(R1(NY)*R4(1)))/(C(1,NY)+F(1,NY)))*P
VCTT = VCTT + VC
VFTT = VFTT + VF

CALCULATING THE VOLUMES IN THE LOWER-RIGHT-HAND CORNER

IF(C(NX,NY), EQ., 0.0, AND, F(NX,NY), EQ., 0.0) GO TO 89
VC = (((4.0*C(NX,NY)**2)*(R2(NX)*R4(NX)))/(C(NX,NY)+F(NX,NY)))*P
VF = (((4.0*F(NX,NY)**2)*(R2(NX)*R4(NX)))/(C(NX,NY)+F(NX,NY)))*P
VCTT = VCTT + VC
VFTT = VFTT + VF

RETURN
END
Appendix F,

Computer Programs for Furrow Irrigation System

Design and Management Optimization
Table 32. List, formats, and descriptions of the input information used in the hydraulic system design and management optimization.

<table>
<thead>
<tr>
<th>Card No.</th>
<th>Name</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>DCCK(I)</td>
<td>20A4</td>
<td>Field description</td>
</tr>
<tr>
<td></td>
<td>SLOP</td>
<td>F10.5</td>
<td>Slope of the furrows expressed as a percent</td>
</tr>
<tr>
<td></td>
<td>LSOIL</td>
<td>I10</td>
<td>Identification of soil type</td>
</tr>
<tr>
<td></td>
<td>ERROR</td>
<td>F10.4</td>
<td>Modification factor to adjust maximum non-erosive furrow stream size expressed as a decimal</td>
</tr>
<tr>
<td>2</td>
<td>S</td>
<td>F10.4</td>
<td>Furrow spacing in feet</td>
</tr>
<tr>
<td></td>
<td>AL</td>
<td>F10.4</td>
<td>Furrow length in feet</td>
</tr>
<tr>
<td></td>
<td>W</td>
<td>F10.4</td>
<td>Field width in feet</td>
</tr>
<tr>
<td></td>
<td>INDEX</td>
<td>I10</td>
<td>Identification of furrow channel shape</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>F10.4</td>
<td>Bottom width of trapezoidal furrow channel in feet</td>
</tr>
<tr>
<td></td>
<td>BP</td>
<td>F10.4</td>
<td>Top width of parabolic furrow channel in feet</td>
</tr>
<tr>
<td>3</td>
<td>Z</td>
<td>F10.4</td>
<td>Side slopes of trapezoidal furrow channel</td>
</tr>
<tr>
<td></td>
<td>DW</td>
<td>F10.4</td>
<td>Estimated normal depth of flow at the head of the furrow in feet</td>
</tr>
</tbody>
</table>
Table 32. Continued.

<table>
<thead>
<tr>
<th>Card No.</th>
<th>Name</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AK</td>
<td>F9.4</td>
<td>K-coefficient of Kostakov intake function in gpm/ft</td>
</tr>
<tr>
<td></td>
<td>AN</td>
<td>F9.4</td>
<td>n-exponent of Kostakov intake function</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>F9.4</td>
<td>f factor used for Davis’ advance prediction method</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>F9.4</td>
<td>e factor used for Davis’ advance prediction method</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>E</td>
<td>F9.4</td>
<td>h factor used for Davis’ advance prediction method</td>
</tr>
<tr>
<td></td>
<td>DK</td>
<td>F9.4</td>
<td>c factor used for Davis’ advance prediction method</td>
</tr>
<tr>
<td></td>
<td>AA</td>
<td>F9.4</td>
<td>a-coefficient of the empirical advance function</td>
</tr>
<tr>
<td></td>
<td>AB</td>
<td>F9.4</td>
<td>b-exponent of the empirical advance function</td>
</tr>
<tr>
<td></td>
<td>MN</td>
<td>F9.4</td>
<td>Manning’s roughness coefficient</td>
</tr>
<tr>
<td></td>
<td>DTV</td>
<td>F9.4</td>
<td>Increment of time in minutes to be used in predicting the advance function</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>DTR</td>
<td>F9.4</td>
<td>Increment of time in minutes used in predicting the runoff hydrograph</td>
</tr>
<tr>
<td></td>
<td>STREAM</td>
<td>F9.4</td>
<td>Supply stream discharge in cfs</td>
</tr>
<tr>
<td></td>
<td>PCENT</td>
<td>F9.4</td>
<td>Segment length used to evaluate the Distribution Uniformity expressed as a fraction of furrow length</td>
</tr>
<tr>
<td>Card No.</td>
<td>Name</td>
<td>Format</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>--------</td>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>DEPL</td>
<td>F9.4</td>
<td>Percent of allowable depletion</td>
</tr>
<tr>
<td></td>
<td>HOLD</td>
<td>F9.4</td>
<td>Soil moisture holding capacity in inches/foot</td>
</tr>
<tr>
<td></td>
<td>ROOT</td>
<td>F9.4</td>
<td>Depth of the root zone in feet</td>
</tr>
<tr>
<td></td>
<td>DMODI</td>
<td>F9.4</td>
<td>Modification factor to adjust the depth of stored water expressed as a decimal</td>
</tr>
<tr>
<td>6</td>
<td>CONSUM</td>
<td>F9.4</td>
<td>Average crop consumptive use rate in inches per day</td>
</tr>
<tr>
<td></td>
<td>DAYS</td>
<td>F9.4</td>
<td>Number of days in the growing season</td>
</tr>
<tr>
<td></td>
<td>RAIN</td>
<td>F9.4</td>
<td>Depth in inches of usable rainfall during the growing season</td>
</tr>
<tr>
<td></td>
<td>PRESEA</td>
<td>F9.4</td>
<td>Depth in inches of pre-season irrigation</td>
</tr>
<tr>
<td></td>
<td>ADJUST</td>
<td>F9.4</td>
<td>Ratio of length of pipe needed for IRRS to furrow length</td>
</tr>
<tr>
<td></td>
<td>YEARS</td>
<td>F9.4</td>
<td>Life of the system in years</td>
</tr>
<tr>
<td></td>
<td>DINTER</td>
<td>F9.4</td>
<td>Current Compound Interest Rate expressed as a percentage</td>
</tr>
<tr>
<td>7</td>
<td>FUELC</td>
<td>F9.4</td>
<td>Fuel cost in dollars per U.S. gallon</td>
</tr>
<tr>
<td></td>
<td>PUCOST</td>
<td>F9.4</td>
<td>Cost of the pumping unit in dollars per BHP</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td>F9.4</td>
<td>Hazen-Williams friction coefficient of the pipes used for IRRS</td>
</tr>
</tbody>
</table>
Table 32. Continued.

<table>
<thead>
<tr>
<th>Card No.</th>
<th>Name</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>COLLEC</td>
<td>F9.4</td>
<td>Ratio of the length of the collection ditches used for IRRS to furrow length</td>
</tr>
<tr>
<td></td>
<td>COHOUS</td>
<td>F9.4</td>
<td>Cost in dollars of pump platform and house used for IRRS</td>
</tr>
<tr>
<td></td>
<td>DITCHR</td>
<td>F9.4</td>
<td>Cost of using the ditcher machine in dollars per 100 feet</td>
</tr>
<tr>
<td></td>
<td>CPCUYD</td>
<td>F9.4</td>
<td>Cost of excavation in dollars per cubic yard</td>
</tr>
<tr>
<td></td>
<td>ACVALU</td>
<td>F9.4</td>
<td>Estimated value of the land used for IRRS storage pond in dollars per acre</td>
</tr>
<tr>
<td></td>
<td>ACREFT</td>
<td>F9.4</td>
<td>Cost of the irrigation water in dollars per acre-foot</td>
</tr>
<tr>
<td>8</td>
<td>DELV</td>
<td>F9.4</td>
<td>Elevation different in feet between the inlet and outlet of the pumpback pipe used for IRRS</td>
</tr>
<tr>
<td></td>
<td>CLANDG</td>
<td>F9.4</td>
<td>Initial cost of land grading in dollars per acre</td>
</tr>
<tr>
<td></td>
<td>CLBR</td>
<td>F9.4</td>
<td>Cost of labor used to manage the system in dollars per hour</td>
</tr>
<tr>
<td></td>
<td>RUNLOS</td>
<td>F9.4</td>
<td>Value of the runoff water when considered as a loss in dollars per acre-foot</td>
</tr>
<tr>
<td>9</td>
<td>PROVL</td>
<td>F9.4</td>
<td>Current crop value in dollars per unit produced</td>
</tr>
<tr>
<td>10</td>
<td>NPSIZ</td>
<td>I10</td>
<td>Number of pipe sizes to be considered in designing an IRRS</td>
</tr>
</tbody>
</table>
Table 32. Continued.

<table>
<thead>
<tr>
<th>Card No.</th>
<th>Name</th>
<th>Format</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>11*</td>
<td>ID(I)</td>
<td>F9.4</td>
<td>Inside pipe diameter in inches</td>
</tr>
<tr>
<td></td>
<td>FCOST(ID(I))</td>
<td>F9.4</td>
<td>Fixed cost of the corresponding pipe size in dollars per 100 feet</td>
</tr>
<tr>
<td>12</td>
<td>NBRK</td>
<td>I10</td>
<td>Number of data points read on the <em>Crop Production Function</em>, <em>CPF</em></td>
</tr>
<tr>
<td>13</td>
<td>CROP(K,1,1)</td>
<td>F9.4</td>
<td>Expected crop yield at the data points considered on the <em>CPF</em></td>
</tr>
<tr>
<td>14</td>
<td>CROP(K,2,1)</td>
<td>F9.4</td>
<td>Depth received by the plants at the data point considered on the <em>CPF</em></td>
</tr>
<tr>
<td></td>
<td>PDCSTA</td>
<td>F9.4</td>
<td>Crop production cost in dollars per acre</td>
</tr>
<tr>
<td></td>
<td>PDCSTU</td>
<td>F9.4</td>
<td>Crop production cost in dollars per unit</td>
</tr>
<tr>
<td></td>
<td>PMPCOST</td>
<td>F9.4</td>
<td>Water pumping cost in dollars per acre-inch</td>
</tr>
<tr>
<td></td>
<td>IPH</td>
<td>I5</td>
<td>Number of optimization levels to be considered</td>
</tr>
<tr>
<td></td>
<td>ICROP</td>
<td>I5</td>
<td>Crop identification number</td>
</tr>
<tr>
<td></td>
<td>NLV(L)</td>
<td>I5</td>
<td>Number of sub-divisions to be considered in each optimization level</td>
</tr>
</tbody>
</table>

*As many cards as NPIZ are needed*
Table 32. Continued.

<table>
<thead>
<tr>
<th>Card No.</th>
<th>Name</th>
<th>Format</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DMMAX</td>
<td>F9.4</td>
<td>Ratio of upper limit to average seasonal depth of irrigation to be considered</td>
</tr>
<tr>
<td>17</td>
<td>DMMIN</td>
<td>F9.4</td>
<td>Ratio of lower limit to average seasonal depth of irrigation to be considered</td>
</tr>
<tr>
<td></td>
<td>FREQ</td>
<td>F9.4</td>
<td>Recommended frequency of irrigation in days</td>
</tr>
<tr>
<td>18</td>
<td>XMAX</td>
<td>F9.4</td>
<td>Maximum X-dimension of the advance function plot in minutes (time of advance)</td>
</tr>
<tr>
<td>19</td>
<td>YMAX</td>
<td>F9.4</td>
<td>Maximum Y-dimension of the advance function plot in feet (advanced distance)</td>
</tr>
<tr>
<td></td>
<td>XMAA</td>
<td>F9.4</td>
<td>Maximum X-dimension of the runoff hydrograph plot in gpm (runoff rate)</td>
</tr>
<tr>
<td></td>
<td>YMAA</td>
<td>F9.4</td>
<td>Maximum Y-dimension of the runoff hydrograph plot in minutes (runoff time period)</td>
</tr>
<tr>
<td></td>
<td>LAD</td>
<td>I5</td>
<td>Control index to select the desired advance prediction method</td>
</tr>
<tr>
<td></td>
<td>LAR</td>
<td>I5</td>
<td>Control index to choose the desired runoff hydrograph</td>
</tr>
<tr>
<td></td>
<td>LAS</td>
<td>I5</td>
<td>Control index to express the advance function by an exponential equation</td>
</tr>
<tr>
<td>20</td>
<td>LELLEP</td>
<td>I5</td>
<td>Control index to select the desired method of advance prediction using front shape method</td>
</tr>
</tbody>
</table>
Table 32. Continued.

<table>
<thead>
<tr>
<th>Card No.</th>
<th>Name</th>
<th>Format</th>
<th>Description</th>
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<tbody>
<tr>
<td>20</td>
<td>LINTAK</td>
<td>I5</td>
<td>Control index to select the desired advance prediction method using integrated intake method</td>
</tr>
<tr>
<td></td>
<td>LRUNO</td>
<td>I5</td>
<td>Control index to select the method of calculating the amount of runoff water</td>
</tr>
<tr>
<td></td>
<td>LAV</td>
<td>I5</td>
<td>Control index to calculate the cost of IRRS</td>
</tr>
<tr>
<td></td>
<td>LAF</td>
<td>I5</td>
<td>Control index to select the desired method of predicting the runoff hydrograph</td>
</tr>
<tr>
<td></td>
<td>LAP</td>
<td>I5</td>
<td>Control index to predict the advance function</td>
</tr>
<tr>
<td></td>
<td>LIRRS</td>
<td>I5</td>
<td>Control index to use an IRRS</td>
</tr>
<tr>
<td></td>
<td>INV</td>
<td>I5</td>
<td>Number of time increments allowed in predicting the advance function</td>
</tr>
<tr>
<td></td>
<td>INR</td>
<td>I5</td>
<td>Number of time increments allowed in predicting the runoff hydrograph</td>
</tr>
<tr>
<td></td>
<td>INI</td>
<td>I5</td>
<td>Control index to calculate the number of irrigations</td>
</tr>
<tr>
<td></td>
<td>IPLOT</td>
<td>I5</td>
<td>Control index to plot the desired function</td>
</tr>
<tr>
<td>Variable</td>
<td>Description</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>Total area of the field, acres (hectares)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AA</td>
<td>Empirical coefficient of the advance function</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AB</td>
<td>Empirical exponent of the advance function</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td>Cost of water used for irrigation, $ /acre-ft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACVALU</td>
<td>Just a guess of the estimated crop return, $ /acre</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ADJUST</td>
<td>A factor when multiplied by field length gives length of pipe required for Irrigation, to be obtained from field layout</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AK</td>
<td>Empirical coefficient of the intake function, gpm/ft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AL</td>
<td>Furrow length, feet (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AN</td>
<td>Empirical exponent of the intake function</td>
<td></td>
<td></td>
</tr>
<tr>
<td>APPL</td>
<td>Cross sectional area of furrow channel, sq ft (sq m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AR</td>
<td>Average depth of infiltrated water, inches (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASUM</td>
<td>Bottom width of a trapezoidal furrow channel, feet (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BP</td>
<td>Top width of a parabolic furrow channel, feet (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Davis' surface storage coefficient</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLANDG</td>
<td>Annual cost of land grading plus any fudge cost to account for furrow length and layout (this is taken from the first model of land grading), $/acre</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLR</td>
<td>Cost of labor required, $/hour</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CHOUS</td>
<td>Cost of pump house used for Irrigation if any is needed, $</td>
<td></td>
<td></td>
</tr>
<tr>
<td>COLLEC</td>
<td>A factor when multiplied by field length gives length of collection ditches required for Irrigation, to be obtained from field layout</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CONSUM</td>
<td>Design daily consumptive use rate, in/day (mm/day)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CPCUYD</td>
<td>Cost of excavation for the sump, $ /cu yd</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CROP</td>
<td>Identification of the crop production function, $ vs. depth of water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>Depth of the sump to be used with Irrigation, feet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DCCK</td>
<td>A dummy variable to read some headings</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEEP</td>
<td>Depth of deep percolated water, inches (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DELV</td>
<td>Difference in elevation along Irrigation return pipe to be used in calculating the total dynamic head, feet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DEPL</td>
<td>Percent of allowable depletion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DINTER</td>
<td>Current market interest rate, expressed in percent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DITCH</td>
<td>Cost of ditching machine, $ /100 ft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DK</td>
<td>Davis' k factor which is equal to 1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DL</td>
<td>Accumulated depth of infiltrated water at the lower end of the furrow, inches (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DMODI</td>
<td>A modification factor to adjust (increase or decrease) the minimum depth of infiltration, expressed as a decimal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DTR</td>
<td>Time increment to be used in the prediction of the runoff prediction of the runoff hydrograph, minutes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DTV</td>
<td>Time increment to be used in the prediction of the prediction of the water advance, minutes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DU</td>
<td>Accumulated depth of infiltrated water at the upper end of the furrow, inches (mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DW</td>
<td>Normal depth of flow at the head of the furrow, feet (m)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DX</td>
<td>Distance advanced in time of, feet (m)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
C

E = PUDDLING FACTOR WHICH IS EQUAL TO 0.003 CU FT / FT
ERROR = PERCENT ERROR TO BE INTRODUCED IN THE PREDICTED FURROW
STREAM SIZE, EXPRESSED AS A DECIMAL
F = DAVIS' INTAKE-METHOD FACTOR
FCOST = FIXED COST OF PIPES USED FOR IRRS, $ / 100 FT
FF = TOTAL NUMBER OF FURROWS FOR THE ENTIRE FIELD
FFP = TOTAL NUMBER OF FURROWS IRRIGATED FROM THE PUMP
FFS = TOTAL NUMBER OF FURROWS IRRIGATED FROM THE SUPPLY STREAM
FP = NUMBER OF FURROWS PER SET IRRIGATED FROM THE PUMP
FS = NUMBER OF FURROWS PER SET IRRIGATED FROM THE SUPPLY
STREAM
FT = TIME OF ADVANCE USING FOX AND BISHOP'S TECHNIQUE, MINUTES
FUEL = DIESEL FUEL COST IN $ PER GALLON
FX = PREDICTED ADVANCED DISTANCE USING FOX AND BISHOP'S
TECHNIQUE
HC = HAZEN - WILLIAMS FRICTION FACTOR
HOLD = SOIL MOISTURE HOLDING CAPACITY, IN/FT (MM/M)
I = INTAKE RATE, GPM/FT (LPS/M)
ICROP = ANY IDENTIFICATION TO IDENTIFY THE CROP FOR FUTURE
REFERENCE
ID(I) = INSIDE DIAMETER TO BE USED IN EVALUATING THE COST OF IRRS
INCHES
INR = NUMBER OF TIME INTERVALS TO BE EVALUATED IN THE
PREDICTION OF THE RUNOFF HYDROGRAPH
INV = NUMBER OF TIME INTERVALS TO BE EVALUATED IN THE
PREDICTION OF THE ADVANCE OF THE WATER FRONT
WHEN INDEX IS
1 SHAPE OF THE FURROW CHANNEL IS TRAPEZOIDAL,
TRIANGULAR, OR RECTANGULAR
2 SHAPE OF THE FURROW CHANNEL IS PARABOLIC
WHEN INIT IS
1 CALCULATE THE NUMBER OF IRRIGATION USING AVERAGE DEPTH
OF STORED WATER
2 CALCULATE THE NUMBER OF IRRIGATION USING AVERAGE
FREQUENCY OF APPLICATION
IPM = NUMBER OF PHASES IN THE OPTIMIZATION PROCESS
WHEN PREDICTING THE ADVANCE OF THE WATER FRONT AND LAF IS
1 CALL SAFAI'S FRONT SHAPE ADVANCE PREDICTION TECHNIQUE
2 CALL SAFAI'S INTAKE ADVANCE PREDICTION TECHNIQUE
3 CALL FOX AND BISHOP'S ADVANCE PREDICTION TECHNIQUE
4 CALL DAVIS' ADVANCE PREDICTION TECHNIQUE
5 CALL PATTERSON'S ADVANCE PREDICTION TECHNIQUE
WHEN PREDICTING THE RUNOFF HYDROGRAPH USING WETTING FRONT SHAPE
TECHNIQUE AND LAF IS
1 USE ELLIPTICAL WETTING FRONT SHAPE
2 USE PARABOLIC WETTING FRONT SHAPE
3 USE LINEAR WETTING FRONT
WHEN LAF IS
1 PREDICT THE ADVANCE OF THE WATER FRONT
2 USE STRAIGHT LINE WETTING FRONT WITHOUT PREDICTING
WATER ADVANCE
WHEN PREDICTING THE RUNOFF HYDROGRAPH AND LAWS IS
  1. CALL FRONT SHAPE RUNOFF PREDICTION TECHNIQUE
  2. CALL ACCUMULATED DEPTH RUNOFF PREDICTION TECHNIQUE
  3. CALL ACCUMULATED INTAKE RUNOFF PREDICTION TECHNIQUE

WHEN LAWS IS
  1. USE PREDICTED ADVANCE FUNCTION AND CONVERT IT TO
     \[ X = A + B \]
  2. USE EMPERICAL ADVANCE FUNCTION AND PROVIDE ITS
     EMPIRICAL COEFFICIENTS

IN EVALUATING THE COST OF IRRS, WHEN LAWS IS
  1. CALCULATE SUMP EXCAVATION COST AND LAND VALUE
  2. CALCULATE ONLY PIPES AND PUMPING COST

WHEN PREDICTING WATER ADVANCE USING DAPA'S FRONT SHAPES TECHNIQUE
AND LAWS IS
  1. USE ELLEP SURFACE STORAGE AND ELLEP WETTING FRONT
  2. USE ELLEP SURFACE STORAGE AND PARABOLIC WETTING FRONT
  3. USE ELLEP SURFACE STORAGE AND LINEAR WETTING FRONT
  4. USE PARABOLIC SURFACE STORAGE AND ELLEP WETTING FRONT
  5. USE PARABOLIC SURFACE STORAGE AND PARABO WETTING FRONT
  6. USE PARABOLIC SURFACE STORAGE AND LINEAR WETTING FRONT

WHEN PREDICTING WATER ADVANCE USING SAFA'S INAKE TECHNIQUE AND
LAWS IS
  1. USE ELLEPTICAL SURFACE STORAGE
  2. USE PARABOLIC SURFACE STORAGE
  3. USE LINEAR SURFACE STORAGE

WHEN LAWS IS
  1. USE AN IRR
  2. DON'T USE AN IRR

WHEN LAUNS IS
  1. USE LINEAR WETTING FRONT TO CALCULATE RUNOFF DEPTH
  2. USE RUNOFF HYDROGRAPH TO CALCULATE RUNOFF PERCENTAGE

WHEN LSOIL IS
  1. SOIL IS TYPE I
  2. SOIL IS TYPE II
  3. SOIL IS TYPE III
  4. SOIL IS TYPE IV
  5. SOIL IS TYPE V
  6. SOIL IS TYPE VI

MN = MANNING'S ROUGHNESS COEFFICIENT
MPAGES = NUMBER OF PAGES TO BE USED FOR PLOTTING
N = NUMBER OF IRRIGATION SETS
MLV(I) = NUMBER OF STEPS TO BE CONSIDERED IN STEP I
MDIRR = NUMBER OF IRRIGATIONS PER SEASON
NPSIZ = NUMBER OF PIPE SIZES TO BE EXAMINED IN DESIGNING IRRS
MU = NUMBER OF FURROWS TO BE EVALUATED
PCENT = SEGMENT LENGTH TO EVALUATE APPLICATION UNIFORMITY
EXRESSED IN DECIMAL FORM
PDCSTA = COST OF PRODUCING CROP INCLUDING FERTILIZERS, SUPERVISION
AND MARKETING, $/ACRE
PDCSTU = COST OF PRODUCING CROP INCLUDING FERTILIZERS, SUPERVISION
AND MARKETING, $/UNIT PRODUCTION
<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMP CST</td>
<td>Pumping Cost, $/acre\cdot inch</td>
</tr>
<tr>
<td>PQ</td>
<td>Recirculating Pump Flow Rate, GPM (LPS)</td>
</tr>
<tr>
<td>PR</td>
<td>Wetted Perimeter of Furrow Channel, Feet (M)</td>
</tr>
<tr>
<td>PRESEA</td>
<td>Moisture Available from Preseason Irrigation, Inches (MM)</td>
</tr>
<tr>
<td>PT</td>
<td>Predicted Advance When Using Patterson’s Advance Prediction Technique, Minutes</td>
</tr>
<tr>
<td>PUCost</td>
<td>Cost of Pumping Unit in $/BHP</td>
</tr>
<tr>
<td>PX</td>
<td>Predicted Advanced Distance Using Patterson’s Technique, Feet (M)</td>
</tr>
<tr>
<td>Q</td>
<td>Furrow Stream Size, GPM (LPS)</td>
</tr>
<tr>
<td>R</td>
<td>Advance Ratio Which Is Equal to TL / TX</td>
</tr>
<tr>
<td>RAE</td>
<td>Runoff Discharge Using Elliptical Surface Storage, GPM (LPS)</td>
</tr>
<tr>
<td>RAIN</td>
<td>Depth of Usable Rain Available During the Irrigation Season, Inches (MM)</td>
</tr>
<tr>
<td>RAP</td>
<td>Runoff Discharge Using Parabolic Surface Storage, GPM (LPS)</td>
</tr>
<tr>
<td>RAT</td>
<td>Runoff Discharge Using Linear Surface Storage, GPM (LPS)</td>
</tr>
<tr>
<td>RF</td>
<td>Percentage of Runoff Water</td>
</tr>
<tr>
<td>ROOT</td>
<td>Depth of the Root Zone, Feet (M)</td>
</tr>
<tr>
<td>S</td>
<td>Furrow Spacing, Feet (M)</td>
</tr>
<tr>
<td>SLOP</td>
<td>Slope of the Furrow Channel Expressed in Percent</td>
</tr>
<tr>
<td>ST</td>
<td>Time of Advance Using Safa’s Intake Technique, Minutes</td>
</tr>
<tr>
<td>STREAM</td>
<td>Inflow Stream Size, CFS (LPS)</td>
</tr>
<tr>
<td>SX</td>
<td>Predicted Advanced Distance Using Safa’s Intake Technique and Elliptical Surface Storage, Feet (M)</td>
</tr>
<tr>
<td>SY</td>
<td>Predicted Advanced Distance Using Safa’s Intake Technique and Parabolic Surface Storage, Feet (M)</td>
</tr>
<tr>
<td>SZ</td>
<td>Predicted Advanced Distance Using Safa’s Intake Technique and Linear Surface Storage, Feet (M)</td>
</tr>
<tr>
<td>T</td>
<td>Time Since the Beginning of Irrigation, Minutes</td>
</tr>
<tr>
<td>TOTI</td>
<td>Total Time of Irrigation Per Set, Hours</td>
</tr>
<tr>
<td>TT</td>
<td>Time of Advance Using Safa’s Intake Advance Prediction Technique, Minutes</td>
</tr>
<tr>
<td>TX</td>
<td>Time of Advance, Minutes</td>
</tr>
<tr>
<td>VT</td>
<td>Time of Advance Using Davis’ Advance Prediction Technique, Minutes</td>
</tr>
<tr>
<td>W</td>
<td>Width of the Field, Feet (M)</td>
</tr>
<tr>
<td>XD</td>
<td>Predicted Advanced Distance Using Davis’ Technique, Feet (M)</td>
</tr>
<tr>
<td>XMAX</td>
<td>Maximum X-Coordinate of a Plot</td>
</tr>
<tr>
<td>XMIN</td>
<td>Minimum X-Coordinate of a Plot</td>
</tr>
<tr>
<td>YEARS</td>
<td>Life in Years of Pipes and Pumps Used for Irrs</td>
</tr>
<tr>
<td>YMAX</td>
<td>Maximum Y-Coordinate of a Plot</td>
</tr>
<tr>
<td>YMIN</td>
<td>Minimum Y-Coordinate of a Plot</td>
</tr>
<tr>
<td>Z</td>
<td>Side Slopes of a Trapezoidal Furrow Channel</td>
</tr>
</tbody>
</table>
```plaintext
DIMENSION DCX(20), DX(300), DY(300), DI(300), AI(300), GI(300),
1 FX(300), PX(300), PXD(300), YST(300), XSE(300), XTH(300), XFO(300)
2, XY(300), XSI(300), S(300), SY(300), SZ(300), PI(300),
3 DX(300), ST(300), YY(300), FYXIS(300), V(300), PT(300), VARY(300),
4, XP(300), TP(300), OI(300), PERCE(300), DDD(300), DI(300),
5 LINE(112), XX(300), YY(300), XAXIS(10), CK(300),
6 DP(300), TAD(300), DA(300), RAI(300), y(300), RA(300), MAP(300),
7, RAI(300), UR(300), YD(300), QI(300), YI(300), FOST(20),
8 V(20), TCO(20), TEO(20), RAP(20), CRIP(2, 2, 3), NLV(10),
9 PRD(300), PERCET(300), DEPTH(300), DPAV(300)
```

**C** FORMAT STATEMENTS FOR READING AND WRITING INPUT AND OUTPUT DATA

| 100 | FORMAT (20,4) |
| 110 | FORMAT (10, 5E4, 10) |
| 120 | FORMAT (10, 10F4, 4) |
| 130 | FORMAT (AF9.4) |
| 140 | FORMAT (I65) |

**350** FORMAT (I1,11111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111111
110 FORMAT( //5X,'FORM&T(1M1,15X,'17M OPTIMIZATION DATA //16X,14,7 PHASES //16X,' 16HUPPER,F7.2//16X,8MLD=EH,M,F7.2//16X,4HNLY,M,F7.2

610 FORMAT( //15X,'PHASE =',13,' INTERVAL =',13,' AV DEPTH =',13,' 1," INCHES (',13,'F8.0',1," MM) AND PROF =',13,' F12.2,' S

610 FORMAT( //5X,'LAU =',12,' LAT =',12,' LAF =',12,' LAP =',12,' LIR =',12,' LIR =',12,' LIR =',12,' LIR =',12,

610 FORMAT( //5X,'MAXIMUM FEASIBLE PAO,IT

710 FORMAT( //5X,'FUEL COST =',10.4,' $/U, S, GALLON')

710 FORMAT( //5X,'COST OF PUMPING UNIT =',10.4,' $/HMP')

710 FORMAT( //5X,'COST OF THE PUMPING PLANT USED FOR IRRS JUST HOUSE =

710 FORMAT( //5X,'COST OF USING A DITCHER MACHINE =',10.4,' $/ 100 FE

710 FORMAT( //5X,'COST OF SUMP EXCAVATION =',10.4,' $/CU YD')

710 FORMAT( //5X,'COST OF DITCHER MACHINE =',10.4,' $/ACRE')

710 FORMAT( //5X,'IDIFFERENCE IN ELEVATION BETWEEN SUMP AND DISCHARGE P

710 FORMAT( //5X,'COST OF LAND GRADING =',10.4,' $/ACRE')

710 FORMAT( //5X,'COST OF LABOR TO MANAGE THE SYSTEM =',10.4,' $/HOUR

815 FORMAT( //1H4,'%%%%%%%%%%%%%%%%%%%% SUMMARY OF THE OPTIMIZATION PROC

815 FORMAT( //5X,'VALUE OF RUNOFF LOSS =',10.4,' $/ACRE=FT OF APPLIED

815 FORMAT( //5X,'MAXIMUM FEASIBLE PROFIT FOR THIS DESIGN =',10.4,' $/ACRE

815 FORMAT( //5X,'CROP PRODUCTION VALUE =',10.4)

815 FORMAT( //5X,'AVERAGE SEASONAL DEPTH OF APPLIED WATER =',9.3,' 1

815 FORMAT( //5X,'PIPE SIZE =',14,' FIXED COST =',10.4,' $/ 100 FE

815 FORMAT( //5X,'GROSS RETURN =',9.3)

815 FORMAT( //5X,'NORMAL DEPTH OF FLOW AT THE HEAD OF THE FURROW =',10.4,' FEET (',10.4,' MM)')

815 FORMAT( //5X,'COST OF PRODUCTION =',10.4,' $/UNIT')

815 FORMAT( //5X,'COST OF PRODUCTION =',10.4,' $/ACRE')

815 FORMAT( //5X,'COST OF PRODUCTION =',10.4,' $/ACRE=INCH')

815 FORMAT( //5X,'RANGE OF SEASONAL DEPTH IS',9.3,' TO ',9.3,' TIM

815 FORMAT( //5X,'FORCED TO INCREASE THE EXPECTED AVERAGE')
CONVERTING INPUT DATA TO METRIC UNITS

```
CONVERTING INPUT DATA TO METRIC UNITS

BM = 8 * 0.3048
ALM = AL * 0.3048
WM = w * 0.3048
STREAM = STREAM * 28,372025
BM = B * 0.3048
BM = BP * 0.3048
AKM = AK * 0.2069
AAM = AA * 0.3048
HOLM = HOLD * 83,3120
ROOM = ROOT * 0,3048
PREM = PRESEA * 25,40
ERR = ERROR * 100,0
DMODM = DMODI * 100,0
CON = CONSUM * 25.40
RAIN = RAIN * 25,40
NMI = NBRK = 1

CALCULATING CAPITAL RECOVERY FACTOR
CRF = (0.01 * DINTER) / (1,0 - (1,0 / (((1,0 + DINTER/100,0) ** 1YEARS)))

CALCULATING DESIRED MINIMUM DEPTH OF INFILTRATED WATER
STORED = HOLD * ROOT * DEPL / 100,0

WRITING INPUT DATA IN ENGLISH AND METRIC UNITS
```

```
WRITE(6, 450) F
WRITE(6, 460) C
WRITE(6, 470) E
WRITE(6, 480) DK
WRITE(6, 490) A2, AB
WRITE(6, 495) AAM, AB
WRITE(6, 500) MN
WRITE(6, 510) DEPL
WRITE(6, 520) MOLM, HOLM
WRITE(6, 530) ROOT, ROOM
WRITE(6, 540) DMOHM
WRITE(6, 550) CONSUM, CON
WRITE(6, 560) DAYS
WRITE(6, 570) MAIN, RAHM
WRITE(6, 580) PRESHA, PREM
WRITE(6, 590) FREQ
WRITE(6, 600) DMIN, DMMAX
WRITE(6, 610) PCENT
WRITE(6, 620) CRF
WRITE(6, 630) AUGUST
WRITE(6, 640) COLLECT
WRITE(6, 650) YEAKS, DINTER
WRITE(6, 660) FUEL
WRITE(6, 670) PUCOST
WRITE(6, 680) HCT
WRITE(6, 690) COMOUS
WRITE(6, 700) DITCH
WRITE(6, 710) CPCUYD
WRITE(6, 720) ACVALU
WRITE(6, 730) ACREFT
WRITE(6, 740) DELV
WRITE(6, 750) CLANDG
WRITE(6, 760) CLNR
WRITE(6, 770) PROVL
WRITE(6, 780) PCSTU
WRITE(6, 790) PCSTOA
WRITE(6, 800) PPMPST

DO 3 IM = 1, NPSIZ
  WRITE(6, 830) ID(I), FCOST(ID(I))
  DO 4 IM = 1, NPSIZ
  WRITE(6, 840) (CROP(K, 1, I), K = 1, NBRK)

C  AMORTIZING THE COST OF LAND GRADING
  CLANDG = CLANDG * CRF
C  CALCULATING THE AREA OF THE FIELD
  AREA = AL * W / 43560.0
C  PREDICTING A NON-EROSIVE FURROW STREAM SIZE
C  CALL FLOW(SLOP, LSOL, Q, ERR0R)
C  CHOOSING THE PROPER METHOD OF PREDICTING THE ADVANCE FUNCTION
  GO TO (10, 11), LAP
C  DECIDING WHETHER AN IRRS WILL OR WILL NOT BE USED
  GO TO (40, 41), LIRRS
C  CALCULATING THE NORMAL DEPTH OF FLOW AT THE HEAD OF THE FURROW
  CALL MANN(AR, B, BP, DM, Z, SLOP, MN, PR, INDEX, Q)
  GO TO 12
  DMKF = DM * 304.80
C  WRITING THE NORMAL DEPTH OF FLOW AT THE HEAD OF THE FURROW
WRITE(6,845) DM, DMMF
C ADJUSTING THE PREDICTED SIZE OF THE FURROW STREAM TO OBTAIN A
C PRACTICAL NUMBER OF IRRIGATION SETS WHEN NO IRRIS IS USED
41 CALL ADJUST(STREAM, Q, W, S, NSET)
C CALCULATING THE NORMAL DEPTH OF FLOW AT THE HEAD OF THE FURROW
CALL MANN(AK, B, GP, DM, Z, SLOP, MN, PR, INDEX, Q)
DMMF = DM * 304.80
C WRITING THE NORMAL DEPTH FOR FLOW AT THE HEAD OF THE FURROW
WRITE(6,845) DM, DMMF
GO TO 12
C CALCULATING THE DEPTH OF APPLICATION PER IRRIGATION, NUMBER OF
C IRRIGATIONS IN THE SEASON, AND STARTING TIME OF APPLICATION PER SET
11 CALL SEASON(AK, AN, B, DEPL, MOLD, ROOT, DHODI, CONSUM, DAYS,
1 RAIN, PRESEA, XP, TP, KN, LAS, AA, AB, TOTI, NOIRR, DL, TX, AL,
1 SEAS, FREW, INTI, OMMIN)
C CHECKING WHETHER AN IRRS WILL OR WILL NOT BE USED
GO TO (77, 78), LIONS
C ADJUSTING THE PREDICTED SIZE OF THE FURROW STREAM TO OBTAIN A
C PRACTICAL NUMBER OF IRRIGATION SETS WHEN NO IRRIS IS USED
76 CALL ADJUST(SSTREAM, Q, W, S, NSET)
77 II = 0
C PREDICTING THE INFILTRATION PATTERN USING LINEAR WETTING FRONT
55 CALL SURF(AK, AN, S, AL, CK, DOI, BK, PCENT, AA, AB, Q, TOTI, DU,
1 APPL, DEEP, AVO, STORED)
KWR = 1.00 / PCENT
GO TO 27
C ANALYZING WATER ADVANCE PHASE
12 CALL ADPACK (Q, TOTI, B, BP, DM, Z, AK, AN, S, AL, F, C, E,
1 DK, AA, AD, MN, SLOP, DTY, INV, INDEX, LAD, XST, XSE, XTH, XFO,
2 XPI, XSI, ST, STL, JST, SEL, JSE, STH, JTH, SFL, FJF, SLV, JFI,
3 BSL, JSI, SX, KSI, STY, KSY, SZ, KZ, TT, FX, FT, PX, INP,
4 VT, XDP, KDA, PX, PT, PPD, KPA, XHAX, YHAX)
II = II + 1
C CHOOSING THE DESIRED METHOD OF ADVANCE PREDICTION
56 GO TO (13, 14, 15, 16, 17)
C CHOOSING THE DESIRED METHOD OF ADVANCE PREDICTION USING FRONT
C SHAPE METHODS
13 GO TO (18, 19, 20, 21, 22, 23), LLEEP
18 TX = ST(JST)
IF(II, NE, 0) GO TO 61
C CALCULATING THE DEPTH OF APPLICATION PER IRRIGATION, NUMBER OF
C IRRIGATIONS IN THE SEASON, AND STARTING TIME OF APPLICATION PER
C SET
50 CALL SEASON(AK, AN, B, DEPL, MOLD, ROOT, DHODI, CONSUM, DAYS,
1 RAIN, PRESEA, XST, ST, JST, LAS, AA, AB, TOTI, NOIRR, DL, TX, STL,
1 SEAS, FREW, INTI, OMMIN)
C PREDICTING THE INFILTRATION PATTERN USING CURVILINEAR WETTING
C PATTERN
61 CALL SHAPE(AK, AN, S, STL, XST, ST, DOI, PERCE, JST, TOTI, Q, DU,
1 APPL, DEEP, AVO, STORED, IPlot)
KWR = JST
GO TO 27
19 TX = ST(JSE)
IF(II, NE, 0) GO TO 62
C CALL SEASON(AK, AN, B, DEPL, MOLD, ROOT, DHODI, CONSUM, DAYS,
1 RAIN, PRESEA, XSE, ST, JSE, LAS, AA, AB, TOTI, NOIRR, DL, TX, SEL,
1 SEAS, FREW, INTI, OMMIN)
62 CALL SHAPE(AK, AN, S, SEL, XSE, ST, DOI, PERCE, JSE, TOTI, Q, DU,
1 APPL, DEEP, AVO, STORED, IPlot)
KWR = JSE
GO TO 27
CALL SHAPE(AK, AN, S, FREQ, INI, OMMIN)
KWR = KPS
GO TO 27
15 IF(I, NE, 0) GO TO 71
CALL SEASON(AK, AN, S, DEPL, HOLD, ROOT, DMODI, CONSUM, DAYS,
IRAIN, PRESEA, PX, FT, INP, LAS, AA, AB, TOTI, NOIRR, DL, TX, PXX,
1 SEAS, FREQ, INI, OMMIN)
71 CALL SHAPE(AK, AN, S, PX, PX, FT, DDI, PERCE, INP, TOTI, Q, DU,
1 APPL, DEEP, AVD, STORED, IPL0T)
KWR = INP
GO TO 27
16 TX = PX(KOA)
IF(I, NE, 0) GO TO 72
CALL SEASON(AK, AN, S, DEPL, HOLD, ROOT, DMODI, CONSUM, DAYS,
IRAIN, PRESEA, XO, VT, KDA, LAS, AA, AB, TOTI, NOIRR, DL, TX, XDP,
1 SEAS, FREQ, INI, OMMIN)
72 CALL SHAPE(AK, AN, S, XDP, XO, VT, DDI, PERCE, KDA, TOTI, Q, DU,
1 APPL, DEEP, AVD, STORED, IPL0T)
KWR = KOA
GO TO 27
17 TX = PT(KPA)
IF(I, NE, 0) GO TO 73
CALL SEASON(AK, AN, S, DEPL, HOLD, ROOT, DMODI, CONSUM, DAYS,
IRAIN, PRESEA, PX, PT, KPA, LAS, AA, AB, TOTI, NOIRR, DL, TX, PPD,
1 SEAS, FREQ, INI, OMMIN)
73 CALL SHAPE(AK, AN, S, PPD, PX, PT, DDI, PERCE, KPA, TOTI, Q, DU,
1 APPL, DEEP, AVD, STORED, IPL0T)
KWR = KPA
C
27 GO TO (42, 32), LIRR

C CHOOSING THE DESIRED METHOD OF CALCULATING THE AMOUNT OF RUNOFF

C WATER

C 42 GO TO (28, 29), LRUNO

C CALCULATING THE AMOUNT OF RUNOFF WATER BY THE TRADITIONAL INFLOW-

C OUTFLOW METHOD

C 28 CALL CUMP (APPL, AVD, RF)

C GO TO 31

C CALCULATING THE AMOUNT OF RUNOFF WATER BY THE RUNOFF HYDROGRAPH

C METHOD

C 29 CALL RUNPAC (Q, TOTI, AK, AN, AA, AB, AL, S, DXR, DW, B, Z,
1 BP, DTR, INR, LAR, INDEX, RFE, RPP, HFT, RDF, RFI, XMCA, YMCA)

C CHOOSING THE DESIRED METHOD OF PREDICTING THE RUNOFF HYDROGRAPH

C 30 GO TO (33, 34, 35), LAR

C CHOOSING THE DESIRED OPTION OF THE FRONT SHAPE METHOD TO PREDICT

C THE RUNOFF HYDROGRAPH

C 33 GO TO (36, 37, 38), LAF

C RF = RFE

C 36 RF = RFE

C GO TO 31

C RF = RFP

C 37 RF = RFP

C GO TO 31

C RF = RPT

C 38 RF = RPT

C GO TO 31

C RF = RDF

C 34 RF = RDF

C GO TO 31

C RF = RFI

C 35 RF = RFI

C SYSTEMS, IRR'S
CALL IRRS STREAM, Q, AVO, AL, N, S, TX, TOTI, RF, ADJUST, YEARS, # 662
1 ENTRY, FUEL, FCOST, ID, MPSIZ, PUCOST, CMHOU, LAV, MC, COLLEC, # 663
2 DITCH, CPCYYD, ICVALU, TO, NOIRR, NSET, ACREFT, DELV, CLBR, # 664
3 SYSCST)
IF(I, EQ., 100) GO TO 99
IF (I, EQ., 0) GO TO 39
K = II
GO TO 81
C CALL COST IRRIGATION COST FOR IRRIGATION SYSTEMS WITHOUT IRRS'S # 670
1 SYSCST, RUNLOS)
IF (I, EQ., 100) GO TO 99
IF (I, EQ., 0) GO TO 39
K = II
GO TO 81
C CALCULATING THE RANGE OF SEASONAL DEPTH OF INFILTRATED WATER TO BE # 676
EXPLORED 39
APDU = DMAX * SEAS
APDL = DMIN * SEAS
C STARTING THE OPTIMIZATION PROCESS FOR THE SPECIFIED LEVELS # 681
DO 90 L = 1, IPM
NL = NLV(L)
NP = NL + 1
C CALCULATING THE INCREMENTS OF DEPTHS TO BE USED # 685
DPM = (APDU - APDL) / NL
C WRITING THE OPTIMIZATION LEVEL, UPPER AND LOWER LIMITS OF THE # 687
INTERVAL CONSIDERED, AND NUMBER OF ITERATIONS PERFORMED
WRITE(6,600) IPM, APDU, APDL, NLV(L)
WRITE(6,610) L, NL, NP, DPM
AP = APDL
APC = 25.4 * AP
APM = AP
DORNE = AP
C STARTING THE OPTIMIZATION PROCESS WITHIN A GIVEN LEVEL # 695
50
DO 70 K = 1, NP
IF (L, EQ., 1, AND, K, EQ., 1) GO TO 51
II = K
C CALCULATING THE ADJUSTED DEPTH OF INFILTRATION AT THE UPPER END OF # 699
THE FURROW
DU = DU * AP / DORNE
TOTI = (((DU = 8 * (AN+1.0)) / (1.6043 * AK)) * (1.0 / (AN+1.0))) # 702
1 60.0
C CHOOSING THE PROPER ADVANCE PREDICTION ROUTE # 703
75
GO TO (56, 55), LAP
C INTEGRATING THE ETING PATTERN AND CROP PRODUCTION FUNCTION # 705
51
CALL CRPPRO (PROF, AP, ICROP, CROP, DDI, KRR, PCOST, # 706
1 PCSTD, ACREFT, PMPCST, SYSCST, CLANDG, PROV, AREA, PERCE, LAP, # 708
1 PCCNT, N, NOIRR)
C CHECKING IF THIS IS A MAXIMIZED NET ANNUAL FARM PROFIT, MNFP # 709
IF (K, EQ., 1) GO TO 52
IF (PROF = LE, APR) GO TO 53
52
APR = PROF
APM = AP
DUPP = DU
DAVO = AVO
TYOTI = TOTI
53
WRITE(6,620) L, K, AP, APC, PROF
DORNE = AP
C CALCULATING A NEW AVERAGE SEASONAL DEPTH OF APPLICATION # 720
54
AP = AP + DPM
APC = AP * 25.4
SUBROUTINE CRPPRD(PROF, AP, ICROP, CROP, DEPTH, KWR, 
1 PDCST, PDCSTU, WATCST, PMPCST, SYSCST, CLANDG, PROVL, AREA, 
2 PERCET, LAP, PCENT, NMI, NOIRR)

SUBROUTINE FOR INTEGRATING THE DEPTH OF INfiltrATION AND CROP 
PRODUCTION FUNCTION, CPF, TO ESTIMATE GRASS YIELD AND NET FARM 

CALCULATING A SEASONAL PATTERN OF INFILTRATION 
DO 10 L=1, KWR 
PRD(L) = 0.0 
D0 = DEPTH(L) * NOIRR 

LOCATING A DEPTH OF INFILTRATION ON THE CROP PRODUCTION FUNCTION 
DO 6 K=1, NMI 
DC = CROP(K, 2, ICROP) 
DC = CROP(K+1, 2, ICROP) 
IF (DC, GE, DC) AND, DT, LT, DCC) GO TO 7 

CONTINUE 

CALCULATING AN INCREMENTAL CROP YIELD 
PRD(L) = CROP(K, 1, ICROP) + PR * (CROP(K+1, 1, ICROP) - CROP(K, 1, ICROP)) 
PRD = 0.00 

CHOOSING THE PROPER WETTING PATTERN 
GO TO (11, 13), LAP 

CALCULATING TOTAL CROP YIELD 
DO 12 L=1, KWR 
PRD = PRD + PERCET(L) * AREA * PRD(L) / 100.0 
GO TO 15 

CALCULATING TOTAL CROP YIELD 
DO 14 L=1, KWR 
PRD = PRD + AREA * PCENT * PRD(L) 

CALCULATING WATER PUMPING COST 
15 PMPC = AP + AREA * PMPCST 

CALCULATING CROP PRODUCTION COST FOR THE ENTIRE AREA 
PDCST = CROP PRODUCTION COST FOR THE ENTIRE AREA 
PDCST = AREA * PDCST 

CALCULATING CROP PRODUCTION COST FOR THE ENTIRE PRODUCTION 
PDCST = CROP PRODUCTION COST FOR THE ENTIRE AREA 
PDCST = AREA * PDCST 

CALCULATING GROSS REVENUE FROM IRRIGATION 
REV = PRD + PROVL 

CALCULATING TOTAL SURFACE IRRIGATION SYSTEM COST 
TLCST = SYSCST + PMPC + CRPCU + CLANDG = AREA 

CALCULATING NET ANNUAL FARM PROFIT, NAPP 
PROF = REV + TLCST * 1.0200 
RETURN
SUBROUTINE ADJUSQ(STREAM, Q, w, S, NSET) # 790
C SUBROUTINE FOR ADJUSTING FURROW STREAM SIZE TO OBTAIN A PRACTICAL # 791
C NUMBER OF IRRIGATION SETS FOR FURROW IRRIGATION SYSTEMS WITHOUT # 792
C IRRSIS # 793
100 FORMAT( /, 'ADJUSTED FURROW STREAM SIZE =', ' (LPS)') # 794
110 FORMAT( /, 'NUMBER OF IRRIGATION SETS WHEN NO IRRS IS USED =', ' (LPS)') # 795
120 FORMAT( /, 'NUMBER OF FURROWS PER SET FROM THE SUPPLY =', ' (LPS)') # 796
130 FORMAT( /, 'CURRENT NUMBER OF IRRIGATION SETS ') # 797
C SUPPLY STREAM # 798
F8 = STREAM / 408.8 / Q # 799
C CALCULATING TOTAL NUMBER OF FURROWS IN THE FIELD # 800
F = w / S # 801
C CALCULATING THE NUMBER OF IRRIGATION SETS # 802
NSET = F / F8 # 803
P = NSET # 804
F8 = P / P # 805
IFS = F8 # 806
XFS = IFS # 807
DEL = F8 = XFS # 808
IFS = IFS + 1 # 809
GO TO 30 # 810
100 IF = IFS # 811
30 F8 = IFS # 812
C ADJUSTING FURROW STREAM SIZE ACCORDING TO THE NUMBER OF IRRIGATION # 813
C SETS # 814
G = STREAM / 408.8 / F8 # 815
QM = 0.06310 / G # 816
C WRITING FINAL RESULTS # 817
WRITE(6,110) Q, QM # 818
WRITE(6,120) F8 # 819
END # 820
SUBROUTINE FLOW(SLOP, LSOIL, Q, ERROR)
SUBROUTINE FOR PREDICTING NON-EROSSIVE FURROW STREAM SIZE FOR A GIVEN FURROW SLOPE AND SOIL TYPE

150 FORMAT (/5X,'NON-EROSSIVE FURROW STREAM SIZE =',F10.5,' GPM ('$10,5,1 LPS))

GO TO (1, 2, 3, 4, 5, 6), LSOIL

1 ALFA = 14.144
BETA = 0.937
GO TO 70

2 ALFA = 15.666
BETA = 0.550
GO TO 70

3 ALFA = 10.216
BETA = 0.704
GO TO 70

4 ALFA = 9.712
BETA = 0.733
GO TO 70

5 ALFA = 17.605
BETA = 0.615
GO TO 70

6 ALFA = 10.543
BETA = 0.548

CALCULATING NON-EROSSIVE FURROW STREAM SIZE

Q = ALFA * SLOP * BETA
QM = Q * 0.0630
IF(ERROR > 0.00) GO TO 99

ADJUSTING THE CALCULATED NON-EROSSIVE FURROW STREAM SIZE IF DESIRED
Q = Q * (1.0 + ERROR)
QM = Q * 0.0630

WRITE FINAL FURROW STREAM SIZE

WRITE(6,150) Q, QM
RETURN
END
SUBROUTINE ADPACK(Q, TOTI, B, BP, DM, Z, AK, AN, S, AL, F, C, E, M,
1, AX, AB, AM, N, SLOP, DTV, INV, INDEX, LAD, XST, XSE, XTM, XPO, 
2, XFI, XSI, ST, STL, JST, SEL, JSE, STM, JTM, STL, JFI, 
3, SSL, JSI, S, KSX, SY, KSY, Z, KSZ, TT, FX, FT, PFX, INP, XD, 
4, VT, XOP, KDA, FX, PT, PHO, KPA, XMAX, YMAX)
SUBROUTINE FOR PREDICTING THE ADVANCE OF THE WATER FRONT DOWN THE 
FURROW CHANNEL
DIMENSION DX(300), DY(300), DZ(300), AI(300), GI(300), FX(300), 
1PX(300), PDX(300), X8T(300), XSE(300), XTM(300), XFO(300), XD(300), 
1XFI(300), XSI(300), SY(300), SX(300), PI(300), DOX(300), 
1ST(300), TT(300), FT(300), VT(300), PT(300), VARY(300)
DIMENSION XP(300), TP(300), DOI(300), PERCE(300), DDD(300), DI(300)
REAL MN
MPAGES = 1
XMIN = 0.00
YMIN = 0.00
C CHOOSING THE DESIRED ADVANCE PREDICTION ROUTE
GO TO (10, 10, 40, 50, 60), LAD
10 CALL COEFF(B, BP, Z, S, ALF, BET, PHI, PSI, ETA, GAM, INDEX, DW)
IF(LAD = EQ , 1) GO TO 20
IF(LAD = EQ, 2) GO TO 50
C PREDICTING WATER ADVANCE FUNCTION USING THE FRONT SHAPE METHOD
20 CALL ELLEP(ALF, BET, PHI, PSI, ETA, OW, AK, AN, DTV, INV, Q, S, XST, 
1XSE, XTM, XFO, XFI, XSI, ST, STL, JST, SEL, JSE, STM, JTM, STL, JFI, 
2JFO, SUL, JFI, SSL, JSI, AL, XMIN, XMAX, YMIN, YMAX, MPAGES)
GO TO 2
C PREDICTING WATER ADVANCE FUNCTION USING THE INTEGRATED INTAKE
30 CALL INTAKE(ALF, BET, GAM, DW, AK, AN, DTV, INV, Q, S, SX, KSX, SY, 
1KSY, SZ, KSZ, TT, AL, XMIN, XMAX, YMIN, YMAX, MPAGES)
GO TO 2
C PREDICTING WATER ADVANCE FUNCTION USING FOX AND BISHOP'S METHOD
40 CALL FOX(AK, AN, AA, AB, G, DM, Z, B, BP, DTV, INV, INDEX, FX, FT, 
1PFX, INP, AL, XMIN, XMAX, YMIN, YMAX, MPAGES)
GO TO 2
C PREDICTING WATER ADVANCE FUNCTION USING DAVIS'S METHOD
50 CALL DAVIS(AK, AN, G, F, C, E, DM, DK, DTV, INV, XD, VT, XDP, KDA, 
1AL, XMIN, XMAX, YMIN, YMAX, MPAGES)
GO TO 2
C PREDICTING WATER ADVANCE FUNCTION USING PATTERSON'S METHOD
60 CALL PATTER(AK, AN, MN, G, Z, B, BP, DM, SLOP, DTV, INDEX, INV, PX, 
1PT, PPD, KPA, AL, XMIN, XMAX, YMIN, YMAX, MPAGES)
RETURN
END

SUBROUTINE COEFF(B, BP, Z, S, ALF, BET, PHI, PSI, ETA, GAM, INDEX)

SUBROUTINE FOR CALCULATING THE ADVANCE COEFFICIENTS

170 FORMAT (/ S, 'ALPHA = ', F10.6, ' FEET (', F10.4, ' M)')
180 FORMAT (/ S, 'PHI = ', F10.6, ' FEET (', F10.4, ' M)')
190 FORMAT (/ S, 'ETA = ', F10.6, ' FEET (', F10.4, ' M)')
200 FORMAT (/ S, 'ETA = ', F10.6, ' FEET (', F10.4, ' M)')
210 FORMAT (/ S, 'ETA = ', F10.6, ' FEET (', F10.4, ' M)')
220 FORMAT (/ S, 'ETA = ', F10.6, ' FEET (', F10.4, ' M)')
230 FORMAT (/ S, 'ETA = ', F10.6, ' FEET (', F10.4, ' M)')

IF (INDEX .EQ. 2) GO TO 10

CALCULATING ADVANCE COEFFICIENTS FOR TRAPEZOIDAL, TRIANGULAR, OR RECTANGULAR CHANNELS

ALF = 0.76539 * 0.66667 * Z * DM
BET = 0.66667 * 0.50000 * Z * DM
GAM = 0.50000 * 0.33333 * Z * DM
GO TO 20

CALCULATING ADVANCE COEFFICIENTS FOR PARABOLIC FURROW CHANNELS

10 ALF = 0.626 * BP
BET = 0.381 * BP
GAM = 0.267 * BP

20 PHI = 0.76539 * S
PSI = 0.66667 * S

CONVERTING THE RESULTS TO METRIC UNITS

ALFM = 0.3048 * ALF
BETM = 0.3048 * BET
GAMM = 0.3048 * GAM
PHIM = 0.3048 * PHI
PSIM = 0.3048 * PSI
ETAM = 0.3048 * ETA

WRITING FINAL RESULTS

WRITEx, 230)
WRITEx, 170) ALFM
WRITEx, 180) BETM
WRITEx, 220) GAM, GAMM
WRITEx, 190) PHIM
WRITEx, 200) PSIM
WRITEx, 210) ETA, ETAM

RETURN
END
SUBROUTINE ELLEP(ALF, BET, PHI, ETA, DW, AK, AN, DT, IN, G, S)
1 XST, XSE, XTH, XFO, XFI, XSI, ST, STL, JST, SEL, JSE, STM, JTH,
2 SFL, JFU, SVL, JFI, SSL, JSI, AL, XMIN, XMAX, YMIN, YMAX, MPAGES)
C SUBROUTINE FOR PREDICTING THE ADVANCE OF THE WATER FRONT DOWN THE
C FURROW CHANNEL USING FRONT SHAPE METHOD
DIMENSION XST(300), XSE(300), XTH(300), XFO(300), XFI(300),
2 XSI(300), ST(300), VARV(300)
10 FORMAT(2X,1X,'TIME='IN, DU=INCHES(MM) FIRST=FEET=(M) SECOND=')
110 FORMAT(1H1, 1 TIME='MM, DU=INCHES(MM) FIRST=FEET=(M) SECOND=')
120 FORMAT(FH.1,F,,1,F&.1,,,.2,,a,2,1,,,2,,a,2,1,,,2,Fa,2,2F1J,2)
WRITE(0,240)
WRITE(0,110)
C CALCULATING VOLUME OF SURFACE STORED WATER
AALF=DW
BET=DW
PQ=Q/7.48
ST(1) = DT
P = (12,0=AK)/(7,48*3*(AN+1,0))
C PREDICTING ADVANCED DISTANCE FOR SEVERAL TIME INCREMENTS FOR SIX
C COMBINATIONS OF SHAPES OF WATER AND WETTING FRONTS
DO 1 J=1, IN
C CALCULATING ACCUMULATED DEPTH OF INFILTRATED WATER AT THE UPPER
C END OF THE FURROW
DU = P = (ST(J) **(AN+1,0))
ST(J+1) = ST(J) + DT
C CONVERTING THE RESULTS TO METRIC UNITS
DUIM=304,80*DU
DHM=IM*DU/12,0
EMP=DU/12,0
FETA=DU/12,0
G = PQ = ST(J)
XST(J) = G / ( A + D )
IF(XST(J) , GT , AL) GO TO 3
JST = J
GO TO 4
3 XST(J) = STL
4 XSE(J) = G / ( A + E )
IF(XSE(J) , GT , AL) GO TO 5
JSE = J
GO TO 6
5 XSE(J) = SEL
6 XTH(J) = G / ( A + F )
IF(XTH(J) , GT , AL) GO TO 7
JTH = J
GO TO 8
7 XTH(J) = STM
8 XFO(J) = G / ( C + D )
IF(XFO(J) . GT. AL) GO TO 9
JFO = J
GO TO 11
9 XFO(J) = SFL
11 XFI(J) = G / ( C + E )
IF(XFI(J) . GT. AL) GO TO 12
JFI = J
GO TO 13
12 XFI(J) = SVL
13 XSI(J) = G / ( C + F )
IF(XSI(J) . GT. AL) GO TO 15
JSI = J
GO TO 14
15 XSI(J) = SSL
14 XSTM =0.3048*XST(J)
XSEM =0.3048*XSE(J)
XTHM =0.3048*XTH(J)
XFOM =0.3048*XFO(J)
XFIM =0.3048*XFI(J)
XBIM =0.3048*XSI(J)
8TL = XST(J)
8SL = XSE(J)
8TM = XTH(J)
8FL = XFO(J)
8VL = XFI(J)
8SL = XSI(J)
C WRITING FINAL RESULTS FOR SIX COMBINATIONS OF THE WATER AND
C WETTING FRONTS
WRITE(6,260) ST(J), DU, DUM, XST(J), XSTM, XSE(J), XSEM, XTH(J),
XTHM, XFO(J), XFOM, XFI(J), XFIM, XSI(J), XBIM
1 CONTINUE
C PLOTTING THE PREDICTED WATER ADVANCE FUNCTIONS
GO TO 2
10 WRITE(6,120)
CALL GRAPH(XST, ST, JST, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)
GO TO 2
20 WRITE(6,130)
CALL GRAPH(XSE, ST, JSE, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)
GO TO 2
30 WRITE(6,140)
CALL GRAPH(XTH, ST, JTH, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)
GO TO 2
40 WRITE(6,150)
CALL GRAPH(XFO, ST, JFO, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)
GO TO 2
50 WRITE(6,160)
CALL GRAPH(XFI, ST, JFI, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)
GO TO 2
60 WRITE(6,170)
CALL GRAPH(XSI, ST, JSI, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)
2 CONTINUE
RETURN
END
SUBROUTINE INTAKE(alf, bet, gam, dw, ak, an, dt, in, q, s, sx, kx)
1, sy, ks, sz, tt, al, xmin, xmax, ymin, ymax, mpages)
C SUBROUTINE FOR PREDICTING THE ADVANCE OF THE WATER FRONT DOWN THE
C FURROW CHANNEL USING THE INTEGRATED INTAKE METHOD
C DIMENSION DX(300), DY(300), DZ(300), AI(300), BX(300), SY(300),
13Z(300), TT(300), VARY(300)
200 FORMAT(1HI, '**** CALCULATED DISTANCE OF ADVANCE USING INTAKE
1 PER UNIT LENGTH ****")
210 FORMAT(1/5X, 'TIME, QX, DX, ELLEPTICAL STORAGE, 10X, PARABOIC
1 STORAGE, 10X, TRIANGULAR STORAGE')
220 FORMAT(13X, 'MIN, 7X, INCHES = M, 6X, DISTANCE = FEET = M, 11X, DISTAN
1CE = FEET = M, 11X, DISTANCE = FEET = M')
230 FORMAT(1HI, 'PLOT OF THE INTEGRAL INTAKE AND ELLEPTIC SURFACE STORAGE')
240 FORMAT(1HI, 'PLOT OF THE INTEGRAL INTAKE AND PARABOLIC SURFACE STORAGE')
250 FORMAT(1HI, 'PLOT OF THE INTEGRAL INTAKE AND LINEAR SURFACE STORAGE')
260 FORMAT(F7,1,F10,3,F7,1,1X,F8,2,10X,2,10x,3,F8,2,10x,2,10x)
WRITE(6,200)
WRITE(6,210)
WRITE(6,220)
TI = DT/2.0
C CALCULATING INSTANTANEOUS INTAKE RATE
DO 1 IM=1, IN
TI = TI + DT
1 AI(I) = (AK * (TI)**AN)/7.48
DINO = DT/(ALF + DW + AI(I) + DT)
DIMO = DT/(BET + DW + AI(I) + DT)
DICO = DT/(GAM + DW + AI(I) + DT)
FLOW = 0./7.48
C CALCULATING THE ADVANCED DISTANCE DURING THE FIRST TIME INCREMENT
C FOR THREE SHAPES OF WATER FRONT
OX(I) = FLOM + DINO
DY(I) = FLOM + DIMO
DZ(I) = FLOM + DICO
TT(I) = DT
BX(I) = DX(I)
SY(I) = DY(I)
SZ(I) = DZ(I)
AM = AN + 1.0
P = (12.0/AN) - (7.48 * 8 + AM)
C CALCULATING THE ACCUMULATED DEPTH OF INFILTRATED WATER AT THE
C UPPER END OF THE FURROW
DU = P = T ** AM
C CONVERTING THE PREDICTED ADVANCED DISTANCES TO METRIC UNITS
DUM = DU = 30.48
XM = BX(1), 3.28
XY = SY(1), 3.28
XZ = SZ(1), 3.28
WRITE(6,200) TT(I), DU, DUM, BX(1), XM, SY(1), XY, SZ(1), XZ
DO 20 JN=2, IN
TT(J) = TT(J-1) + DT
C CALCULATING THE ACCUMULATED DEPTH OF INFILTRATED WATER AT THE
C UPPER END OF THE FURROW
DU = P = TT(J)**AM
DUM = DU = 30.48
BX = 0.00
BUY = 0.00
SUZ = 0.00
M = J
DO 10 KM = 2, J
M = M + 1
C
ACCUMULATING THE INSTANTANEOUS INTAKE RATES ALONG THE ADVANCED DISTANCE
SUX = SUX + AI(K) * DX(M)
SUY = SUY + AI(K) * DY(M)
SUX = SUZ + AI(K) * DZ(M)
10 PREDICTING THE ADVANCED DISTANCES FOR SEVERAL TIME INCREMENTS AND THREE SHAPES OF THE WATER FRONT
DX(J) = (FLOW = SUX) * DINO
DY(J) = (FLOW = SUY) * DINO
DZ(J) = (FLOW = SUZ) * DICO
IF(SX(J-1), GT, AL) GO TO 3
8X(J) = SX(J-1) + DX(J)
KBX = J
GO TO 4
3 SX(J) = SX(J)
4 IF(SY(J-1), GT, AL) GO TO 5
8Y(J) = SY(J-1) + DY(J)
KSY = J
GO TO 6
5 SY(J) = SY(J)
6 IF(SZ(J-1), GT, AL) GO TO 7
8Z(J) = SZ(J-1) + DZ(J)
KSZ = J
GO TO 8
7 SZ(J) = SZ(J)
C
CONVERTING THE PREDICTED ADVANCED DISTANCES TO METRIC UNITS
XM = SX(J) / 3.28
XY = SY(J) / 3.28
XZ = SZ(J) / 3.28
SXE = SX(J)
SYP = SY(J)
SZT = SZ(J)
WRITE(6,240) TT(J), DU, DUM, 8X(J), XM, BY(J), XY, SZ(J), XZ
20 CONTINUE
C
PLOTTING THE PREDICTED WATER ADVANCE FUNCTIONS
DO 2 K = 1, 3
GO TO (30, 40, 50), K
30 WRITE(6,230)
CALL GRAPM(SX, TT, KBX, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)
GO TO 2
40 WRITE(6,240)
CALL GRAPM(SY, TT, KSY, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)
GO TO 2
50 WRITE(6,250)
CALL GRAPM(SZ, TT, KSZ, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)
2 CONTINUE
RETURN
END
SUBROUTINE FOK(AK, AN, AA, AB, Q, DM, Z, B, BP, DT, IN, INDEX, FX,  
1FT, PFx, INP, AL, XM11, XMAX, YMIN, YMAX, MPAGES)  
SUBROUTINE FOR PREDICTING THE ADVANCE OF THE WATER FRONT DOWN THE  
FURROW CHANNEL USING FOK AND BISHOP'S METHOD  
DIMENSION FX(300), FT(300), VARY(300)  
100 FORMAT(1H1, 'CALCULATED ADVANCE DISTANCE USING FOK AND BI-  
SHOP S APPROACH **********')  
120 FORMAT(1H1, 'TIME=MINUTES=  
DISTANCE =FEET=(M)')  
130 FORMAT(5X,11,  
140 FORMAT(5X,F10.2,11X,F10.2)  
150 FORMAT(1H1, 'PLOT OF FOK AND BISHOP S TECHNIQUE')  
IF (INDEX = EQ. 2) GO TO 2  
CALCULATING THE VOLUME OF SURFACE STORED WATER FOR TRAPEZOIDAL,  
TRIANGULAR, OR RECTANGULAR FURROW CHANNEL  
1 A = B + DM + Z = DM + DN  
GO TO 3  
CALCULATING THE VOLUME OF SURFACE STORED WATER FOR PARABOLIC  
FURROW CHANNELS  
2 A = 0,6666667 * BP = DN  
3 FLOW = Q / 7,48  
M = 1,00  
AM = AN + 1,00  
A2 = AN + 2,00  
CALCULATING THE CORRECTION FACTOR "F"  
F = AB*A2*((1,0/AB) = (AM/(AB+1,0))* (AN=AM)/(2,0=(AB+2,0)))  
P = (M = F = AK)/((7,48 = AM = A2)  
S = A/ (1,0 + AB)  
WRITE(6,100)  
WRITE(6,120)  
WRITE(6,130)  
FT(I) = DT  
PREDICTING ADVANCED DISTANCES FOR SEVERAL TIME INCREMENTS  
DO 10 I=1, IN  
FX(I) = (FLOW *FT(I)) / ( 3 + P * FT(I) = AM)  
CONVERTING THE RESULTS TO METRIC UNITS  
XM =FX(I) / 3,28  
WRITE(6,140) PT(I), FX(I), XM  
PFx = FX(I)  
INP = I  
IF(FX(I) = GT + AL) GO TO 11  
ACCUMULATING THE TIME OF ADVANCE  
FT(I+1) = FT(I) + DT  
CONTINUE  
PLOTTING THE PREDICTED ADVANCE FUNCTION  
11 WRITE(6,150)  
CALL GRAPH(FX, PT, INP, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)  
RETURN  
END
SUBROUTINE DAVIS(AK, AN, Q, F, C, E, D, DX, DT, IN, XD, VT, 
IXDP, KDA, AL, XMIN, XMAX, YMIN, YMAX, MPAGES) 

SUBROUTINE FOR PREDICTING THE ADVANCE OF THE WATER FRONT DOWN THE 
FURROW CHANNEL USING DAVIS'S METHOD 

DIMENSION DX(300), Q(300), XD(300), VT(300), VARY(300) 

FORMAT(1M1, 1 **CALCULATED DISTANCE OF ADVANCE USING DAVIS'S 
APPROACH:**********)**) 

INCREMENT DISTANCE FEET = (M) 

DIMENSION(300), G(100), XD(300), VARYC300) 

CALCULATING THE G=INDEX OF DAVIS'S METHOD 

RI = I 

G(I) = (RI**AM) = (RI=2,0)**AM 

C  **WRITE THE HEADINGS OF THE OUTPUT** 

HEREWRITE(6,200) 

HEREWRITE(6,240) 

HEREWRITE(6,250) 

C  **CALCULATING THE VOLUME OF SURFACE STORED WATER** 

P = (FA AK MK DT)**AM)/(2,0**AM) 

R = 2,0 * P * DX 

W = IC = D = (2,0 + E)*7,48 

V = R + W 

C  **CALCULATING THE VOLUME OF APPLIED WATER** 

C  **PREDICTING THE FIRST INCREMENT OF PREDICTED DISTANCE** 

DDX(1) = FLOW / V 

DDMX =DX(1) / 3,28 

X(1) = DX(1) 

VT(1) = DT 

HEREWRITE(6,260) VT(1), DD(1), DDMX , XD(1), DDMX 

C  **PREDICTING AND ACCUMULATING THE ADVANCED DISTANCE FOR VARIOUS** 

C  **TIME INCREMENTS** 

DO 10 J=2, IN 

SUM = 0,00 

M = J 

DO 20 K=2, J 

M = M + 1 

20 SUM = SUM + G(K) *DDX(M) 

DDX(J) = FLOW = (SUM+P))/V 

DDMX =DDX(J) / 3,28 

XD(J) = XD(J-1) + DDX(J) 

XM = XD(J) / 3,28 

KDA(4) 

C  **ACCUMULATING THE TIME OF ADVANCE** 

VT(J) = VT(J-1) + DT 

C  **CHECKING THE LIMITS OF THE PREDICTED DISTANCE AND WRITING THE** 

C  **RESULTS** 

IF(XD(J) , GT , AL) GO TO 11 

HEREWRITE(6,260) VT(J), DDX(J), DDMX , XD(J), XM 

CONTINUE 

C  **PLOTTING THE PREDICTED ADVANCE FUNCTION** 

HEREWRITE(6,270) 

CALL GRAPH(XD, VT, KDA, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES) 

RETURN 

END
SUBROUTINE PATTERN(AK, AN, MN, O, Z, B, BP, DW, SLOP, DT, INDEX, IN;)
SUBROUTINE FOR PREDICTING THE ADVANCE OF THE WATER FRONT DOWN THE
FURROW CHANNEL USING PATTERSON'S METHOD
DIMENSION PI(300), PX(300), PD(300), PT(300), VARY(300)
100 FORMAT(1H1, ****** CALCULATED ADVANCED DISTANCE USING PATTERN
IN S APPROACH ******)
110 FORMAT(//,5X,'TIME=MIN=1,10X,'INCREMENT DIST=FEET=(M)',10X,'ACC DISTA
INCE =FEET=(M);)
120 FORMAT(5X,'----------')
130 FORMAT(5X,F6,2,11X,F210,2,10X,F211,2)
140 FORMAT(1H1, 'PILOT OF PATTERSON S TECHNIQUE')
WRITE(6,100)
WRITE(6,110)
WRITE(6,120)
C CALCULATING THE WATERWAY CROSS_SECTIONAL AREA FOR VARIOUS CHANNEL
SHAPES
IF(INDEX .EQ. 0) GO TO 2
A = B + DW + Z + DW
GO TO 11
2 A = 0,667 * BP + DW
GO TO 11
11 P = 0
C CALCULATING INSTANTANEOUS INTAKE RATES
T = 0,00
DO 8 I=1, IN
T = T + DT
8 PI(I) = AK * TI**AN
C PREDICTING THE FIRST INTERVAL OF ADVANCED DISTANCE
FLOW = P = DT
PAT = PI(1) * DT
PDX(1) = FLOW/(5,61 * A + PAT)
PT(1) = DT
PX(1) = PDX(1)
DXM = PDX(1) / 3,28
WRITE(6,130) PT(1), PDX(1), DXM, PX(1), DXM
P = P = PI(2) * PDX(1)
PPP = P
C CALCULATING THE NORMAL DEPTH OF FLOW
CALL MANN(A, B, BP, DW, Z, SLOP, MN, P, INDEX, PPP)
C PREDICTING AND ACCUMULATING THE PREDICTED ADVANCED DISTANCE
12 DO 20 J=2, IN
IF(INDEX .EQ. 2) GO TO 31
A = B + DW + Z + DW
GO TO 32
31 A = 0,6667 * BP + DW
32 SUM = 0,00
M = J
DO 30 K=2, J
M = M + 1
30 SUM = SUM + PI(K) * PD(M)
PDX(J) = (FLOW = SUM)/(PAT + 5,61 * A)
PX(J) = PX(J-1) + PDX(J)
PT(J) = PT(J-1) + DT
XM = PX(J) / 3,28
DXM = PDX(J) / 3,28
WRITE(6,130) PT(J), PDX(J), DXM, PX(J), XM
PPD = PX(J)
KPA = J
IF(PX(J), GT, AL) GO TO 13
NI = J + 1
DO 40 NN = 1, J
SU = 0.00
NI = NI - 1
40 SU = SU + PI(NN) * PDX(NI)
P = PPP
PPP = P
C CALCULATING THE NORMAL DEPTH OF FLOW
CALL MANN(A, B, BP, DM, Z, SLOP, MN, P, INDEX, PPP)
CONTINUE
C PLOTTING THE PREDICTED ADVANCE FUNCTION
WRITE(6,140)
CALL GRAPH(PlC, PT, KPA, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)
RETURN
END
C
C SUBROUTINE MANN(A, B, BP, DM, Z, SLOP, MN, P, INDEX, Q)
C SUBROUTINE FOR CALCULATING THE NORMAL DEPTH OF FLOW AT THE HEAD
C OF THE FLOW USING MANNING'S EQUATION
REAL MN
190 FORMAT( '5X,' 'LIMITS ON NUMERICAL ITERATIONS WERE EXCEEDED!')
C CALCULATING THE WATERWAY CROSS-SECTIONAL AREA AND WETTED PERIMETER
C FOR VARIOUS FLOW CHANNEL SHAPES
IF(INDEX , EQ, 2) GO TO 60
PD = 2.0 * SQRT(Z*Z+1.0)
DA = B + 2.0 * Z * DW
GO TO 63
60 PD = 5.334 * DM / BP
DA = 0.6667 * BP
63 NCT = 0
K = 1
C USING AN ITERATIVE PROCEDURE TO CALCULATE THE NORMAL DEPTH OF FLOW
66 IF(INDEX , EQ, 2) GO TO 64
61 P = B + 2.0 * DM / SQRT(Z*Z+1.0)
A = B + DM + Z * DW + DW
GO TO 65
64 P = BP + 2.667 * DM + DW / BP
A = 0.6667 * BP + DW
65 FM=(MN*Q*P**0.667/448.8)**1.486*(SQRT(SLOP)**1.486+1.486)**0.667
DF=(0.667*MN*Q*PD/(448.4*P**0.333) - 2.607*(SQRT(SLOP))*DA+1.0,1.667)
DIF = F / DF
DEE = DW
DM = DW - DIF
C CHECKING THE LIMITS ON THE CALCULATED DEPTH AND NUMBER OF
C ITERATIONS PERFORMED
IF(DW , GT, 0.00) GO TO 90
IF(ABS(DIF) , GT, 0.001, AND, NCT LT 200) GO TO 66
1448 IF(NCT , EQ, 500) GO TO 80
GO TO 99
70 NCT = NCT + 1
80 WRITE(6,190)
90 DW = DEE
99 RETURN
END
SUBROUTINE GRAPH(XX, YY, M, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)
SUBROUTINE FOR PLOTTING THE PREDICTED ADVANCE FUNCTION, SETTING
FRONT, OR RUNOFF HYDROGRAPH
REAL LINE(111), BLANK,' ', DOT,' .', X,'X', OD, O'/,
Y,'Y', PLUS,' +'/
REAL AST,'*/'/
DIMENSION LINE(112), XX(300), YY(300), YAXIS(20)
DIMENSION VARY(100), XAXIS(101)
DIMENSION YAXIS(MPAGES)

GO TO (12,14), MPAGES
10 DYMHN = YMAX - YMIN
YAXIS(1) = YMIN
GO TO (12,14), MPAGES
12 XSPACE = 50, 0
MSPACE = 51
GO TO 16
14 XSPACE = 100, 0
MSPACE = 101
GO TO 16
16 DO 20 K=2,11
20 YAXIS(K) = YAXIS(K-1) + 0,1*DYMHN
30 IF (DYMHN = 1000,0) 40,100,100
40 IF (YMAX = 1000,0) 50,100,100
50 IF (YMIN + 100,0) 100,100,60
60 IF (ABS(YMIN) = (1,0E=02)) 70,70,80
70 IF (YMIN + 100,0) 100,80,100
80 IF (ABS(YMAX) = (1,0E=02)) 90,90,110
90 IF (YMAX) 100,110,100
100 WRITE (6,1) (YAXIS(K), K=2,11)
GO TO 120
110 WRITE (6,2) (YAXIS(K), K=2,11)
120 DO 130 J=1,112
130 LINE(J) = BLANK
WRITE (6,3) LINE
KOUNT = 0
IF (XMIN) 140,170,170
140 IF (XMAX) 170,170,150
150 DO 160 J=10,112
160 LINE(J) = BLANK
GO TO 200
170 DO 180 J=10,110
180 LINE(J) = DOT
DO 190 J=10,110,10
190 LINE(J) = PLUS
LINE(112) = Y
200 DYMHN = XMAX - XMIN
XAXIS(1) = XMIN
DO 210 KK=11, MSPACE, 10
210 XAXIS(KK) = XAXIS(KK-10) + (10,0/XSPACE)*DYMHN
KK = 1
XNYL = DYMHN/XSPACE
VARK = XMIN
220 DO 770 J=1, MSPACE
IF (YMIN) 230, 260, 260
230 JY = (100,0/DYMHN)*ABS(YMIN) + 9,5
IF (JY=110) 250,240,240
WRITE(6,1)
240 JY = 9
250 LINE(JY+1) = DOT
GO TO 270
260 LINE(10) = DOT
JY = 9
270 IF (L=1) 260,330,280
280 IF (L=1) 290,340,290
290 IF (L=21) 300,340,300
300 IF (L=21) 310,340,310
310 IF (L=01) 320,340,320
320 IF (L=01) 321,340,321
321 GO TO (430,322),HPAGES
322 IF (L=61) 323,340,323
323 IF (L=71) 324,340,324
324 IF (L=01) 325,340,325
325 IF (L=01) 326,340,326
326 IF (L=01) 430,340,430
330 LINE(JY+1) = X
340 LINE(JY+1) = PLUS
KK = L
350 IF (DXMXMN = 1000,0) 350,410,410
360 IF (XMAX = 1000,0) 360,410,410
370 IF (ABS(XMIN) = (1,0E-02)) 380,380,390
380 IF (XMIN) 410,390,410
390 IF (ABS(XMAX) = (1,0E-02)) 400,400,420
400 IF (XMAX) 410,420,410
410 WRITE (6,4) XAXIS(KK)
GO TO 430
420 WRITE (6,5) XAXIS(KK)
430 IF ((VARX + XINVL/2,0) = ABS(VARX)) 480,440,440
440 KOUNT = KOUNT + 1
450 DO 460 J=10,110
460 LINE(J) = DOT
GO TO 470
470 LINE(J) = PLUS
LINE(111) = BLANK
LINE(112) = Y
480 K = 0
490 DO 530 I=1,M
TRY = XX(I) = VARX
TRY = TRY = (XINVL/2,0)
500 IF (TRY) 490,530,530
510 IF (TRY + XINVL) 500,510,510
520 GO TO 530
530 K = (YY(I) = YMIN)*100,0/DYMXMN + 9,5
540 IF (K=11) 512,525,525
550 IF (K=11) 515,525,525
560 LINE(K+1) = 0
GO TO 530
570 CONTINUE
J = (VARY(L) = YMIN)*100,0/DYMXMN + 9,5
580 IF (J=11) 540,580,580
590 IF (J=11) 550,580,580
600 IF (LINE(J+1) = 0) 570,560,570
610 LINE(J+1) = 0
GO TO 590
570 LINE(J+1) = A80
GO TO 590
580 J = 0
590 J1 = J + 1
K1 = KMAX + 1
JY1 = JY + 1
IF (LINE(112) = Y) 600, 720, 600
600 IF (JY = J) 620, 610, 610
610 IF (JY = K) 660, 650, 610
620 IF (J = K) 660, 690, 640
630 IF (L = KK) 640, 650, 640
640 WRITE (6,3) (LINE(JJ), JJ = 10, JY1)
GO TO 750
650 WRITE (6,6) (LINE(JJ), JJ = 10, JY1)
GO TO 750
660 IF (L = KK) 670, 680, 670
670 WRITE (6,6) (LINE(JJ), JJ = 10, K1)
GO TO 750
680 WRITE (6,6) (LINE(JJ), JJ = 10, K1)
GO TO 750
690 IF (L = KK) 700, 710, 700
700 WRITE (6,3) (LINE(JJ), JJ = 10, J1)
GO TO 750
710 WRITE (6,6) (LINE(JJ), JJ = 10, J1)
GO TO 750
720 IF (L = KK) 740, 750, 740
730 WRITE (6,6) (LINE(JJ), JJ = 10, 112)
GO TO 750
740 WRITE (6,3) (LINE(JJ), JJ = 10, 112)
750 DO 760 J = 10, 112
760 LINE(J) = BLANK
VARX = VARX + XINVL
770 CONTINUE
1 FORMAT (/16X,1PE9,2,9(1X,1PE9,2))
2 FORMAT (/17X,F7.3,9(3X,F7.3))
3 FORMAT (1H9,9X,10341)
4 FORMAT (',1PE9.2)
5 FORMAT (',1F9.4)
6 FORMAT ('49,9X,10341)
9 FORMAT ('1',20A4)
900 RETURN
END

SUBROUTINE COMP(APPL, AVD, RF)
SUBROUTINE FOR CALCULATING THE DEPTH AND PERCENTAGE OF RUNOFF
USING THE TRADITIONAL INFLOW-OUTFLOW METHOD
100 FORMAT (/5X,'RUNOFF DEPTH =',F10.4,' INCHES ('F10.4,' MM)'),
110 FORMAT (/5X,'RUNOFF PERCENTAGE =',F10.4,'%')
CALCULATING THE RUNOFF PERCENTAGE AND PRINTING THE RESULTS
RUN = APPL = AVD
RUNM = RUN = 25.40
RF = (RUN = 100.0) / APPL
WRITE(6,100) RUN, RUNM
WRITE(6,110) RF
RETURN
END
SUBROUTINE RUNCAP(Q, TOTI, AK, AN, AA, AB, AL, S, DXR, DW, B, Z, 
1 BP, DTR, INR, LAR, INDEX, RFE, RFP, RFT, RFI, XMAX, YMAX) 
# 1638
SUBROUTINE FOR ESTIMATING THE EXPECTED VOLUMES AND PERCENTAGES OF 
RUNOFF USING THE RUNOFF HYDROGRAPH METHODS 
DIMENSION TAD(300),DAV(300), RAT(300), Y(300), RAE(300), RAP(300), 
1RAT(300), VARY(300), DW(300), YD(300), GI(300), YI(300) 
# 1643
INTEGER AD 
C BETTING THE LOWER LIMITS OF THE PLOT AND THE NUMBER OF PAGES 
MPAGES = 1 
XMIN = 0.00 
YMIN = 0.00 
C CALCULATING THE TIME OF ADVANCE 
CALL ADVANCE(AA, AB, AL, TX, TAD, DXR, AD) 
C CHOOSING THE DESIRED METHOD OF PREDICTING THE RUNOFF HYDROGRAPH 
GO TO (10, 20, 30), LAR 
10 CALL FRONT(AK, AN, S, AL, DTR, INR, Q, TX, TOTI, XMIN, XMAX, YMIN, 
YMAX, MPAGES, INDEX, DW, B, Z, BP, RFE, RFP, RFT) 
GO TO 2 
20 CALL DEETH(AK, AN, DTR, TAD, TX, Q, INR, YD, QR, TOTI, XMIN, XMAX, 
YMAX, MPAGES, INDEX, DW, B, Z, BP, AL, RFD, AD, DXR) 
GO TO 2 
30 CALL RUNOFF(AK, AN, TAD, TX, Q, INR, YI, GI, TOTI, XMIN, XMAX, 
YMAX, MPAGES, INDEX, DW, B, Z, BP, AL, RFI, AD, DXR) 
RETURN 
END 
# 1639
SUBROUTINE ADVANCE(AA, AB, AL, TX, TAD, DXR, AD) 
C SUBROUTINE FOR ESTIMATING THE TIME OF ADVANCE USING THE EMPERICAL 
METHOD OF PREDICTION 
DIMENSION TAD(300) 
INTEGER AD 
100 FORMAT(/,5X,'TIME OF ADVANCE = ',F10.4, ' MINUTES') 
AD = AL / DXR 
DIS = 2.00 
1 DIS = DIS + DXR 
C CALCULATING AN ARRAY OF TIME VS. DISTANCE OF ADVANCE 
DO 1 I=1, AD 
1 TAD(I) = (DIS/AA)**(1.0/AB) 
C CALCULATING THE TOTAL TIME OF ADVANCE 
TX = (AL / AA)**(1.0 / AB) 
WHITE(*,100) TX 
RETURN 
END 
# 1640
# 1641
# 1642
# 1643
# 1644
# 1645
# 1646
# 1647
# 1648
# 1649
# 1650
# 1651
# 1652
# 1653
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# 1679
# 1680
# 1681
# 1682
# 1683
# 1684
SUBROUTINE RUNOFF(AK, AN, DT, TAD, TX, Q, IN, YI, QI, TOTI, XMIN, XMAX, YMIN, YMAX, MPAGES, INDEX, DN, B, Z, BP, AL, RFI, AO, DXR)  
SUBROUTINE FOR PREDICTING THE RUNOFF HYDROGRAPH USING THE INTEGRATED INTAKE METHOD  
DIMENSION TAD(300), RAI(300), QI(300), VARY(300), YI(300)  
INTEGER AO  
100 FORMAT(1HI, 'SECTION 4 RUNOFF HYDROGRAPH PREDICTION BY CALCULATING INAKE RATE')  
110 FORMAT(//,5X, 'TIME-MIN=',10X, 'RUNOFF RATE=GPM=(LPS)')  
120 FORMAT(5X, 'TIME-MIN='  
130 FORMAT(6X, 'runoff hydrograph using acc intake')  
150 FORMAT(1X, 10X, 'runoff percentage =',F10.5,'%')  
C WRITING THE HEADINGS OF THE OUTPUT  
WRITE(6,100)  
WRITE(6,110)  
WRITE(6,120)  
C CALCULATING THE RUNOFF TIME PERIOD  
T = TX  
YI(I) = DT / 2.0  
C CALCULATING THE RUNOFF RATE FOR VARIOUS TIME PERIODS  
DO 1 I=1, IN  
T = T + DT  
RI = 0.00  
DO 2 K=1, AO  
TI = T - TAD(K)  
RAI(K) = AK * TI**AN  
2 RI = RI + RAI(K) * DXR  
QI(I) = Q - HI  
IF(QI(I) .LT. 0.00) QI(I) = 0.00  
GQ = QI(I) / 0.0630  
WRITE(6,130) YI(I), QI(I), GQ  
QIP = QI(I)  
IF(YI(I), .GT., TR) GO TO 3  
YI(I+1) = YI(I) + DT  
1 CONTINUE  
3 CONTINUE  
C PLOTTING THE RUNOFF HYDROGRAPH AND CALCULATING THE TIME OF RECESSION  
C RECESSION  
CALL GRAPH(YI, QI, INP, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)  
CALL RECESSION(AK, AN, TOTI, B, BP, Z, DT, INDEX, AL, QIP, TIME)  
C CALCULATING THE VOLUME AND PERCENTAGE OF RUNOFF WATER  
VRI = 0.50 * DT * QI(I)  
DO 4 I=2, INP  
VRI = VRI + 0.50 * DT * (QI(I) + QI(I-1))  
4 VRI = VRI + 0.50 * QIP * TIME  
RFI = (VRI * 100.0) /(Q * TOTI + 60.0)  
WRITE(6,150) RFI  
RETURN  
END
SUBROUTINE FRONT(AK, AN, S, AL, DT, IN, Q, TX, TOTI, XMINT, XMAX, 
YMIN, YMAX, MPAGES, INDEX, Dk, B, Z, BP, RFE, RFP, RFT) 
SUBROUTINE FOR PREDICTING THE RUNOFF HYDROGRAPH USING THE FRONT 
SHAPE METHOD 
DIMENSION Y(300), RAE(300), HAP(300), RAT(300), VARY(300) 
170 FORMAT(1Hi, '**** SECTION 2 RUNOFF HYDROGRAPH PREDICTION BY ASSUMI 
ING THE SHAPE OF THE WETTING FRONT') 
180 FORMAT(/, 2X, 'TIME = ', 13X, 'RE = ', GPM(LP8)'s', 13X, 'RP = ', GPM(LP8)'s') 
190 FORMAT(F10.2, 6X, 2F10.3, 6X, 2F10.3, 6X, 2F10.3) 
200 FORMAT(/, 2X, '---') 
210 FORMAT(1Hi, 'RUNOFF HYDROGRAPH USING ELLEPTICAL WETTING FRONT') 
220 FORMAT(1Hi, 'RUNOFF HYDROGRAPH USING PARABOLIC WETTING FRONT') 
230 FORMAT(1Hi, 'RUNOFF HYDROGRAPH USING LINEAR WETTING FRONT') 
240 FORMAT(/, 10X, 'RUNOFF PERCENTAGE = ', F10.2, 8P1) 
WRITE(6, 170) 
WRITE(6, 180) 
WRITE(6, 200) 
CALCULATING THE RATE OF INFILTRATION ALONG THE FURROW 
T = TX 
TR = TOTI * 0.10 = TX 
Y(1) = DT / 2.00 
P = (AK = AL = (DT*AN)/(AN + 1.0)) 
R = (AK = AL) / (DT = (AN + 1.0)) 
APP = Q = TOTI = 60.0 
DO 1 = 1, IN 
AI = I = 1, IN 
G = (AI = 1.0) * (AN + 1.0) = (AI = 1.0) * (AN + 1.0) 
TMT + DT 
FMT = (TX + DT*(AI = 1.0) + DT)}* (AN + 1.0) = (TX + (AI = 1.0) + DT) * (AN + 1.0) 
CALCULATING THE RATE OF RUNOFF AT THE END OF THE FURROW 
1741 
RAE(I) = Q = 0.21461 * P * G = 0.78539 * R * F 
RAP(I) = Q = 0.33333 * P * G = 0.66667 * R * F 
RAT(I) = Q = 0.50000 * P * G = 0.50000 * R * F 
IF(RAE(I) = LT = 0.00) RAE(I) = 0.00 
IF(RAP(I) = LT = 0.00) RAP(I) = 0.00 
IF(RAT(I) = LT = 0.00) RAT(I) = 0.00 
CONVERTING THE RESULTS TO METRIC UNITS AND PRINTING THE RESULTS 
REM = 0.0630 = RAE(I) 
RPM = 0.0630 = RAP(I) 
RMS = 0.0630 = RAT(I) 
WRITE(6, 190) Y(I), RAE(I), REM, RAP(I), RPM, RAT(I), RMS 
CHECKING PEAK RUNOFF RATE 
QEP = RAE(I) 
QPP = RAP(I) 
QTP = RAT(I) 
IF(Y(I) = GT = TR) GO TO 3 
Y(I+1) = Y(I) + DT 
CONTINUE 
1 INP = I 
PLOTTING THE RUNOFF HYDROGRAPH AND CALCULATING THE TIME OF 
RECESSION 
DO 4 J = 1, 3 
GO TO (10, 20, 30), J 
10 WRITE(6, 210)

346
CALL GRAPH(Y, RAE, INP, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)  \# 1799
CALL RECESS(AK, AN, TOTI, B, RP, Z, Dm, INDEX, AL, QEP, TIME)  \# 1800
CALCULATING THE VOLUME AND PERCENTAGE OF RUNOFF WATER  \# 1801
VRE = 0.50 * DT * RAE(1)  \# 1802
DO 2 I = 2, INP  \# 1803
VRE = VRE + 0.50 * DT * (RAE(I) + RAE(I+1))  \# 1804
VRE = VRE + TIME * QEP / 2.0  \# 1805
RFP = (VRE / APP) * 100.0  \# 1806
WRITE(b,240) RFP  \# 1807
SAME ABOVE COMMENTS APPLY TO THE STATEMENTS BELOW  \# 1808
GO TO 4  \# 1809
2 WRITE(b,220)  \# 1810
CALL GRAPH(Y, RAP, INP, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)  \# 1811
CALL RECESS(AK, AN, TOTI, B, BP, Z, Dm, INDEX, AL, QPP, TIME)  \# 1812
VRP = 0.50 * DT * RAP(1)  \# 1813
DO 5 I = 2, INP  \# 1814
VRP = VRP + 0.50 * DT * (RAP(I) + RAP(I+1))  \# 1815
VRP = VRP + TIME * QPP / 2.0  \# 1816
RFP = (VRP / APP) * 100.00  \# 1817
WRITE(b,240) RFP  \# 1818
GO TO 4  \# 1819
5 WRITE(b,230)  \# 1820
CALL GRAPH(Y, RAT, INP, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)  \# 1821
CALL RECESS(AK, AN, TOTI, B, RP, Z, Dm, INDEX, AL, QTP, TIME)  \# 1822
VRT = 0.50 * DT * RAT(1)  \# 1823
DO 6 I = 2, INP  \# 1824
VRT = VRT + 0.50 * DT * (RAT(I) + RAT(I+1))  \# 1825
VRT = VRT + TIME * QTP / 2.00  \# 1826
RFP = (VRT / APP) * 100.00  \# 1827
WRITE(b,240) RFP  \# 1828
6 CONTINUE  \# 1829
RETURN  \# 1830
END  \# 1831
SUBROUTINE DEETH(AK, AN, DT, TAD, TX, Q, IN, YD, QR, TOTI, XMIN, XMAX, YMIN, YMAX, MPAGES, INDEX, DW, B, Z, BP, AL, RDF, AD, DXT)

SUBROUTINE FOR PREDICTING THE RUNOFF HYDROGRAPH USING THE INTEGRATED INFILTRATION DEPTH METHOD.

DIMENSION TAD(300), DAV(300), YD(300), QR(300), VARY(300)

INTEGER AD

100 FORMAT(1H1, '*** SECTION 3 RUNOFF HYDROGRAPH PREDICTION BY CALCULATING DEPTH OF INFILTRATION!')

110 FORMAT(1H5, 'TIME=MIN=', 10X, 'RUNOFF RATE=GM=(LP3)!')

120 FORMAT(1H5, 'TIME=MIN=', 10X, 'RUNOFF RATE=GM=(LP3)!')

130 FORMAT(6X, F7, 1, 9X, 2F11, 3)

140 FORMAT(1H1, 'RUNOFF HYDROGRAPH USING ACCUMULATED DEPTH OF INFILTRATION')

150 FORMAT(1H1, 'RUNOFF HYDROGRAPH USING ACCUMULATED DEPTH OF INFILTRATION')

C CALCULATING THE ACCUMULATED DEPTH OF INFILTRATED WATER

YOD(1) = DT/2.0
T = TX
TR = TOTI - 60.0 = TX
AM = AN + 1.0
P = (AK/AM)*DXT

C WRITING THE HEADINGS OF THE OUTPUT

WRITE(i, 100)
WRITE(i, 110)
WRITE(i, 120)

C CALCULATING THE RUNOFF RATE FOR VARIOUS TIME PERIODS

DO 1 I=1, IN
T = T + DT
VI = 0,00
DO 2 K=1, AD
TI = T + TAD(K)
DAV(K) = P*(T1**AM -(T1-DT)**AM)
2 VI = VI + DAV(K)
QR(I) = Q - VI / DT
IF(QR(I) .LT. 0,00) QR(I) = 0,00
GM = QR(I) - 0,0630
GRP = QR(I)
WRITE(i, 130) YD(I), QR(I), GM
IF(YD(I) .GE. TI) GO TO 3
YD(I+1) = YD(I) + DT
1 CONTINUE

C PLOTTING THE RUNOFF HYDROGRAPH AND CALCULATING THE TIME OF RECESSON

CALL GRAPH(YO, QR, INP, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)
CALL RECESS(AK, AN, TOTI, B, BP, Z, DW, INDEX, AL, QRP, TIME)

C CALCULATING THE VOLUME AND PERCENTAGE OF RUNOFF WATER

VRD = 0,50 * DT = GR(I)
DO 4 I=2, INP
VRD = VRD + 0,50 * DT + (QR(I) + QR(I+1))
VRD = VRD + 0,50 * QRP + TIME
RFO = (VRD + 100,0) / (Q * TOTI = 60.0)
WRITE(i, 150) RFO
END
SUBROUTINE RECESS(AX, AN, TOTI, B, BP, Z, DM, INDEX, AL, GP, TIME) = 1893
C SUBROUTINE FOR PREDICTING THE TIME OF RECESSION = 1894
100 CALCULATING THE AVERAGE INTAKE RATE DURING THE TIME OF RECESSION = 1895
AW = AX + (TOTI + 150) / 60.0 ** 1.0 = 1896
DINO = (AW + GP) / 14.98 = 1897
C CALCULATING THE VOLUME OF SURFACE STORED WATER = 1898
GO TO (10, 20), INDEX = 1899
10 STO = AL = (B + DM + Z * DM) = 1900
GO TO 20 = 1901
20 STO= 0.6667 * AL + BP = DM = 1902
C CALCULATING THE TIME OF RECESSION = 1903
30 TIME = STO / DINO = 1904
WRITE(6,100) TIME = 1905
RETURN = 1906
END = 1907
C = 1908
C = 1909
C = 1910
C = 1911

SUBROUTINE SEASON(AX, AN, S, DEPL, HOLD, ROOT, DMMOD, CONSUM, DAYS) = 1912
1, RAIN, PRESEA, XP, TP, KN, LAS, AA, AB, TOTI, NOIRR, DL, TX, AL, = 1913
1 SEA, FREU, INI, DMIN) = 1914
C SUBROUTINE FOR CALCULATING THE MINIMUM DEPTH OF IRRIGATION, NUMBER = 1915
C OF IRRIGATIONS PER SEASON, AND TIME OF APPLICATION PER IRRIGATION = 1916
DIMENSION XP(300), TP(300) = 1917
REAL NOIRR = 1918
100 FORMAT(1H1,'**************************************************** ANALYSIS OF CROP CONSUMTIV = 1919
1 E USE ******************************************') = 1920
110 FORMAT (/5X,'PREDICTED ADVANCE FUNCTION IS X='F10.4, ' T='F10 = 1921
4 ,4) = 1922
120 FORMAT (/5X,'MINIMUM DEPTH OF INFILTRATION =','F10.4, ' INCHES ('= 1923
1F10.4, ' HM)') = 1924
130 FORMAT (/5X,'NUMBER OF IRRIGATIONS PER SEASON =','F10.0) = 1925
140 FORMAT (/5X,'TIME OF APPLICATION PER SET =','F10.4, 'I HOURS') = 1926
150 FORMAT (/5X,'TIME OF ADVANCE =','F10.4, ' MINUTES') = 1927
C CALCULATING THE ADVANCE FUNCTION AS AN EXPONENTIAL FUNCTION = 1928
GO TO (10, 20), LAS = 1929
10 AB = (ALOG(XP(KN)) - ALOG(XP(1))) / (ALOG(TP(KN)) = 1930
AA = XP(KN) / ((TP(KN))** AB) = 1931
TX = TP(KN) = 1932
GO TO 30 = 1933
20 TX = (AL / AA) ** (1.0 / AB) = 1934
C CALCULATING THE DEPTH OF STORED WATER = 1935
30 DE = HOLD + ROOT * DEPL / 100.0 = 1936
C CALCULATING THE SEASONAL DEPTH OF APPLIED WATER = 1937
IF(PRESEA, GT, DE) PRESEA = DE = 1938
SEAS = CONSUM + DAYS - RAIN - PRESEA = 1939
DPIR = (1.0 + DMMOD) * HOLD + ROOT * DEPL / 100.0 = 1940
DPIR = DPIR = 25.40 = 1941
C CALCULATING THE NUMBER OF IRRIGATIONS IN THE SEASON = 1942
GO TO (40, 50), INI = 1943
40 QIRR = SEAS / DPIR = 1944
GO TO 60 = 1945
50 QIRR = DAYS / FREQ = 1946
60 DL = DPIR = (DMMIN = 0.05) = 1947
NEAR = QIRR = 1948
DIF = NEAR - QIRR = 1949
IF(DIF = LT, 0.00) NOIRR = NEAR + 1 = 1950
IF(DIF = GT, 0.00) NOIRR = NEAR = 1951
IF(DIF = EQ, 0.00) NOIRR = QIRR = 1952
C CALCULATING THE TIME OF APPLICATION = 1953
AM = AN + 1.0 = 1954
TL = ((DL + S * AM) / (1.6043 = AX)) ** (1.0 / AM) = 1955
TOTI = (TL + TX) / 60.0 = 1956
SEAS = DPIR * NOIRR = 1957
C WRITING THE FINAL RESULTS = 1958
WRITE(6,100) = 1959
WRITE(6,110) AA, AB = 1960
WRITE(6,120) DPIR, DPIR = 1961
WRITE(6,130) NOIRR = 1962
WRITE(6,150) TX = 1963
SUBROUTINE SHAPE(AK, AN, S, AL, XP, TP, DDI, PERCE, KN, TOTI, Q)

C

C

IF(DO(l) .LT. 100)

WRITE(b,130)

WRITE(b,140)

WRITE(b,110)

WRITE(b,100)

APP1 = 96.3 * U / TOTI / (S + AL)

APLM = APP1 * 25.40

WRITE(6,100)

WRITE(6,110)

WRITE(6,120)

C

C

C

PREDICTING THE PATTERN OF INFILTRATION

AM = AN + 1.00

CO = (11.04) / (S + AM)

DU = CO * (60.0 * TOTI)**AM

DO 1 I=1, KN

TO = 60.0 * TOTI * TP(l)

1 DDl(l) = CO * TO ** AM

DDI(l) = (DU + DI(l)) / 2.00

C

C

C

CALCULATING THE PERCENTAGE OF LAND RECEIVING A GIVEN DEPTH OF INFILTRATION

P = 100.00 / AL

PERCE(l) = XP(l) * P

DDM = DDI(1) * 25.40

WRITE(6,130) DDI(l), DDM, PERCE(l)

DO 3 J=2, KN

3 PERCE(J) = (XP(J) - XP(J-1)) * P

DO 4 K=2, KN

DDI(K) = (DI(K-1) + DI(K))/2.00

DDM = DDI(K) * 25.40

4 WRITE(6,130) DDI(K), DDM, PERCE(K)

C

C

C

CALCULATING THE AVERAGE DEPTH OF INFILTRATED WATER

AV = 0.00

DO 5 I=2, KN

5 AV = AV + DDI(l) = (XP(I) - XP(I-1))

AV = AV + DDI(l) * XP(1)

AV = AV / AL

AVDM = AVD = 25.40

C

C

C

CALCULATING THE DEPTH OF DEEP-PERCOLATED WATER

DEP = 0.0

IF(DDI(l) * LT * STORED) GO TO 2

DEP = (DDI(l) = STORED)* XP(1)

DO 7 I=2, KN
IF(DDI(I) . LT . STORED) GO TO 2
7 DEP = DEP + (DDI(I) - STORED) * (XP(I) = XP(I-1))
2 DEEP = DEP / AL
DEEMP = DEEP * 25.40
C WRITING THE FINAL RESULTS
WRITE(6,170) APPL, APPLM
WRITE(6,140) AVU, AVUM
WRITE(6,150) DEEP, DEEMP
WRITE(6,190) TUTI
C PLOTTING THE PATTERN OF INFILTRATION
DO 9 I = 1, KN
IF(DDI(I) . GT . STORED) DDI(I) = STORED
9 CONTINUE
IF(IPILOT . EQ . 1) GO TO 8
MPAGES = 1
XMIN = 0.00
XMAX = AL
YMIN = -10.0
YMAX = 0.00
DO (I = 0U)
DO 6 J = 2, KN
DDD(J) = - DII(J-1)
CALL GRAPH(XP, DDD, KN, VARY, XMIN, XMAX, YMIN, YMAX, MPAGES)
6 RETURN
END
SUBROUTINE SURF(AK, AN, S, AL, CK, DP, BK, PCENT, AA, AB, Q, TOTI, # 2055
1 DU, APPL, DEEP, AVD, STORED) # 2056
C SUBROUTINE FOR USING A LINEAR PATTERN OF INFILTRATION ALONG THE # 2057
C FURROW TO CALCULATE THE AVERAGE DEPTHS OF INFILTRATED AND DEEP- # 2058
C PERCOLATED WATER # 2059
INTEGER BK, CK # 2060
DIMENSION CK(300), DP(300), DPAV(300) # 2061
160 FORMAT(1M1,5X, 'PREDICTED WETTING FRONT USING STRAIGHT LINE APPROX # 2062
1M') # 2063
170 FORMAT(1/10X, 'SEGMENT NUMBER DEPTH = INCHES = (MM)') # 2064
180 FORMAT(16X, '1X, 15X, 2F9.4) # 2065
190 FORMAT(10X, '-------') # 2066
200 FORMAT(/,5X, 'TOTAL DEPTH APPL = ',F10.4, ' INCHES (',F10.4, ' MM)') # 2067
210 FORMAT(/,5X, 'AVERAGE DEPTH INFILTRATED = ',F10.4, ' INCHES (',F10.4 # 2068
1, ' MM)') # 2069
220 FORMAT(/,5X, 'DEEP PERCOLATION DEPTH = ',F10.4, ' INCHES (',F10.4, # 2070
1MM)') # 2071
230 FORMAT( /,5X, 'TOTAL TIME OF APPLICATION PER SET = ',F10.4, ' HOURS') # 2072
C WRITING THE HEADINGS OF THE OUTPUT # 2073
WRITE(6,160) # 2074
WRITE(6,180) # 2075
WRITE(6,190) # 2076
C CALCULATING THE DEPTHS OF INFILTRATED WATER AT THE UPPER AND LOWER # 2077
C ENDS OF THE FURROW # 2078
AM = AN / 1.0 # 2079
CO = (1.6043 * AK) / (S * AM) # 2080
TL = 60.0 * TOTI = (AL / AA) **(1.0 / AB) # 2081
DU = CO = (60.0 * TOTI) ** AM # 2082
DL = CO = TL * AM # 2083
C CALCULATING THE PERCENTAGE OF LAND RECEIVING A GIVEN DEPTH OF # 2084
C INFILTRATED WATER # 2085
FAC = PCENT = (DU - DL) # 2086
BK = 1.00 / PCENT # 2087
C PREDICTING THE PATTERN ALONG THE FURROW AND # 2088
C AVERAGE DEPTH OF INFILTRATED WATER # 2089
SUM = 0.00 # 2090
DO 1 I=1, BK # 2091
CK(I) = I # 2092
1 DPAY(I) = DU - CK(I) * FAC # 2093
DP(I) = (DPAY(I) + DU) / 2.0 # 2094
DPM = DP(I) * 25.40 # 2095
WRITE(6,180) CK(I), DP(I), DPM # 2096
DO 7 I = 2, BK # 2097
DP(I) = (DPAY(I) + DPAY(I=1)) / 2.0 # 2098
DPM = DP(I) * 25.40 # 2099
WRITE(6,190) CK(I), DP(I), DPM # 2100
7 CONTINUE # 2101
C CALCULATING THE DEPTHS OF APPLIED WATER # 2102
APPL = 96.3 * Q * TOTI / (S = AL) # 2103
APPLM = APPL = 25.40 # 2104
AVO = (DU + DL) / 2.0 # 2105
AVM = AVO = 25.40 # 2106
C IF(DL = GE = STORED) GO TO 2 # 2107
C CALCULATING THE DEPTH OF DEEP-PERCOLATED WATER # 2108
DO 5 I = 1, BK # 2109
IF(DP(I) LT STORED) GO TO 6 # 2110
SUM = SUM + (DP(I) - STORED) * PCENT # 2111
ENDIF # 2112
6 DEEP = SUM # 2113
GO TO 3 # 2114
3 DEEP = (DU + DL = 2.0 = STORED) / 2.0 # 2115
2 DEEP = (DU + DL = 2.0 = STORED) / 2.0 # 2116
C WRITING THE FINAL RESULTS # 2117
WRITE(6,200) APPL, APPLM # 2118
WRITE(6,210) AVO, AVM # 2119
WRITE(6,220) DEEP, DEEP # 2120
WRITE(6,230) TOTI # 2121
C PLOTTING THE WETTING PATTERN ALONG THE FURROW # 2122
FORMAT(1/10X, '-------') # 2123
DO 4 I = 1, BK # 2124
IF(DP(I) GT STORED) DP(I) = STORED # 2125
4 CONTINUE # 2126
RETURN # 2127
END
SUBROUTINE IHRS(STREAM, Q, AVD, AL, M, S, TX, TOTI, HF, ADJUST, 
YEARS, WATER, FUEL, FCOST, ID, NP$12, PUCOST, COMHS, LAH, MC, 
2 COLLEC, DITCH, CPCOUT, ACVALU, TU, NOIRR, NSET, ACREF, DELV, 
3 CLIP, CJREN)  
C SUBROUTINE FOR EXECUTING A COMPLETE DESIGN FOR IRRIGATION RUNOFF  
C RECOVERY SYSTEMS, IHRS'S, USING TWO CONSECUTIVE SET NUMBERS  
REAL NOIRR  
DIMENSION FCOST(20), ID(20), V(20), TCOC(20)  
260 FORMAT(1H1,'********************************************************************** DESIGN OF IHRS **')  
270 FORMAT(1H5X,'TOTAL NUMBER OF FURROWS IN THE FIELD = ',I10)  
280 FORMAT(1H5X,'NUMBER OF FURROWS PER SET FROM THE SUPPLY = ',I10)  
290 FORMAT(1H5X,'NUMBER OF FURROWS PER SET FROM THE PUMP = ',I10)  
300 FORMAT(1H5X,'TOTAL NUMBER OF FURROWS FROM THE SUPPLY = ',I10)  
310 FORMAT(1H5X,'TOTAL NUMBER OF FURROWS FROM THE PUMP = ',I10)  
320 FORMAT(1H5X,'TOTAL TIME NEEDED FOR IRRIGATING THE FIELD = ',F10.4,  
1H4' HOURS')  
330 FORMAT(1H5X,'REAL NUMBER OF IRRIGATION SETS = ',F10.3)  
335 FORMAT(1H5X, '**********************************************************************')  
340 FORMAT(1H5X,'NUMBER OF IRRIGATION SETS USED = ',I5)  
350 FORMAT(1H5X,'RECIRCULATING PUMP FLOW RATE = ',F10.3,  
1H4' GPM (', F10.5, ' LPS)')  
400 FORMAT(1H5X,'VOLUME OF RUNOFF WATER AFTER SET = ',F10.3,  
1H4' AC•IN ('F10.0, ' CU M)')  
410 FORMAT(1H5X,'VOLUME OF WATER APPLIED IN THE LAST SET = ',F10.3,  
1H4' AC•IN ('F10.0, ' CU M)')  
420 FORMAT(1H5X,'SURPLUS OR DEFICIT IN THE POND = ',F10.3,  
1H4' AC•IN ('F10.0, ' CU M)')  
430 FORMAT(1H5X,'VOLUME OF THE POND = ',F10.3,  
1H4' AC•IN ('F10.0, ' CU M)')  
440 FORMAT(1H5X,'TOTAL ANNUAL COST OF IRRIGATION = ',F10.2,  
1H4' $/ACRE ('F10.2, ' $/AC')  
C PRELIMINARY DESIGN CALCULATIONS  
1 Y = AL = S  
WRITE(6,260)  
2 FF = M / S  
WRITE(6,261)  
3 MF = FF  
WRITE(6,262)  
4 TO = (AVD + AL + M) / (STREAM + 43560.0)  
WRITE(6,263)  
5 RN = TO / TOTI  
WRITE(6,264)  
6 FS = 448.8 * STREAM / Q  
WRITE(6,265)  
7 IFS = FS  
WRITE(6,266)  
8 XFS = IFS  
WRITE(6,267)  
9 DEL = FS - XFS  
WRITE(6,268)  
10 IF(DEL = 0.50) 2, 2, 1  
1 IF = IFS + 1  
GO TO 3  
2 IF = IFS  
WRITE THE PRELIMINARY RESULTS  
3 WRITE(6,270) MF  
WRITE(6,271) IFS  
WRITE(6,272) TO  
WRITE(6,273) RN  
BASIC DESIGN FOR THE GIVEN CONDITIONS  
N = RN  
DIFF = M - RN  
 IF(DIFF . GT . 0.00) N = N - 1  
IF(DIFF . LE . 0.00) N = N  
J = 0  
TCOST = 0.00  
EXECUTING A SYSTEM DESIGN FOR TWO IRRIGATION SETS  
DO 10 K = 1, 2  
IF(N . EQ . 1) GO TO 9  
C  
C
WRITE(6,335)
WRITE(6,340) N
PN = N
IFFS = PN * IFS
IFFP = MF = IFFS
IFP = IFFP / PN
FP = IFP
IF(IFP * LT * 0.0) GO TO 9
PQ = Q * FP
PQM = 0.06310 * PQ

C WRITING SOME OF THE RESULTS
WRITE(6,290) IFP
WRITE(6,300) IFFS
WRITE(6,310) IFFP
WRITE(6,350) PQ, PQM
RFF = RF / 100.0
VAL = FP = Y = AVD / 43560.0
VALM = 102.83 = VAL
PQF = PQ / 408.8

C CALCULATING THE VOLUME OF RUNOFF WATER IN STORAGE AFTER THE
C IRRIGATION OF CONSECUTIVE SETS
DO 6 L=1, N
ZZ = L
V(L) = ((ZZ * STREAM + (ZZ - 1.0) * PQF) - RFF - (ZZ - 1.0) *
1 PQF) * TOTI
IF(V(L) * LT * 0.0) GO TO 9
VRV = 102.83 * V(L)
WRITE(6,400) L, V(L), VRV

6 C CALCULATING THE VOLUME OF THE STORAGE POND
VSUMP = V(1)
DO 7 L=2, N
IF(V(L) * GE * VSUMP) VSUMP = V(L)
7 CONTINUE
WRITE(6,410) VAL, VALM
DIFRUN = V(N) - VAL
DIFM = DIFRUN - 102.83
WRITE(6,420) DIFRUN, DIFM
IF(DIFRUN * LT * 0.0) GO TO 9
VSUMP = VSUMP - 102.83
WRITE(6,430) VSUMP, VSUMP
J = J + 1

C CALCULATING SYSTEM COST
CALL COSTIC(COST, AL, ADJUST, PQ, YEARS, DINTER, PN, FUELC, FCOST,
1 ID, NPSIZ, TOTI, PUCOST, COMOUS, LAV, VSUMP, HC, COLLEC, H,
2 ACH, CMCUYS, ACVALU, NOIRR, ACHEFT, STREAM, DELV, CLBH, TCOST)
C COMPARING THE COSTS OF THE TWO IRRIGATION SETS CONSIDERED
IF(J * EQ * 2) GO TO 8
GO TO 13
9 FIRST = 10000000.00
J = J + 1
GO TO 14
13 FIRST = TCOST
14 NSET = N
GO TO 11

8 IF(TCOST = FIRST) 30, 40, 40
30 NSET = N
COIRRS = TCOST
IF(J * EQ * 2) GO TO 10
GO TO 11
40 COIRRS = FIRST
IF(J * EQ * 2) GO TO 10
11 N = N + 1
10 CONTINUE
COIRR = 43560.0 * COIRRS / (AL * H)
COMI = COIRR * 2.47
WRITE(6,440) COIRR, COMI, NSET
RETURN
END
SUBROUTINE CUSTIR (COST, AL, ADJUST, PU, YEARS, DINTER, PN, FUEL,  
ICOST, ID, NHSIZ, TOTI, PUCOST, COMHOS, LAV, VSUMP, MC, COLLEC,  
2 W, DITCHM, CPCUDY, ACVALU, NOIRR, ACREF, STREAM, DELV, CLBR,  
3 TCOST)  
SUBROUTINE FOR CALCULATING FIXED AND OPERATING COSTS OF IRRS FOR  
TWO CONSECUTIVE SET NUMBERS  
DIMENSION FCUST(20), ID(20), TCO(20), HEAD(20), BHP(20)  
100 FORMAT ( /,5X, 'TOTAL ANNUAL COST OF IRRS WITH N OF', l4, ', =',  
1F10.4, ')  
110 FORMAT( /,5X, 'TOTAL ANNUAL COST OF IRRS WITH N OF', l4, ', =',  
1F10.4, ')  
120 FORMAT( /,5X, 'TOTAL ANNUAL COST OF IRRS INCLUDING WATER COST =',  
1F10.4, ')  
130 REAL NOIRR  
C CALCULATING THE CAPITAL RECOVERY FACTOR  
CRF = (0.01 * DINTER) / (1.0 - (1.0 / ((1.0 + DINTER/100.0) **  
1YEARS))  
C CALCULATING THE VOLUME, AREA, AND COST OF CONSTRUCTING THE STORAGE  
POND AND COLLECTION DITCHES  
GO TO (10, 2U), LAV  
10 VOL = VSUMP * 134.444444  
D = 6.00  
DSM = D * 0.3048  
WRITE(6,140) D, DSM  
SM = (3.0 * D * D + SURT(9.0 * D ** .4 + 8.0 * D * (2.0 * D **  
1.3 - 27.0 * VOL))) / (4.0 * D)  
SH = SM + 2.0 * D  
SMH = SM ** 0.3048  
WRITE(6,130) SM, SH, SMH  
SUMPL = 2.0 * SMH  
SUMPLM = SUMPL * 0.3048  
WRITE(6,135) SUMPL, SUMPLM  
SAREA = 2.0 * SMH * (SM + D) / 43560.0  
DNM = 2.00  
COLLAR = 2.0 * DNM * AL * COLLEC / 43560.0  
AREA = 1.25 * SAREA + COLLAR  
COOS = AREA + ACVALU + (AL * COLLEC * DITCHM / 100.0 + VOL +  
1 CPCUDY) * CRF  
GO TO 21  
20 COOS = 0.00  
C FINDING THE MOST ECONOMICAL PIPE SIZE FOR THE PUMPBACK PIPE AND  
PUMP CAPACITY  
21 BM = PQ / 2970.0  
PIPE = ADJUST * AL / 100.0  
FAC = (FUEL /15,000) * PN / TOTI * NOIRR  
DO 1 K=1, NPSIZ  
1 HEAD = 1050.0 * ((PQ / HC) ** 1.562) / (ID(K) ** 4.87)  
HEAD(K) = 1.15 * HEAD0 * PIPE + DELV + D  
FCO = CRF * FCOST(ID(K)) * PIPE
BMP(K) = BH * HEAD(K)  # 2322
VCO = FAC * BMP(K)  # 2323
CLABOR = CLBR * TOTI * PN * NOIWR  # 2324
C = CREATING TOTAL COSTS OF THE SYSTEM EXCEPT COST OF WATER  # 2325
TCO(K) = FCD + VCO + PUCOST * BMP(K) * CHF + COMOUS * CHF + CLABOR  # 2326
IF(K = EQ = 1) GO TO 2  # 2327
GO TO 3  # 2328
2 COSE = TCO(1)  # 2329
JJ = 1  # 2330
3 IF(TCO(K) = LE = COSE) GO TO 6  # 2331
GO TO 7  # 2332
6 COSE = TCO(K)  # 2333
JJ = K  # 2334
7 IF(TCO(K) = GT = COSE) GO TO 4  # 2335
1 CONTINUE  # 2336
4 COST = COSE + COOS  # 2337
DIM = ID(JJ) * 25.40  # 2338
WRITE(6,110) ID(JJ), DIM  # 2339
HEAM = HEAD(JJ) * 0.3048  # 2340
WRITE(6,150) HEAD(JJ), HEAM  # 2341
WRITE(6,160) BHP(JJ)  # 2342
WRITE(6,160) PN , COST  # 2343
C = CALCULATING UNIT SYSTEM COST  # 2344
UCOST = $43560.0 * COST / (AL * W)  # 2345
UCOSTM = UCOST * 2.47  # 2346
WRITE(6,120) PN, UCOST, UCOSTM  # 2347
C = CALCULATING TOTAL SYSTEM COST INCLUDING WATER COST  # 2348
TCOST = COST + ACREFT * STREAM * PN * TOTI * NOIWR / 12.0  # 2349
TCOSM = TCOST * 2.47  # 2350
WRITE(6,170) TCOST, TCOSM  # 2351
RETURN  # 2352
END  # 2353

Appendix G.

Sample Design Input Data and Outputs From
the Presented Models
I. Input data used for the sample land grading design.

92.940000 12.680000

8.10 8.40 7.50 7.10 6.20 6.00 5.10 5.20 4.80
8.50 7.40 7.30 7.40 6.30 6.30 5.70 5.60 5.70
8.00 8.20 7.40 7.60 7.00 6.70 6.10 5.90 6.40
8.10 8.40 8.10 7.50 7.50 7.00 6.50 6.50 6.70
8.60 8.10 7.60 7.10 7.60 8.00 7.70 7.30 7.50
8.50 8.10 7.70 7.70 8.10 8.10 8.10 8.10 8.00
8.90 8.60 8.70 8.60 8.60 8.40 8.00 8.70 7.60
8.20 8.40 8.00 8.30 8.00 7.30 7.00 6.70 6.70
8.40 8.10 8.40 8.60 8.30 7.30 7.20 6.70 6.40
8.60 8.30 8.50 8.00 7.50 7.50 6.80 6.30 6.10
8.40 8.70 7.80 8.10 8.40 7.00 6.60 6.10 5.90
8.60 8.70 8.00 7.80 8.40 7.20 6.80 6.30 6.10
9.90 9.00 8.20 7.50 6.70 6.50 6.50 6.20 6.20
9.50 8.60 8.20 7.50 6.30 7.00 6.30 6.30 6.10
9.20 8.40 7.90 7.50 6.70 6.80 6.70 6.30 6.20
8.90 8.30 7.50 7.10 6.30 6.20 6.20 6.20 6.30
8.80 8.40 7.60 7.30 7.10 6.70 6.40 6.10
8.30 8.30 6.10 7.40 6.50 7.00 6.60 6.10
8.90 9.10 8.70 8.40 8.10 8.00 7.40 5.90 5.50
9.00 9.10 8.50 8.10 7.90 7.90 7.90 6.90 6.20
50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00
50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00
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50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00
50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00 50.00

100.00
20 9 2.500 0.100 1.500 0.050 1.250 0.050 0.400 10.00 0.100 1.00-1.00
GRATING METHOD PROGRAMMED BY SAFA NOORI HAMAD OCTOBER 26, 1978
DATA FROM FIELD WORK 9-1 DESIGNED FOR LAND GRADING USING THE SCS LAND
II. Sample outputs of the land grading model.

Chart 2. Sample land grading design using Paul’s computer-minimized-cost method.

<table>
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<th>ELEVATIONS AT STAKES</th>
<th>CALM (CALCULATED ELEVATIONS)</th>
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<td>8.58</td>
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Chart 2. Continued.

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<th>NUMBER</th>
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<th>Fills NEGATIVE</th>
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<td>20</td>
<td>-0.48</td>
<td>-0.03</td>
</tr>
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</table>

**NUMBER OF STATIONS IN THE X-DIRECTION = 9 AND NUMBER OF STATIONS IN THE Y-DIRECTION = 20**

**LOAD FACTOR = 82.960 %/FT AND DISTANCE FACTOR = 12.620 $/FT/100 FT**

**TOTAL AREA OF THE FIELD = 41.322 ACRES**

**SLOPE IN THE X-DIRECTION = -0.318 AND SLOPE IN THE Y-DIRECTION = -0.015**

**CENTROID ELEVATION = 7.51 FEET**

**EXPECTED CUT-FILL RATIO = 1.250 AND CALCULATED CUT-FILL RATIO = 1.255**

**TOTAL DEPTH OF CUT = 48.22 FT AND TOTAL DEPTH OF FILL = -38.32 FT**

**EXCAVATION VOLUME = 432.165 CU YD/ ACRE**

**TOTAL COST = 6223.40 $ AND UNIT COST = 150.61 $/ACRE**
**Chart 3. Sample land grading design using Shih and Kriz's methods.**

**---------------------------------------------------------------------------------------------------------------**

<table>
<thead>
<tr>
<th>DATA FROM FIELD YOLO # 1 DESIGNED FOR LAND GRADING USING SHIH AND KRIZ METHODS PROGRAMMED BY SAFA NOORI HAMAD OCTOBER 26, 1976</th>
</tr>
</thead>
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**DESIGN REQUIREMENTS**

<table>
<thead>
<tr>
<th>ALLOWABLE SLOPES IN PERCENT</th>
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<tbody>
<tr>
<td>+</td>
</tr>
<tr>
<td>+</td>
</tr>
<tr>
<td>ROW DIRECTION</td>
</tr>
<tr>
<td>+</td>
</tr>
<tr>
<td>+</td>
</tr>
</tbody>
</table>

| MINIMUM SLOPE | 0.100 |
|               | 0.050 |

| MAXIMUM SLOPE | 2.500 |
|               | 1.500 |

**EXPECTED CUT/FILL RATIO BY VOLUME=1.250**

<table>
<thead>
<tr>
<th>TOLERANCE=0.100</th>
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<tbody>
<tr>
<td>EXTRA VOLUME OF CUT=</td>
</tr>
<tr>
<td>EXTRA VOLUME OF FILL=</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>DEVIATION OF EXPECTED CUT/FILL RATIO=0.050** COST=50.400 PER CUBIC YARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER OF STATIONS IN ROW=</td>
</tr>
<tr>
<td>PROPOSED MAXIMUM DEPTH OF CUT=</td>
</tr>
<tr>
<td>NUMBER OF STATIONS IN CROSS ROW=</td>
</tr>
<tr>
<td>PROPOSED MAXIMUM DEPTH OF FILL=</td>
</tr>
</tbody>
</table>

**DISTANCES TO FIELD BOUNDARIES FROM:**

<table>
<thead>
<tr>
<th>FIRST ROW</th>
<th>R(I)=</th>
<th>50.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAST ROW</td>
<td>R(J)=</td>
<td>50.00</td>
</tr>
<tr>
<td>FIRST CROSS ROW</td>
<td>R(C)=</td>
<td>50.00</td>
</tr>
<tr>
<td>LAST CROSS ROW</td>
<td>R(C)=</td>
<td>50.00</td>
</tr>
</tbody>
</table>

**ORIGINAL FIELD ELEVATION**

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<th>CROSS ROW DIRECTION</th>
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<tr>
<td>1 9.30 9.10 8.50 8.10 7.90 7.80 7.00 6.60 6.20</td>
</tr>
<tr>
<td>2 9.20 9.10 8.70 8.40 8.10 8.00 7.40 5.90 6.50</td>
</tr>
<tr>
<td>3 8.90 8.30 8.10 7.70 7.60 6.50 6.60 6.10</td>
</tr>
<tr>
<td>4 8.60 8.40 7.60 7.30 7.10 7.10 6.70 6.40 6.10</td>
</tr>
<tr>
<td>5 8.90 8.30 7.50 7.10 6.60 6.80 6.70 6.60 6.30</td>
</tr>
<tr>
<td>6 9.20 8.40 7.90 7.50 6.70 6.80 6.60 6.30 6.20</td>
</tr>
<tr>
<td>7 9.50 8.60 8.20 7.50 6.80 7.00 6.80 6.30 6.10</td>
</tr>
<tr>
<td>8 9.90 9.00 8.20 7.50 6.70 6.50 6.50 6.20 6.20</td>
</tr>
<tr>
<td>9 9.60 8.70 8.00 7.20 6.40 6.70 6.30 5.90 6.10</td>
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<tr>
<td>10 9.40 8.70 7.80 6.40 6.50 7.00 6.60 6.10 5.90</td>
</tr>
<tr>
<td>11 9.60 8.90 8.50 8.00 7.50 7.50 6.80 6.30 6.10</td>
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<tr>
<td>12 9.40 9.10 8.90 8.60 8.30 7.80 7.20 6.70 6.40</td>
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<tr>
<td>13 9.20 9.10 8.90 8.60 8.70 8.00 7.10 6.70</td>
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<tr>
<td>14 8.90 8.60 8.70 8.60 8.40 8.00 7.70</td>
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<td>15 8.50 8.10 7.70 7.70 8.10 8.40 8.10 8.10 8.00</td>
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<tr>
<td>16 8.60 8.10 7.60 7.10 7.60 8.00 7.70 7.30 7.50</td>
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<tr>
<td>17 8.10 8.40 8.10 7.50 7.50 7.90 6.90 6.50 6.70</td>
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<td>18 8.20 8.20 7.40 7.60 7.00 6.70 6.10 5.90 6.40</td>
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<td>19 8.60 7.40 7.80 7.40 6.90 6.30 5.70 5.60 5.70</td>
</tr>
<tr>
<td>20 8.10 8.10 7.80 7.10 6.80 6.00 5.40 5.20 4.80</td>
</tr>
</tbody>
</table>

**TOTAL AREA= 41.322 ACRES**

**TYPE I - UNIFORM SLOPE (PLANE SURFACE) WITH ROW AND CROSS ROW DIRECTION**

**---------------------------------------------------------------------------------------------------------------**

<table>
<thead>
<tr>
<th>DESIGN SLOPES IN PERCENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>+</td>
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</tbody>
</table>
Chart 3. Continued.

<table>
<thead>
<tr>
<th>Number of Stations</th>
<th>Cut/Fill Ratio</th>
<th>Number of Stations with Cut</th>
<th>Number of Stations with Fill</th>
</tr>
</thead>
<tbody>
<tr>
<td>89</td>
<td>1.253</td>
<td>95</td>
<td>91</td>
</tr>
<tr>
<td>23661.161 Cy.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FINAL CUT/FILL RATIO BY VOLUME= 1.253</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TOTAL VOLUME OF CUT= 23661.161 Cy.  FINAL CUT/FILL RATIO BY VOLUME= 1.253

<table>
<thead>
<tr>
<th>Depths of Cuts and Fills</th>
<th>Cut/Fill Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chart 3. Continued.</td>
<td></td>
</tr>
</tbody>
</table>

**Note:** A minus slope indicates a drop in elevation. An indi- cates a rise in elevation away from station all. A positive slope indicates a rise in elevation towards station all.

<table>
<thead>
<tr>
<th>Depth of Cut or Fill (ft)</th>
<th>Cut/Fill Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.36</td>
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<tr>
<td>16</td>
<td>0.40</td>
</tr>
<tr>
<td>20</td>
<td>0.44</td>
</tr>
<tr>
<td>24</td>
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<td>28</td>
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</tr>
<tr>
<td>32</td>
<td>0.56</td>
</tr>
<tr>
<td>36</td>
<td>0.60</td>
</tr>
<tr>
<td>40</td>
<td>0.64</td>
</tr>
<tr>
<td>44</td>
<td>0.68</td>
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<td>72</td>
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**Final Design Elevations**

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<tr>
<td>4</td>
<td>9.36</td>
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<td>9.26</td>
<td>8.92</td>
<td>5.01</td>
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<td>8.62</td>
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<tr>
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<td>8.53</td>
<td>4.67</td>
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<tr>
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<tr>
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<td>4.03</td>
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<td>7.69</td>
<td>3.95</td>
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</table>

**Row 2 + Row 3:**

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<tr>
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<td>9.16</td>
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<td>5.01</td>
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<td>8.96</td>
<td>8.62</td>
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<td>4.75</td>
</tr>
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<td>8.76</td>
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<td>4.67</td>
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<td>4.59</td>
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<td>4.43</td>
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<td>4.35</td>
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<td>8.26</td>
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<td>4.27</td>
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<td>4.19</td>
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<td>4.11</td>
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**Row 4:**

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**Row 5:**

<table>
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<th>Average Cut/Fill Ratio</th>
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</tr>
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<td>8.76</td>
<td>8.44</td>
<td>5.01</td>
</tr>
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<td>4.92</td>
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<td>7.60</td>
<td>4.27</td>
</tr>
<tr>
<td>7.76</td>
<td>7.51</td>
<td>4.19</td>
</tr>
</tbody>
</table>
Chart 3. Continued.

NUMBER OF STATIONS WITH FILL OVER THE PROPOSED MAXIMUM DEPTH= 10
AVERAGE VOLUME = 577.489 CY/ACRE, AVERAGE COST = $231.00 PER ACRE
TOTAL COST = $9434.26

TYPE II - VARIABLE SLOPE WITH ROW AND CROSS ROW DRAINAGE

<table>
<thead>
<tr>
<th>DEPTHS OF CUTS AND FILLS (NOTE: &quot;CUTS ARE SHOWN AS POSITIVE AND FILLS AS NEGATIVE&quot;)</th>
<th>CROSS ROW DIRECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-0.38 -0.25 -0.54 -0.62 -0.50 -0.28 -0.76 -0.84 -0.92</td>
</tr>
<tr>
<td>2</td>
<td>-0.38 -0.16 -0.24 -0.22 -0.20 -0.02 -0.26 -1.44 -0.52</td>
</tr>
<tr>
<td>3</td>
<td>-0.58 -0.90 -0.97 -1.04 -1.00 -0.68 -0.76 -0.74 -0.72</td>
</tr>
<tr>
<td>4</td>
<td>-0.58 -0.66 -1.14 -1.22 -1.20 -0.88 -0.66 -0.44 -0.42</td>
</tr>
<tr>
<td>5</td>
<td>0.12 -0.06 -0.64 -0.72 -1.20 -0.78 -0.05 -0.64 -0.42</td>
</tr>
<tr>
<td>6</td>
<td>0.42 -0.16 -0.24 -0.62 -1.00 -0.48 -0.36 -0.54 -0.42</td>
</tr>
<tr>
<td>7</td>
<td>0.92 0.14 -0.14 -0.52 -1.00 -0.88 -0.56 -0.54 -0.22</td>
</tr>
<tr>
<td>8</td>
<td>0.72 0.14 -0.24 -0.72 -1.20 -0.58 -0.66 -0.74 -0.22</td>
</tr>
<tr>
<td>9</td>
<td>0.62 0.24 -0.34 -1.42 -1.00 -0.18 -0.26 -0.44 -0.32</td>
</tr>
<tr>
<td>10</td>
<td>0.92 0.34 0.46 0.28 0.10 0.42 0.04 -0.14 -0.02</td>
</tr>
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<tr>
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<td>0.32 0.04 0.66 0.28 0.30 0.00 0.00 0.00 0.00</td>
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FINIAL DESIGN ELEVATIONS

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<td>2 9.56 9.26 8.94 8.62 8.30 7.98 7.66 7.34 7.02</td>
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<td>3 9.44 9.16 8.84 8.52 8.20 7.88 7.56 7.24 6.92</td>
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<td>4 9.32 9.05 8.74 8.42 8.10 7.78 7.46 7.14 6.82</td>
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<td>6 9.18 8.86 8.54 8.22 8.00 7.68 7.36 7.04 6.72</td>
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<td>7 9.06 8.76 8.44 8.12 7.80 7.46 7.16 6.80 6.52</td>
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<td>8 8.98 8.66 8.34 8.02 7.70 7.38 7.06 6.74 6.42</td>
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<td>12 8.58 8.26 7.94 7.62 7.30 6.98 6.66 6.34 6.02</td>
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<td>16 8.18 7.86 7.56 7.24 6.92 6.60 6.28 5.96 5.64 5.32</td>
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<tr>
<td>17 8.08 7.76 7.44 7.12 6.80 6.48 6.16 5.84 5.52 5.20 4.80</td>
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</tbody>
</table>

TOTAL VOLUME OF CUT= 23582.796 CY, FINAL CUT/FILL RATIO= 1.253
NUMBER OF STATIONS WITH CUT= 89, NUMBER OF STATIONS WITH FILL= 91
NUMBER OF STATIONS WITH CUMULATIVE MAXIMUM DEPTH= 21
NUMBER OF STATIONS WITH FILL OVER THE PROPOSED MAXIMUM DEPTH= 10
AVERAGE VOLUME = 570.704 CY/ACRE, AVERAGE COST = $4228.28 PER ACRE
TOTAL COST = $9433.12

TYPE III - UNIFORM SLOPE IN INDIVIDUAL ROWS IN THE ROW DIRECTION AND VARIABLE
**Chart 3. Continued.**

**SLOPE IN THE CROSS ROW DIRECTION WITH ROW AND CROSS ROW DRAINAGE**

**FINAL DESIGN SLOPES IN ROW DIRECTION**

(Note: Minus sign indicates a drop in elevation away from the first cross row)

-0.10 -0.10 -0.10 -0.10 -0.10 -0.10 -0.10 -0.10 -0.10

<table>
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<tr>
<th>DEPTHS OF CUTS AND FILLS</th>
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<td>-0.21 -0.63 -0.71 -1.19 -0.83 -0.66 -0.44 -0.42</td>
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<td>-0.03 -0.45 -0.63 -0.71 -1.19 -0.77 -0.55 -0.63 -0.41</td>
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<td>0.43 -0.15 -0.23 -0.61 -0.99 -0.67 -0.34 -0.53 -0.41</td>
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<td>0.93 -0.35 -0.11 -0.51 -0.99 -0.67 -0.54 -0.53 -0.21</td>
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<td>0.73 -0.15 -0.23 -0.71 -1.19 -0.57 -0.63 -0.72 -0.20</td>
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<tr>
<td>0.63 -0.25 -0.33 -1.41 -0.99 -0.17 -0.22 -0.42 -0.30</td>
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<td>0.93 -0.55 -0.47 -0.29  0.11  0.63  0.08 -0.12 -0.01</td>
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<tr>
<td>0.83 -0.45 -0.37 -0.29  1.01  0.84  0.59  0.19 -0.41</td>
</tr>
<tr>
<td>0.73 -0.95 -1.17 -1.39 -1.51 -1.14 -0.80  0.79 -0.82</td>
</tr>
<tr>
<td>0.53 -0.55 -0.97 -1.19 -1.51 -1.64 -1.61 -1.60 -1.82</td>
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<tr>
<td>0.23 -0.15 -0.07 -0.39 -1.11 -1.74 -1.81 -2.10 -2.32</td>
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<tr>
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<tr>
<td>0.73 -0.15 -0.49 -0.31 -0.31 -0.29 -0.15 -0.28 -0.36</td>
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**FINAL DESIGN ELEVATIONS**

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<td>7.97 7.65 7.33 7.01 6.69 6.37 6.05 5.73 5.41</td>
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<td>4.51 4.19 3.87 3.55 3.23 2.91 2.59 2.27 2.05</td>
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<td>0.57 0.25 0.15 0.12 0.11 0.09 0.07 0.05 0.03</td>
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<tr>
<td>-0.03 -0.05 -0.07 -0.09 -0.11 -0.13 -0.15 -0.17 -0.20</td>
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**TOTAL VOLUME OF CUT = 2460.4399 CF.**

**FINAL CUT/FILL RATIO BY VOLUME = 1.253**

**NUMBER OF STATIONS WITH CUT = 91.**

**NUMBER OF STATIONS WITH FILL OVER THE PROPOSED MAXIMUM DEPTH = 22**

**AVERAGE VOLUME = 58.1778 CF/ACRE.**

**AVERAGE COST = $32.32/1 PER ACRE**

**TOTAL COST = $9616.16**

**TYPE IV - UNIFORM SLOPE IN INDIVIDUAL ROWS WITH ROW DRAINAGE AND A MINIMUM**
AND MAXIMUM ALLOWABLE CROSS ROW SLOPE (NO CROSS ROW DRAINAGE)

FINAL DESIGN SLOPES IN ROW DIRECTION

<table>
<thead>
<tr>
<th>DEPTHS OF CUTS AND FILLS</th>
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<tr>
<td>NOTE: &quot;CUTS ARE SHOWN AS POSITIVE AND FILLS AS NEGATIVE&quot;</td>
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</table>

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| -0.57 | -0.52 | -0.46 | -0.44 | -0.36 | -0.29 | -0.27 | -0.24 | -0.21 | -0.18 | -0.15 | -0.12 | -0.09 | -0.06 | -0.03 | -0.01 | -0.08 | -0.05 | -0.02 | 0.01 |
| 0.57 | 0.52 | 0.46 | 0.44 | 0.36 | 0.29 | 0.27 | 0.24 | 0.21 | 0.18 | 0.15 | 0.12 | 0.09 | 0.06 | 0.03 | 0.01 | 0.08 | 0.05 | 0.02 | 0.01 |

TOTAL VOLUME OF CUT = 23409.539 CY

FINAL CUT/FILL RATIO = EY VOLUME = 1.253

NUMBER OF STATIONS WITH CUT = 10

NUMBER OF STATIONS WITH CUT OVER THE PROPOSED MAXIMUM DEPTH = 10

AVERAGE VOLUME = 568.423 CY/ACRE

AVERAGE COST = $227.37 PER ACRE

TOTAL COST = $9535.42

TYPE V - VARIABLE SLOPE IN INDIVIDUAL ROWS WITH ROW DRAINAGE AND A MINIMUM
Chart 3. Continued.

AND MAXIMUM ALLOWABLE CROSS ROW SLOPE (NO CROSS ROW DRAINAGE)

DEPTHS OF CUTS AND FILLS

(Note: *Cuts are shown as positive and fills as negative*)

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TOTAL VOLUME OF CUT= 12230.165 CY FILL RATIO BY FINAL CUT/FILL RATIO = 1.261
NUMBER OF STATIONS WITH CUT= 59 NUMBER OF STATIONS WITH CUT= 122
NUMBER OF STATIONS WITH CUT OVER THE PROPOSED MAXIMUM DEPTH= 12
AVERAGE VOLUME = 295.97 CY/ACRE AVERAGE COST=$118.39 PER ACRE
TOTAL COST=$ 4892.07
IV. Sample output of the hydraulic system design and management optimization model.

******************************************************************** INPUT DATA ********************************************************************

OPTIMIZATION OF FURROW IRRIGATION FOR FIELD YOLO # 1 USING CORN AT DAVIS CALIFORNIA

FURROW SLOPE IN PERCENT = 0.32780
PERCENT ERROR INTRODUCED IN THE PREDICTED STREAM SIZE = -70.00000
SUPPLY STREAM FLOW RATE = 3.0000 CFS (85.1179 LPS)
FURROW SPACING = 3.0000 FEET (0.9144 M)
FURROW LENGTH = 400.0000 FEET (274.3200 M)
FIELD WIDTH = 2000.0000 FEET (609.6000 M)
BOTTOM WIDTH OF A TRAPEZOIDAL FURROW CHANNEL = 0.3333 FEET (0.1016 M)
TOP WIDTH OF A PARABOLIC FURROW CHANNEL = 0.0000 FEET (0.0000 M)
SIDE SLOPES OF A TRAPEZOIDAL FURROW CHANNEL = 1.0000
INTAKE FUNCTION IS I = 0.09000 T** = 0.51000 GPM/FT
INTAKE FUNCTION IS I = 0.01862 T** = 0.51000 LPS/M
DAVIS -F- FACTOR = 1.0000
DAVIS -C- FACTOR = 0.5000
DAVIS PUDDLING FACTOR -E- = 0.00300
DAVIS -K- FACTOR = 1.0000
ADVANCE FUNCTION IS x = 80.20000 T** 0.67400 FEET
ADVANCE FUNCTION IS x = 24.44496 T** 0.67400 M
MANNINGS ROUGHNESS COEFFICIENT = 0.04000
PERCENT OF ALLOWABLE DEPLETION = 50.00000
SOIL MOISTURE HOLDING CAPACITY = 2.00000 IN/FT (166.6240 MM/M)
DEPTH OF THE ROOT ZONE = 4.00000 FEET (1.2192 M)
MINIMUM DEPTH OF INFILTRATION WAS CHANGED BY 0.0000
DESIGN DAILY CONSUMPTIVE USE RATE = 0.2500 IN/DAY (6.350 MM/DAY)
NUMBER OF DAYS IN THE IRRIGATION SEASON = 100.00
DEPTH OF USEABLE RAIN DURING THE SEASON = 0.0000 INCHES (0.00 MM)
PRESEASON STORRED SOIL MOISTURE = 0.0000 INCHES (0.00 MM)
RECOMMENDED FREQUENCY OF IRRIGATION = 16.00 DAYS
RANGE OF SEASONAL DEPTH IS 0.4000 TO 1.2000 TIMES THE EXPECTED AVERAGE
CROP TO BE EVALUATED ON 0.0500 AREA INCREMENTS
CAPITAL RECOVERY FACTOR = 0.17698
LENGTH OF PIPE USED FOR IRRS IS 3.00 TIMES FURROW LENGTH
LENGTH OF COLLECTION DITCHES USED FOR IRRS 2.10 TIMES FURROW LENGTH
LIFE OF THE SYSTEM IS 10.00 YEARS, AND INTEREST RATE IS 12.00 %
FUEL COST = 0.4000 $/U. S. GALLON
COST OF PUMPING UNIT = 120,000 $/BHP
HAZEN-WILLIAMS FRICTION FACTOR = 150,000
COST OF THE PUMPING PLANT USED FOR IRRS -JUST HOUSE- = 300,000 $
COST OF USING A DITCHER MACHINE = 3,0000 $/100 FEET
COST OF SUMP EXCAVATION = 0.4000 $/CU YD
ESTIMATED RETURN OF LAND = 150,000 $/ ACRE
COST OF WATER = 3,0000 $/ACRE-FT
DIFFERENCE IN ELEVATION BETWEEN SUMP AND DISCHARGE PIPE OF IRRS = 5,0000 FEET
COST OF LAND GRAADING = 162,0000 $/ACRE
COST OF LABOR TO MANAGE THE SYSTEM = 1,5000 $/HOUR
VALUE OF RUNOFF LOSS = 0.0000 $/ACRE-FT OF APPLIED WATER
CROP PRODUCTION VALUE = 3,0000
COST OF PRODUCTION = 0.0000 $/UNIT
COST OF PRODUCTION = 60,0000 $/ACRE
PUMPING COST = 0.0000 $/ACRE-INCH
PIPE SIZE = 3 FIXED COST = 37.8400 $/ 100 FEET
PIPE SIZE = 4 FIXED COST = 62.2200 $/ 100 FEET
PIPE SIZE = 5 FIXED COST = 95.8800 $/ 100 FEET
PIPE SIZE = 6 FIXED COST = 135.1500 $/ 100 FEET
PIPE SIZE = 8 FIXED COST = 229.5000 $/ 100 FEET
PIPE SIZE = 10 FIXED COST = 357.5000 $/ 100 FEET
PIPE SIZE = 12 FIXED COST = 469.7100 $/ 100 FEET
GROSS RETURN = 0.000 113.330 133.330 150.000 166.670 150.000
DEPTH APPLIED: 0.000 18.000 24.000 26.000 32.000 50.000
LAD = 4 LAR = 0 LAS = 1 LELLEP = 0 LINTAK = 0 LRUNO = 0
LAV = 1 LAF = 1 LAP = 1 LIRHS = 1 INV = 100 INR = 100 INDEX = 1
LSOIL = 2 I PLOT = 1 INI = 1
NON-EROSIVE FURROW STREAM SIZE = 8,67949 GPM ( 0.5464 LPS)
**CALCULATED DISTANCE OF ADVANCE USING DAVIS'S APPROACH**

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<th>ACC DISTANCE-FEET-(M)</th>
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PLOT OF DAVIS TECHNIQUE

30,000  60,000  90,000  120,000  150,000  180,000  210,000  240,000  270,000  300,000

Y
**ANALYSIS OF CROP CONSUMPTIVE USE**

**PREDICTED ADVANCE FUNCTION IS X = 39.9151 T**² **0.5641**

**MINIMUM DEPTH OF INFILTRATION = 4,0000 INCHES (101,6000 MM)**

**NUMBER OF IRRIGATIONS PER SEASON = 7**

**TIME OF ADVANCE = 260,000 MINUTES**

**TIME OF APPLICATION PER SET = 8,1072 HOURS**

**PREDICTED WETTING FRONT USING DETAILED TECHNIQUE**

<table>
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<tr>
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<th>PERCENT OF LAND</th>
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<td>1.942 49.320</td>
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<tr>
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<tr>
<td>1.831 46.498</td>
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<td>1.808 45.912</td>
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<tr>
<td>1.784 45.318</td>
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<tr>
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<tr>
<td>1.445 36.693</td>
<td>2.2235</td>
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<tr>
<td>1.415 35.941</td>
<td>2.1813</td>
</tr>
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**TOTAL DEPTH APPLIED = 2.4566 INCHES (62.3981 MM)**

**TOTAL AVERAGE DEPTH INFILTRATED = 1.8203 INCHES (46,2356 MM)**

**DEEP-PERCOLATED DEPTH = 0.0000 INCHES (0.0000 MM)**

**TOTAL TIME OF APPLICATION PER SET = 8,1072 HOURS**

**RUNOFF DEPTH = 0.6363 INCHES (16,1624 MM)**

**RUNOFF PERCENTAGE = 25.9022%**
DESIGN OF IMRS

TOTAL NUMBER OF FURROWS IN THE FIELD = 666
NUMBER OF FURROWS PER SET FROM THE SUPPLY = 155
TOTAL TIME NEEDED FOR IRRIGATING THE FIELD = 25.0730 HOURS
REAL NUMBER OF IRRIGATION SETS = 1,093

NUMBER OF IRRIGATION SETS USED = 3
NUMBER OF FURROWS PER SET FROM THE PUMP = 67
TOTAL NUMBER OF FURROWS FROM THE SUPPLY = 465
TOTAL NUMBER OF FURROWS FROM THE PUMP = 201
RECIRCULATING PUMP FLOW RATE = 581.526 GPM (36,69430 LPS)
VOLUME OF RUNOFF WATER AFTER SET 1 = 6,300 AC-IN (648, CU M)
VOLUME OF RUNOFF WATER AFTER SET 2 = 4,816 AC-IN (495, CU M)
VOLUME OF RUNOFF WATER AFTER SET 3 = 3,332 AC-IN (343, CU M)
VOLUME OF WATER APPLIED IN THE LAST SET = 7,560 AC-IN (777, CU M)
SURPLUS OR DEFICIT IN THE POND = -4,228 AC-IN (-435, CU M)

NUMBER OF IRRIGATION SETS USED = 4
NUMBER OF FURROWS PER SET FROM THE PUMP = 11
TOTAL NUMBER OF FURROWS FROM THE SUPPLY = 620
TOTAL NUMBER OF FURROWS FROM THE PUMP = 46
RECIRCULATING PUMP FLOW RATE = 95.474 GPM (6.02444 LPS)
VOLUME OF RUNOFF WATER AFTER SET 1 = 6,300 AC-IN (648, CU M)
VOLUME OF RUNOFF WATER AFTER SET 2 = 11,322 AC-IN (1164, CU M)
VOLUME OF RUNOFF WATER AFTER SET 3 = 16,344 AC-IN (1681, CU M)
VOLUME OF RUNOFF WATER AFTER SET 4 = 21,365 AC-IN (2197, CU M)
VOLUME OF WATER APPLIED IN THE LAST SET = 1,281 AC-IN (128, CU M)
SURPLUS OR DEFICIT IN THE POND = 20,124 AC-IN (2069, CU M)
VOLUME OF THE POND = 21,365 AC-IN (2197, CU M)
DEPTH OF THE SUMP = 6.000 FEET (1.829 M)
### OPTIMIZATION DATA

2 PHASES

**UPPER** = 33.60
**LOWER** = 11.20
**NLV** = 4

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<th>PROF</th>
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<tr>
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<td>16,900 INCHES (427, MM)</td>
<td>8572.61 $</td>
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<tr>
<td>1</td>
<td>3</td>
<td>22,400 INCHES (569, MM)</td>
<td>12875.15 $</td>
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<tr>
<td>1</td>
<td>4</td>
<td>28,000 INCHES (711, MM)</td>
<td>11240.44 $</td>
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<tr>
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<td>33,600 INCHES (653, MM)</td>
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### OPTIMIZATION DATA

2 PHASES

**UPPER** = 28.00
**LOWER** = 16.80
**NLV** = 4

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<td>16,800 INCHES (427, MM)</td>
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<td>19,600 INCHES (498, MM)</td>
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<tr>
<td>2</td>
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<td>25,200 INCHES (640, MM)</td>
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<tr>
<td>2</td>
<td>5</td>
<td>28,000 INCHES (711, MM)</td>
<td>11240.44 $</td>
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**SUMMARY OF THE OPTIMIZATION PROCESS**

**MAXIMUM FEASIBLE PROFIT FOR THIS DESIGN = 12875.15 $**

**AVERAGE SEASONAL DEPTH OF APPLIED WATER = 27.829 INCHES (707.765 MM)**

**PREDICTED WETTING FRONT USING DETAILED TECHNIQUE**

<table>
<thead>
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<th>DEPTH RECEIVED-INCHES(MM)</th>
<th>PERCENT OF LAND</th>
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**TOTAL DEPTH APPLIED = 10.1084 INCHES (256.7544 MM)**

**TOTAL AVERAGE DEPTH INFILTRATED = 3.9756 INCHES (100.9813 MM)**

**DEEP-PERCULATED DEPTH = 0.0215 INCHES (0.5456 MM)**

**TOTAL TIME OF APPLICATION PER SET = 33.3592 HOURS**

**RUNOFF DEPTH = 6.1328 INCHES (155.7732 MM)**

**RUNOFF PERCENTAGE = 60.6701%**
TOTAL NUMBER OF FURROWS IN THE FIELD = 666
NUMBER OF FURROWS PER SET FROM THE SUPPLY = 155
TOTAL TIME NEEDED FOR IRRIGATING THE FIELD = 54.7609 HOURS
REAL NUMBER OF IRRIGATION SETS = 1,642

NUMBER OF IRRIGATION SETS USED = 1
NUMBER OF FURROWS PER SET FROM THE PUMP = 511
TOTAL NUMBER OF FURROWS FROM THE SUPPLY = 155
TOTAL NUMBER OF FURROWS FROM THE PUMP = 511
RECIRCULATING PUMP FLOW RATE = 4435.222 GPM (279.86250 LPS)
VOLUME OF RUNOFF WATER AFTER SET 1 = 60,717 AC-IN (6244.1 CU M)
VOLUME OF WATER APPLIED IN THE LAST SET = 125,923 AC-IN (12949.1 CU M)
SURPLUS OR DEFICIT IN THE POND = -65,205 AC-IN (-6705.1 CU M)

NUMBER OF IRRIGATION SETS USED = 2
NUMBER OF FURROWS PER SET FROM THE PUMP = 178
TOTAL NUMBER OF FURROWS FROM THE SUPPLY = 310
TOTAL NUMBER OF FURROWS FROM THE PUMP = 356
RECIRCULATING PUMP FLOW RATE = 1544.950 GPM (97.48635 LPS)
VOLUME OF RUNOFF WATER AFTER SET 1 = 60,717 AC-IN (6244.1 CU M)
VOLUME OF RUNOFF WATER AFTER SET 2 = 76,270 AC-IN (7843.5 CU M)
VOLUME OF WATER APPLIED IN THE LAST SET = 43,863 AC-IN (4510.3 CU M)
SURPLUS OR DEFICIT IN THE POND = 32,406 AC-IN (3332.1 CU M)
VOLUME OF THE POND = 76,270 AC-IN (7843.5 CU M)
DEPTH OF THE SUMP = 6,000 FEET (1.829 M)
WIDTH OF THE SUMP = 159.34 FEET (48.57 M)
LENGTH OF THE SUMP = 318.683 FEET (97.134 M)
PIPE SIZE SELECTED = 11.97 INCHES (303.94 MM)
TOTAL DYNAMIC HEAD = 24,784 FEET (7,554 M)
BREAK HOREPOWER REQUIRED = 12,8925 BHP
TOTAL ANNUAL COST OF IRRS WITH N OF 2 = \$2160,3469
TOTAL ANNUAL COST OF IRRS WITH N OF 2 = 52,26 $/ACRE (129.13 $/HA)
TOTAL ANNUAL COST OF IRRS INCLUDING WATER COST = 2510.62 $ (6201.23 $)
TOTAL ANNUAL COST OF IRRS = 60.76 $/ACRE (150.07 $/HA), ASSOCIATED WITH AN N OF 2
VITA

Safa Noori Hamad

Candidate for the Degree of

Doctor of Philosophy

Dissertation: A Rationale for Furrow Irrigation System Design and Management

Major Field: Agricultural and Irrigation Engineering

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Received Bachelor of Science degree in Civil Engineering from Baghdad University in 1971.

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