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The overall irrigation season is quantified by four parameters: marginal water costs, yield-water economic relations, crop water use efficiency and yield per unit of area. Besides the yield categories, the overall and seasonal levels of performance are quantified by the four water parameters and environmental and economic inputs. Evaluation leads to recommendations toward improvements of the irrigation system in regards to management and regime.

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EVALUATION AND IMPROVEMENT OF IRRIGATION SYSTEMS

By Gideon Peri and Gaylord V. Skogerboe

Water Management Research Project
Colorado State University
Fort Collins, Colorado

May 1979

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ABSTRACT

A comprehensive procedure for the evaluation and improvement of irrigation systems is suggested. The procedure is based on the analysis of the performances of the system for an individual application, along with the irrigation management regime (intervals and depths of application), resulting in an analysis for the whole irrigation season.

The irrigation system is quantified by four parameters: distribution uniformity and delivery, deep-percolation and storage efficiencies. The irrigation management and irrigation regime are quantified by ratios of recommended and determined intervals and depths for the individual application.

Evaluation of performance of an individual application is based on the water distribution profile after irrigation. Efficiencies and coefficients that describe the irrigation performance are derived directly from the water distribution profile. Based on these efficiencies, the irrigation performance is determined and classified into the appropriate performance categories and subsequently, the need for improvement and types of improvements are determined.

The overall irrigation season is quantified by four parameters: marginal water costs, yield-water economic relations, crop water use efficiency and yield per unit of area. Besides the yield categories, the overall and seasonal levels of performance are quantified by the four water parameters and environmental and economic inputs. Evaluation leads to recommendations toward improvements of the irrigation system in regards to management and regime.

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NOMENCLATURE

A = field area.

AD = actual depth of water application.

ADY = additional yield due to irrigation.

AI = actual interval between irrigations.

AMC = available soil moisture capacity

A_R = fraction of total field area where infiltrated depth equals or exceeds the volume of available root zone storage at the time of irrigation.

AWI = beneficial water applied by irrigation.

A_T = total field area.

A_i = field area associated with y_i.

a = area fraction in cumulative water distribution.

B = volume of deficient water after an irrigation, measured from the required depth, h_R.

C = volume of deficit (or excess) water after an irrigation, in relation to the mean depth applied.

C* = percent of available water greater than the wilting point when irrigation is performed.

CP = critical point of soil moisture content at which irrigation should take place.

CW = cost of irrigation water.

CWUE = crop water use efficiency.

C_V = unit cost of applying water.

C_Y = unit product price.

C_a = ratio of actual to expected yield per unit of area.

C_i = weighting factors for each of the four irrigation performance parameters.

C_v = ratio of actual to expected yield per unit of water.

D = volume of water delivered to the irrigated area, including field runoff, evaporation and wind losses.

DAR = ratio of recommended to actual depths of water application.

D_I = depth of water consumed by crop during T_I days.

E = volume of water which infiltrated beyond the required depth, h_R.

ET_a = actual evapotranspiration.

ET_p = potential evapotranspiration

E_P = deep percolation efficiency.

E_S = storage efficiency.

E_d = delivery efficiency.

F = volume of water which infiltrated beyond the average depth, $\bar{y}$.

FC = moisture content at field capacity as mass fraction.

G = sensible heat flux to or from the soil.

G_o = sensible heat flux to or from the soil for a reference crop.

H_B = $h_B/\bar{y}$.

H_C = $h_C/\bar{y}$.

H_E = $h_E/\bar{y}$.

h_F = $h_F/\bar{y}$.

h_R = average requirement divided by the mean depth (i.e., the available root zone water storage divided by the product of the mean depth infiltrated and the area irrigated) = h_R/y.

H_T = $h_T/\bar{y}$ = 1 (= H_{av}).

H_{av} = mean infiltrated depth divided by the mean infiltrated depth = 1.

H_i = nondimensional water depth, $y_i/\bar{y}$.

H_{max} = maximum depth infiltrated divided by the mean depth infiltrated = $y_{max}/\bar{y}$.

H_{min} = minimum depth infiltrated divided by the mean depth infiltrated = $y_{min}/\bar{y}$.

h_B = volume of deficient water after an irrigation, divided by the area irrigated = B/A_T.

h_C = volume of deficient water after an irrigation measured from the mean depth, $\bar{y}$, divided by the area irrigated = C/A_T.

h_D = volume of water delivered to the irrigated area, divided by the area irrigated = D/A_T.

h_E = volume of water that infiltrated beyond the required depth, h_R, divided by the irrigated area = E/A_T.

h_F = volume of water that infiltrated beyond the average depth, $\bar{y}$, divided by the irrigated area = F/A_T.

h_R = volume of available root zone water storage at the time of irrigation, divided by the area irrigated = R/A.

h_T = volume of water absorbed in the irrigated area, divided by the area irrigated = $T/A_T = \bar{y}$.

h_W = volume of water that was delivered to the irrigated area but was not absorbed by it, divided by the irrigated area = W/A_T.

IE = irrigation efficiency in percent.

INR = ratio of recommended to actual irrigation intervals.

IS = relative level of farm investment.

K = crop growth stage coefficient.

L_i = amount of water losses in section i.

MAD = management allowed deficit of soil moisture.

MVWA = marginal value of water application.

$MVWA_c$ = marginal value of water application measured as the ratio of marginal product price to cost of water.

$MVWA_y$ = marginal value of water application measured as the ratio of incremental crop yield to incremental depth of water application.

N = number of days from present time to next irrigation.

NR = net return from irrigated crop excluding the cost of irrigation water.

PIA = potential irrigated area.

PMC = present soil moisture content.

Q_o = objective function.

R = volume of available root zone water storage at the time of irrigation (i.e., the requirement).

RAM = remaining available soil moisture.

RD = recommended depth of water application.

RI = recommended interval between irrigations.

RIC = net return ratio for the irrigated crop.

RP = relative level of crop production.

R_e = seasonal effective rainfall.

R_{et} = ratio of actual evapotranspiration to potential evapotranspiration.

R_n = net radiation.

R_{no} = net radiation for a reference crop.

SMC = soil moisture content.

T = volume of water absorbed in the irrigated area.

T_I = number of days between two successive irrigations.

TSW = total required seasonal irrigation water depth.

TV = total available quantity of water.

U_{cc} = Christiansen's uniformity coefficient.

U_d = distribution uniformity.

V = quantity of water associated with actual yield.

$\bar{V}$ = quantity of water associated with expected yield per unit of area.

V_c = beneficially applied quantity of water per unit of area.

V_{ci} = amount of water beneficially consumed in the i section of a water delivery system.

V_d = amount of water delivered.

V_{di} = amount of water delivered to section i.

W = volume of water which was delivered to the irrigated area but was not absorbed by it.

WD = accumulated soil moisture depletion since last irrigation.

WDP = nondimensional water distribution profile.

WP = moisture content at wilting point in percent by weight.

Y = crop yield.

Y_1 = functional relationship between crop yield and water beneficially consumed.

Y_2 = function relationship between crop yield and the ratio of actual to potential evapotranspiration.

Y_{uoa} = yield per unit of area.

Y_{uow} = yield per unit of water.

$\bar{Y}_{uoa}$ = expected yield per unit of area.

$\bar{Y}_{uow}$ = expected yield per unit of water.

$\bar{y}$ = mean depth of water infiltrated at end of irrigation.

y_i = depth of infiltrated water at point i in an irrigated field.

y_k = depth of water infiltrated at fractional area k of total field area.

y_{max} = maximum depth of water infiltrated.

y_{min} = minimum depth of water infiltrated.

y_p = depth of water infiltrated at fractional area p of total field area.

Z = soil profile depth.

α = dummy variable.

β = ratio of sensible heat flux to or from the air to the actual evapotranspiration.

β_o = ratio of sensible heat flux to or from the air to the actual evapotranspiration of a reference crop.

γ_d = soil bulk density.

Chapter 1

INTRODUCTION

Poor water delivery and irrigation application efficiencies[1] may lead to some unfavorable effects resulting in lower yield per unit of area and per unit of water, less total area irrigated, and detrimental environmental effects, as well as lower returns from the irrigated crops. These unfavorable effects will be considered in turn.

1. Lower yields per unit of area.

A potential production (and income) function is demonstrated in Fig. 1-1 and Table 1-1, where yield is expressed as a percent of the maximum potential yield obtained for an irrigation efficiency of 100 percent, assuming all other parameters affecting crop yields are constant. Three regions may be identified.

a. A region of high efficiency (region A in Fig. 1-1) where changes in efficiency affect yield only slightly. Irrigation systems that operate at high efficiencies can tolerate minor changes (changes during or between irrigations, as well as in areas and crops, etc.) without affecting the yield, which is already high. Improvement of highly efficient irrigation systems is only marginally economical since the expected benefits are relatively low.

1/Irrigation efficiencies will be further defined. However, for this general purpose, efficiency can be regarded as suggested by the ICID (1978) standards for the calculation of irrigation efficiencies as the field application efficiency. It is expressed as the ratio of the volume of water needed to bring the soil moisture up to a minimum level required for the crop to the volume of water furnished to the field.

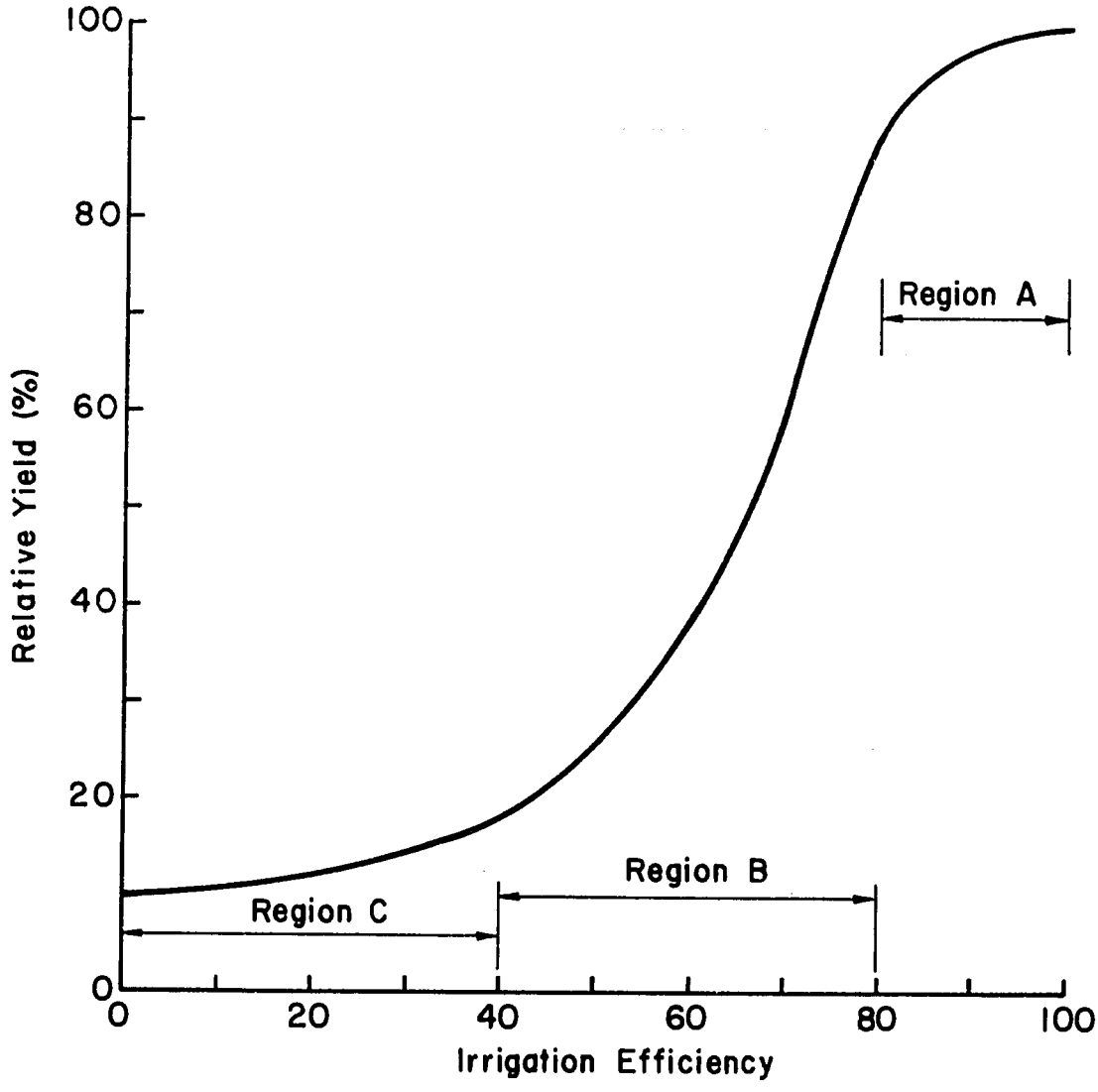


Fig. 1-1. General relationship of yield per unit of area and water as a function of irrigation efficiency.

Table 1-1. Typical data for the relationship between yield per unit of area and water and irrigation efficiency.

Actual quantity of beneficially applied water, in % of required quantity (1)	Irrigation Efficiency, in %* (2)	Yield per unit of area and water (from Fig. 1-1)** (3)
100	100	100
90	90	98
80	80	90
70	70	60
60	60	40
50	50	25
40	40	18
30	30	15
20	20	12
10	10	11
0	0	10

*For this purpose, irrigation efficiency is defined as the portion of the water beneficially applied to the crop. It is equal therefore to the data given in Column (1). The term "100 minus irrigation efficiency" represents the deficit portion in the irrigated field.

**Based on the assumption that 100% of the required water is delivered to the irrigated area, so that the yield per unit of area is equal to the yield per unit of water.

b. Region of medium efficiencies (region B in Fig. 1-1) where minor changes in efficiencies strongly affect yields.

c. Region of low efficiencies (region C in Fig. 1-1) where changes will affect yield only slightly, as yield is already at a low level. Minor improvements in irrigation efficiencies in this range will usually result in relatively insignificant yield increases.

2. Lower yields per unit of water.

Lower irrigation efficiencies lead also to a reduction in yield per unit of water since both an increase in water quantities used and a decrease in yield per unit of area may be involved. If the yield per unit of water is denoted by Y_{uow}

$$Y_{uow} = \frac{Y_{uoa}}{V_d} \tag{1-1}$$

where:

Y_{uow} = yield per unit of water

Y_{uoa} = yield per unit of area, and

V_d = actual applied quantity of water per unit of area (L).

With the irrigation efficiency defined as

$$IE = \frac{V_c}{V_d} 100 \tag{1-2}$$

where:

IE = irrigation efficiency in percent, and

V_c = beneficially applied quantity of water per unit of area, (L).

Then,

$$Y_{uow} = \frac{Y_{uoa} \cdot IE}{V_c} \tag{1-3}$$

With V_d taken as the requirement and expressed as V_d = 100%, then IE = V_c and

$$Y_{uow} = Y_{uoa} \tag{1-4}$$

Hence, yield per unit of water is also decreased with the decrease of irrigation efficiency as is shown in Fig. 1-1.

3. Total area irrigated.

Irrigated areas under most projects are limited by the total available water quantities. Its size is directly and linearly dependent on irrigation efficiency. The potential irrigated area is given in general terms by:

$$PIA = \frac{TV}{V_d} \tag{1-5}$$

where:

PIA = potential irrigated area, and

TV = total available water quantity.

Substituting Eq. 1-2 into Eq. 1-5 results in

$$PIA = \frac{TV \cdot IE}{V_c 100} \tag{1-6}$$

For a given total available water quantity, TV, and a recommended beneficially applied quantity of water, V_c, the irrigated area is directly dependent on the irrigation efficiency, IE. A decrease in the irrigation efficiency will result in a decrease in the irrigated area.

4. Lower returns from the irrigated crops

Low irrigation efficiency is associated with lower production and decreased net income. The relationship between the total production and investment may be established for each project as illustrated by the

example given in Fig. 1-2. Net profits are also a function of efficiency levels and change with the relative investment level. Also, the lower the efficiency, the smaller the net profit and the range of investments where it occurs. Functions describing the relationship between production and investment may take different curvilinear forms. From Fig. 1-2, the relationships between production and investment, for an efficiency level (IE) of 100%, are given in comparison to those of lower efficiency levels (IE = 80, 70, 60, 50, 30). While production is expected to be lower than the investment at a level of investment (IS) > 10, for the 100% efficiency level, it is 8.5, 4.2, 2.0, 0.8, and 0.1 respectively with the lower efficiency levels.

5. Environmental effects.

Lower irrigation efficiency may also contribute to various unfavorable environmental impacts:

a. leaching of nutrients from the root zone;

b. soil erosion and deterioration of soil texture;

c. raising the ground water table, thereby increasing the potential for drainage problems; and

d. increased salinity levels.

6. Summary.

According to the topics discussed above, the need for higher irrigation efficiency is obvious. Efforts should be continuously made towards achieving increased irrigation efficiencies. Irrigation efficiencies can be increased by evaluation and improvement of irrigation systems in three main areas:

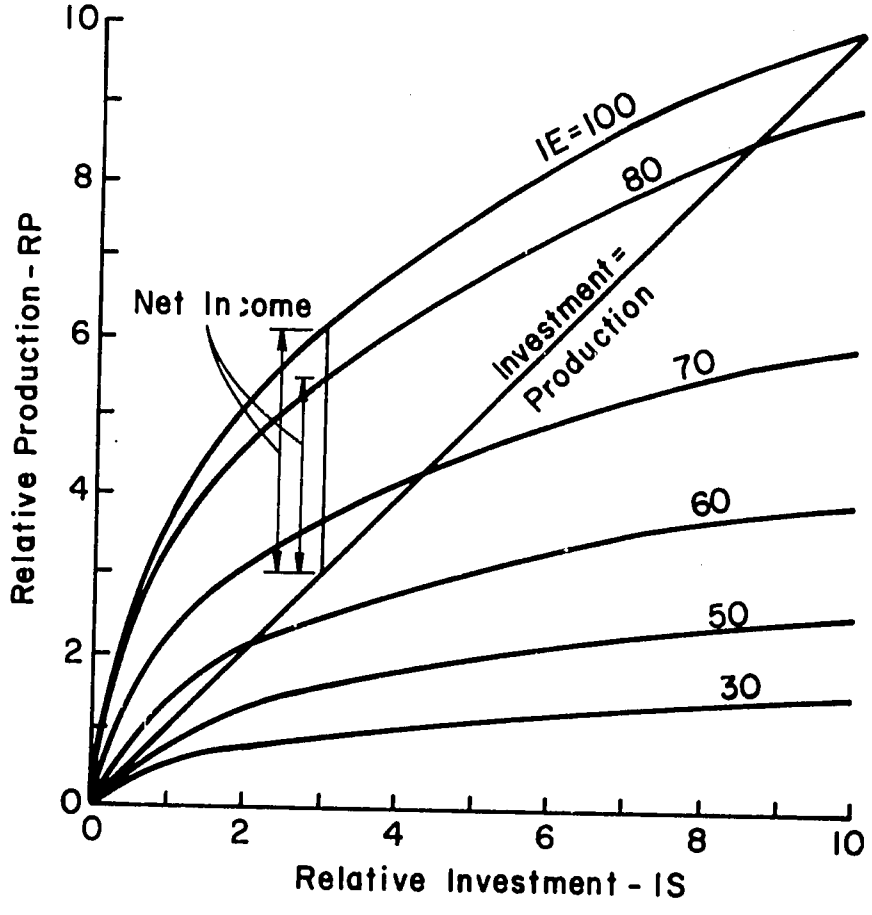


Fig. 1-2. Example of relative relationships between production and investment for various irrigation efficiencies.

a. Scheduling--this is concerned mainly with proper irrigation intervals and dates of irrigation (when to irrigate) and depth of application (how much to irrigate).

b. Operational conditions--this is concerned mainly with flows, pressures, quantities of water, time of irrigation and system layout and dimensions.

c. Changes in the system--this involves additional construction or equipment installation for the control of flows and pressures.

The process of evaluating and improving irrigation systems is discussed in this report, together with the required field measurements, equipment and data collection program, which are discussed in greater detail in each report covering a particular irrigation method (e.g., Water Management Research Project Technical Report 49B, "Evaluation and Improvement of Basin Irrigation").

Chapter 2

PROCEDURE FOR THE EVALUATION AND IMPROVEMENT OF IRRIGATION SYSTEMS

A comprehensive procedure for the evaluation and improvement of irrigation systems is suggested in Fig. 2-1. The procedure is based on the analysis of the performances of the system for an individual application, along with the irrigation management regime (intervals and depths of application), resulting in an analysis for the whole irrigation season.

1. Analysis of system performance for an individual application.

The performance of the system for an individual application is evaluated by four performance parameters (Chapter 5):

a. The irrigation pattern or the "Distribution Uniformity" - U_d;

b. The "Delivery Efficiency" - E_d;

c. The "Deep Percolation Efficiency" - E_p; and

d. The "Storage Efficiency" - E_s.

These four performance parameters are sufficient to define the performance of the system for an individual application.

Values for the four performance parameters are derived from the use of available models that utilize the present existing values of the system parameters (dimensions, pressures, flows, soil properties, slope, etc.) as well as feasible ranges of values for these system parameters. Each of the major irrigation methods (basins, borders, furrows, sprinkler and trickle) is analyzed by a specific model designed to evaluate the four different performance parameters in the study of a specific system.

The system evaluation and improvement is an iterative procedure where, following an initial establishment of levels of performance parameters,

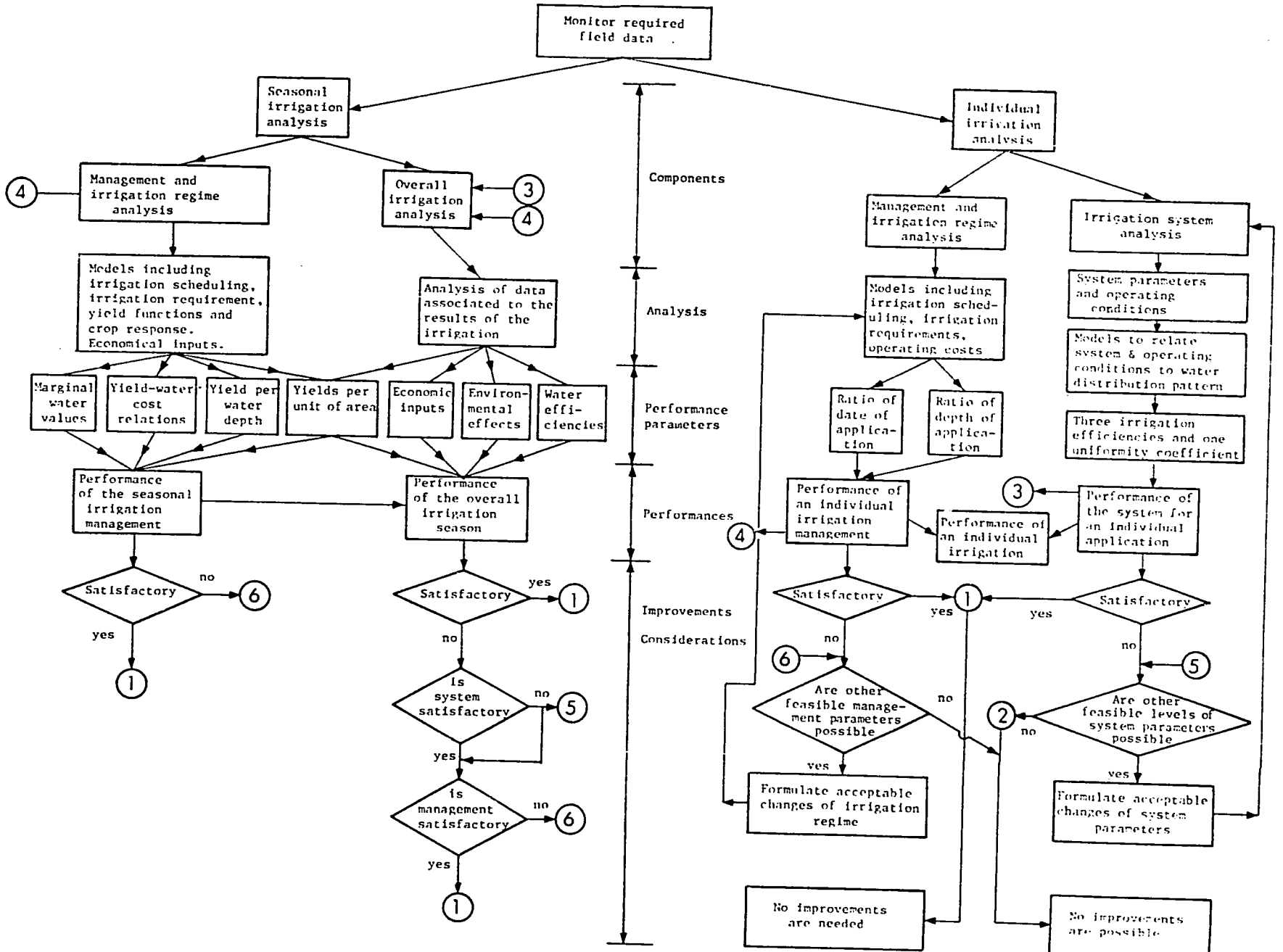


Fig. 2-1. Procedure for the evaluation and improvement of irrigation systems.

other levels may be reached using the same models but with different levels of satisfaction, established by the farmer, design engineer, operator, planner, etc. Unsatisfactory levels of performance parameters require improvement of the irrigation system by changes in the system parameters.

2. Analysis of performance of the irrigation management and irrigation regime.

Analysis of performance of the irrigation management and irrigation regime is performed separately for an individual irrigation and for the overall seasonal irrigation. The performance of the seasonal irrigation management is evaluated by four performance parameters (Chapter 3):

a. average yield expressions;

b. crop water use efficiency;

c. yield-water economic relationships; and

d. marginal water values.

The performance of an individual irrigation management is evaluated by the ratios between the recommended and actual depths of application and interval between irrigations (Chapter 4).

Values of the performance parameters of the irrigation regime are derived from the use of available models which are basically independent of the irrigation system. These models utilize existing data of evapotranspiration, soil moisture stress and yield-water relationships.

Values for the management performance parameters of the seasonal and individual irrigations are obtained by utilizing existing values of the irrigation regime parameters (depths of application and intervals between irrigations), as well as from feasible ranges of values of these irrigation regime parameters.

The irrigation regime evaluation and improvement is an iterative procedure, where following an initial establishment of levels of performance parameters, other levels may be reached, using the same models but with different values for the irrigation regime parameters.

For each study case, there will be different levels of satisfaction established by the farmer, design engineer, operator, planner, etc. Unsatisfactory levels of performance parameters require improvement of the irrigation system by changes in the irrigation regime parameters by the use of different values of the irrigation regime parameters.

3. Analysis of results of an overall irrigation season.

The performance of the overall irrigation season is evaluated by four performance parameters (Chapter 6):

a. Economic inputs;

b. Yield categories;

c. Water efficiencies; and

d. Environmental effects.

Values for the four performance parameters are derived from the use of available models utilizing values of the performance parameters of the system for an individual application and the performance parameters of the irrigation regime. Consequently, the evaluation of the overall irrigation season is related to both the performance of an individual application and the overall irrigation regime. The overall irrigation season evaluation and improvement is an iterative procedure, where following an initial establishment of levels of performance parameters, other levels may be reached using the same models but different values for the system and/or irrigation regime parameters.

For each study case, there will be different levels of satisfaction, established by the farmer, design engineer, operators, planner, etc. Unsatisfactory levels of the performance parameters require improvement of the overall irrigation by changes in either the system parameters or the irrigation regime parameters or both.

The major available models and the performance parameters for the evaluation of the irrigation management and irrigation regime are described in Chapters 3 and 4 for the overall irrigation season and for the individual application, respectively. The performance parameters of an overall irrigation season and an individual application are described in Chapters 6 and 5, respectively.

Models to derive the performance parameters for an individual application, utilizing the system parameters are described separately for each of the main irrigation methods ("Evaluation and Improvement of Basin Irrigation" and "Evaluation and Improvement of Border Irrigation").

4. Summary.

Evaluation, as shown in this model, relates to the irrigation system, the irrigation management and the irrigation regime separately, and as a result to the overall irrigation process. The irrigation system is quantified by four parameters: distribution uniformity and delivery, deep-percolation and storage efficiencies. The irrigation management and irrigation regime are quantified by ratios of recommended and determined intervals and depths for the individual application. The overall irrigation season is quantified by four parameters: marginal water costs, yield-water economic relations, crop water use efficiency and yield per unit of area. Besides the yield categories, the overall

and seasonal levels of performance are quantified by water efficiencies and environmental and economic inputs. Evaluation leads to recommendations toward improvements of the irrigation system in regards to management and regime.

Chapter 3

EVALUATION OF THE PERFORMANCE OF IRRIGATION REGIME - OVERALL IRRIGATION SEASON

Irrigation regime is associated with two parameters: the depth of application and the interval between irrigations. The performance parameters of the irrigation management and its relationship to the irrigation regime are described below.

1. Yields.

Assuming no water limitations, yield is related to the seasonal depth of application by an appropriate yield function, where the yield is related to one of the two most common variables:

a. Total water volume, or volume per unit area, consumed by the crop, V_c, including irrigation and effective rainfall (Fig. 3-1).

$$Y = Y_1(V_c) \tag{3-1}$$

b. The ratio of the actual evapotranspiration, ET_a, to the potential evapotranspiration ET_p: $R_{et} = ET_a/ET_p$ (Fig. 3-2).

$$Y = Y_2(R_{et}) \tag{3-2}$$

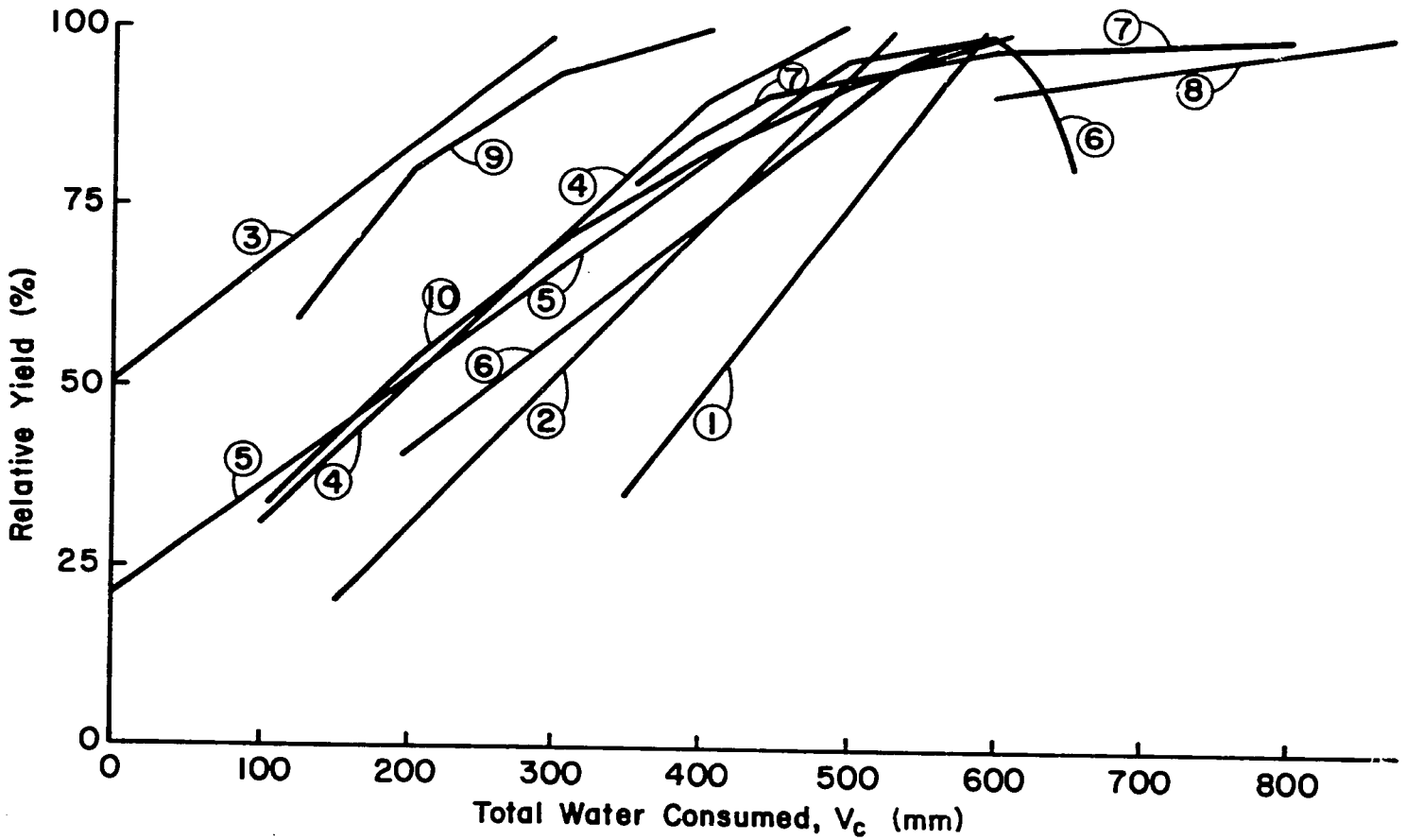
In Eqs. 3-1 and 3-2, Y_1 and Y_2 are functional relationships. Since the actual evapotranspiration, ET_a, represents the water consumed by the crop, the total water to be applied to the irrigated crop can be calculated from:

$$TSW = V_c - R_e \tag{3-3}$$

Since $V_c = ET_a$,

$$TSW = ET_a - R_e = R_{et}ET_p - R_e \tag{3-4}$$

where TSW = total required seasonal irrigation water depth, and R_e = seasonal effective rainfall. The total water quantity consumed by the



1. Wheat in the Jordan Rift and Bet Shean Valley, Israel (Shalevet, 1976).
2. Wheat in the northern Negev, Israel (Shalevet, 1976).
3. Sorghum in the Coastal Plain, Israel (Shalevet, 1976).
4. Grain corn in the Jezreel Valley, Israel (Shalevet, 1976).
5. Cotton in the eastern Jezreel Valley, Israel (Shalevet, 1976).
6. Peanuts in the northern Negev, Israel (Shalevet, 1976).
7. Citrus in the Central coastal Plain, Israel (Shalevet, 1976).
8. Avacado (Fuerte) in the western Galilee, Israel (Shalevet, 1976).
9. Grain sorghum (Shipley, 1978).
10. Corn (Shipley, 1978).

Fig. 3-1. Yield as a function of total water consumed for several crops.

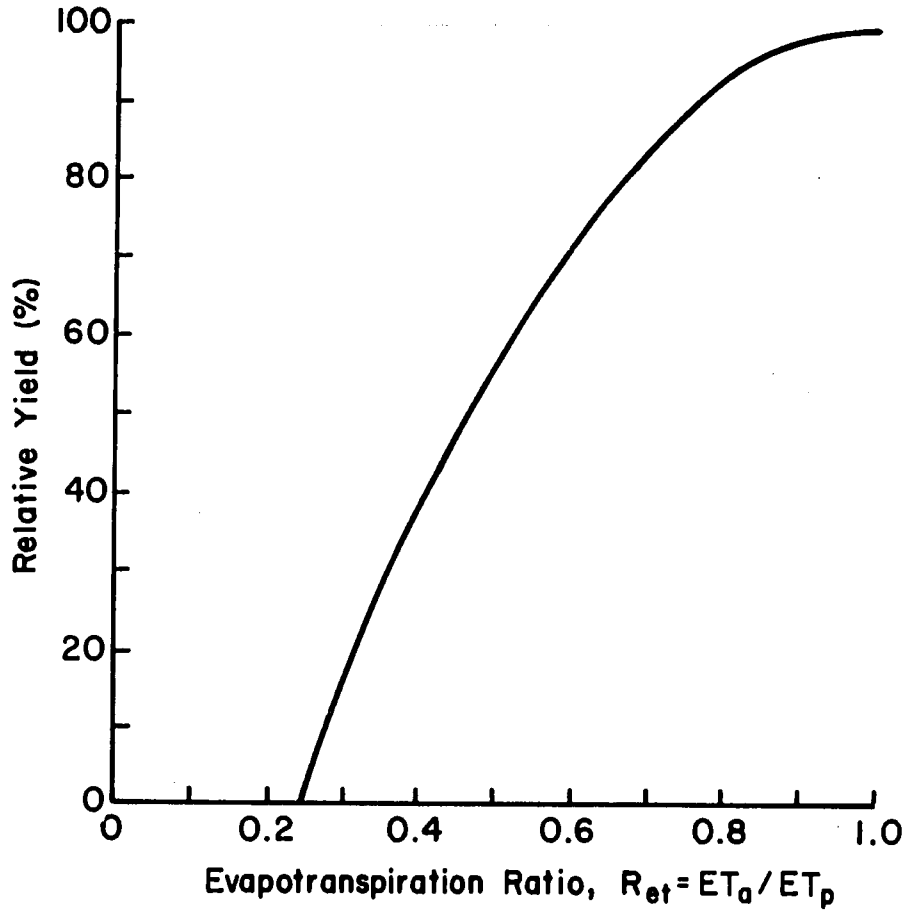


Fig. 3-2. Typical functional relationship between relative yield and evapotranspiration ratio.

crop, V_c, and the evapotranspiration ratio, R_{et}, are determined from yield functions (Figs. 3-1 and 3-2, for example).

Although the yield is most commonly related to the total water consumed by the crop, the intervals between irrigations (and the resulting number of irrigations) also affect the yield.

The recommended number of irrigations, N, (based on the appropriate intervals) is usually established for each crop under its specific growing conditions. The intervals (as well as the specific dates and application depth) are related to the soil moisture stress. During the interval between irrigations, the soil moisture content is decreased as a result of evapotranspiration, which causes an increase in the soil moisture stress. Each crop has recommended stress levels associated with the specific stages of crop growth. The irrigation intervals should be set so as to prevent overstressing between irrigations, or the moisture content should not fall below a recommended level, which for most crops is well above the wilting point. (The soil moisture content is related to the soil moisture stress with each soil type having a unique relationship.) This is illustrated in Fig. 3-3 and will be discussed in more detail in Chapter 4. As shown in Eq. 3-2, the yield function can also be expressed in terms of the ratio of actual to potential evapotranspiration. This ratio is dependent on climatic conditions, the crop growth stage and the soil moisture content (or stress). Defining this ratio by $R_{et} = ET_a/ET_p$, each crop has a recommended evapotranspiration ratio, R_{et}, for which an optimal yield can be obtained.

Generally speaking, the recommended evapotranspiration ratio, R_{et}, has a medium value during the early stages of development

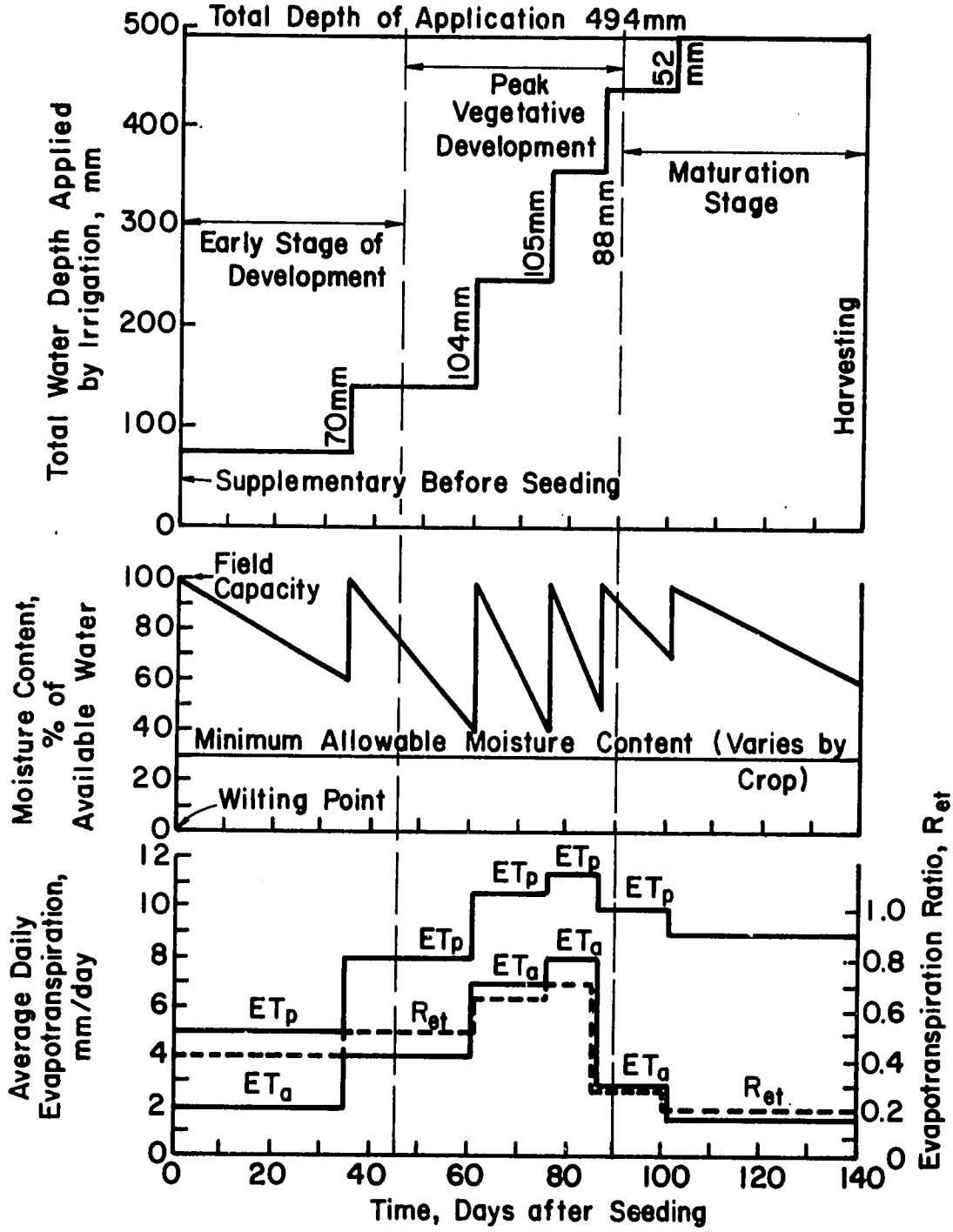


Fig. 3-3. Illustrative example of parameters associated with the seasonal irrigation regime.

($R_{et} \simeq 0.4 - 0.5$), high values during the peak vegetative development ($R_{et} \simeq 0.8$) and low values during maturation ($R_{et} \simeq 0.2 - 0.3$). Qualitatively, the evapotranspiration ratio, R_{et}, will be similar to the crop growth stage coefficient, K, used by the Soil Conservation Service (1970). The irrigation scheduling (namely number, dates and depths of irrigation applications) should provide the recommended value of R_{et}. Typical values of the evapotranspiration ratio, R_{et}, for optimal yields are given in Table 3-1. The ratio R_{et} is represented schematically in Fig. 3-3.

Table 3-1. Some recommended values of the evapotranspiration ratio $R_{et} = ET_a/ET_p$ for several crops.

Crop	Values of Evapotranspiration Ratio, $R_{et} = ET_a/ET_p$		
	Early Stages	Peak Vegetative Development	Maturation
Sugar cane		0.75	
Wheat	0.5	0.80	0.2
Sorghum	0.37	0.66	0.3
Forage Corn	0.3	0.75	
Cotton		0.66	
Sugar beets			
Peanuts	0.6	0.75	0.78
Alfalfa	0.3	0.80	

The seasonal amount of water to be applied by irrigation is not necessarily aimed at the maximum yield, but more generally at a maximum net return. The other performance parameters of the seasonal irrigation regime are related to these yield-water relations.

2. Crop water use efficiency.

The crop water use efficiency, CWUE, can be derived from the yield function (Fig. 3-4) and is defined by:

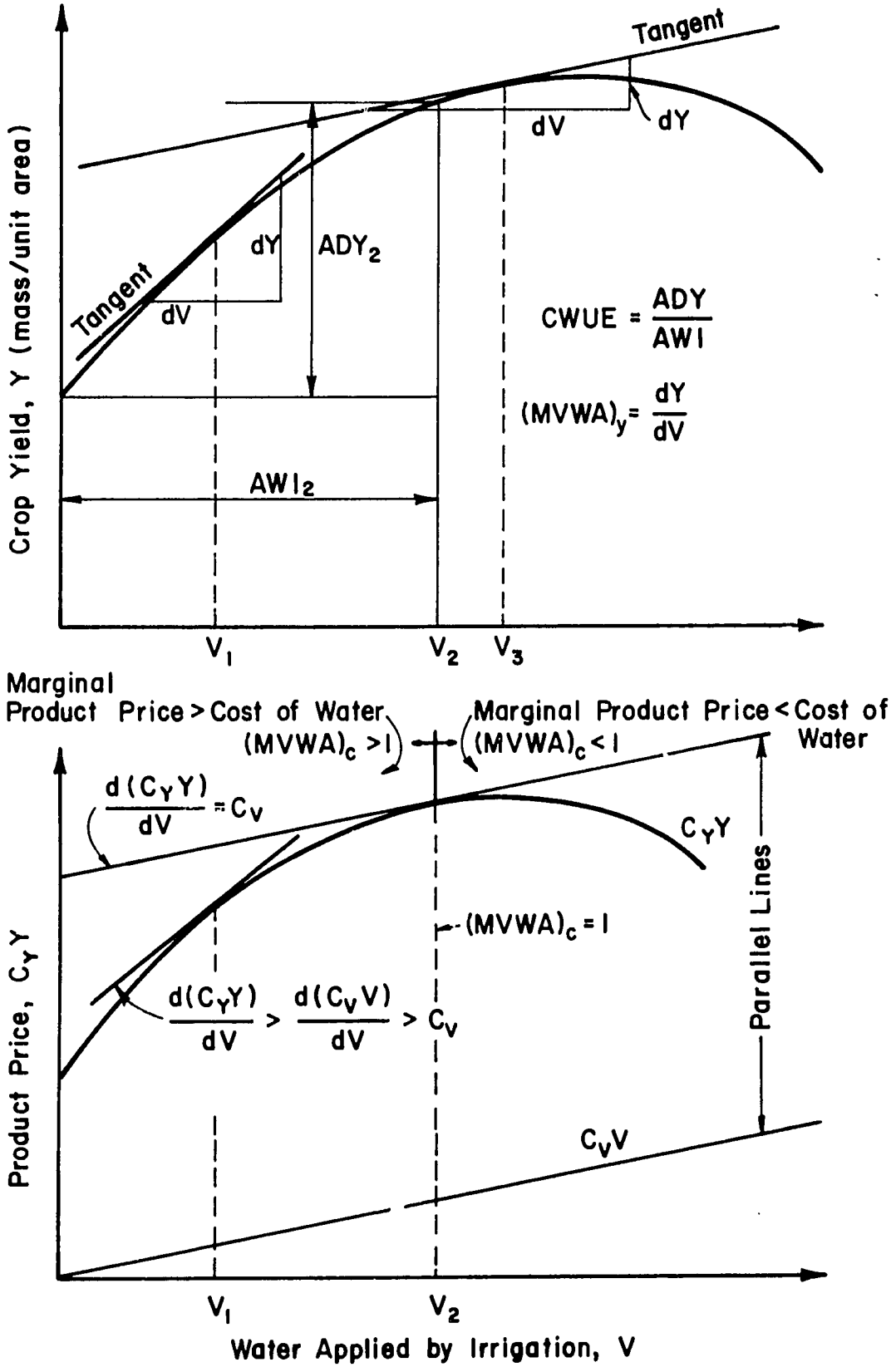


Fig. 3-4. Schematic description of yield-water relations for the determination (analysis) of the annual depth of application.

$$CWUE = \frac{ADY}{AWI} \tag{3-5}$$

where ADY = additional yield due to irrigation, mass per unit of area, and AWI = beneficial water applied by irrigation. However, for many specific crops, a recommended range of crop water use efficiencies (CWUE) is well known, and the planned annual water application provides the minimal CWUE (Table 3-2). The CWUE is strongly affected by both irrigation regime and effective rainfall.

3. Yield-Water costs relations.

The relationship between the cost of water and yield can be expressed by the net return ratio from the irrigation crop (RIC). This term is given by:

$$RIC = \frac{NR}{CW} \tag{3-6}$$

where NR = net return from irrigated crop, but does not include the cost of irrigation, and CW = cost of irrigation water. The seasonal amount of water to be applied by irrigation should be associated with an RIC > 1.0.

4. Marginal value of water application (MVWA).

This term is concerned with the marginal value of water applied in irrigation and it can be expressed in terms of yields and costs. The ratio of the incremental yield, ΔY, and water application, ΔV, is expressed by:

$$(MVWA)_y = \frac{\Delta Y}{\Delta V} = \frac{dY}{dV} = \frac{d\left[Y_1(V)\right]}{dV} \tag{3-7}$$

where $Y_1(V)$ is defined in Eq. 3-1 and $MVWA_y$ is a function of the total depth of application (V). For a typical yield function, $MVWA_y$ decreases with an increase in V and may reach zero or negative values.

Table 3-2. Some crop water use efficiencies for several crops (after Shalhevet, 1976).

Crop	Water Applied by Irrigation,* AWI in mm	Additional Yield due to Irrigation, ADY in kg/ha	Crop Water Use Efficiency, CWUE in kg/ha-mm
Wheat	350	6725	13.5
	180	2880	16.0
	224	3562	15.9
	240	3432	14.3
	150	1920	12.8
	240	2448	10.2
Grain Sorghum	292	3270	11.2
	582	5878	10.1
	394	5437	13.8
	271	5691	21.0
	235	5405	23.0
Grain Corn	433	6192	14.3
	408	7629	18.7
	469	9521	20.3
	510	8058	15.8
	310	7595	24.5
Cotton	1020	4998	4.90
	696	4942	7.10
	553	4203	7.60
	450	3600	8.00
	310	4495	14.5
	270	4752	17.6

*Values are for various years, locations and irrigation regimes.

The ratio between the yield return, C_Y (per unit of yield), and cost of applying water, C_V (cost per unit of water), in relation to the incremental yield, ΔY, and water, ΔW, is expressed by:

$$(MVWA)_c = \frac{C_Y \Delta Y}{C_V \Delta Y} = \frac{C_Y}{C_V} \frac{dY}{dV} = \frac{C_Y}{C_V} \frac{d[Y_1(V)]}{d_V} = \frac{C_Y}{C_V} (MVWA)_y \qquad (3\text{-}8)$$

It is desirable that $MVWA_c > 1$ for given C_Y and C_V. The various yield-water defined relationships (CWUE, $MVWA_y$ and $MVWA_c$) are demonstrated schematically in Fig. 3-4.

5. Summary

The seasonal irrigation regime parameters (seasonal depth of application and intervals between irrigations) can be determined so that desirable levels of the parameters of the irrigation regime can be obtained. The considerations are:

a. The seasonal depth of application, as derived from the crop yield function, should provide the desired yield level (Eqs. 3-1, 3-2, 3-3, and 3-4).

b. The seasonal depth of application should be such that a reasonable crop water use efficiency, CWUE, (Eq. 3-5) is obtained.

c. The seasonal depth of application should provide a net return ratio for the irrigated crop, RIC, (Eq. 3-6) of greater than 1.0, where the recommended total required seasonal water depth, TSW, and the value of RIC should satisfy a desired level.

d. The seasonal depth of application should provide a minimal level of $MVWA_y$, where $MVWA_y > 0$ and $MVWA_c > 1.0$.

The seasonal irrigation regime parameters should be determined on the basis of given yield functions as well as yield and irrigation costs;

however, assumptions may have to be made when required data is not available.

Chapter 4

EVALUATION OF THE PERFORMANCE OF IRRIGATION REGIME--INDIVIDUAL APPLICATION

The performance of an individual irrigation regime may be described by ratios between recommended and actual application depths and irrigation intervals, that is:

$$INR = \frac{RI}{AI} \tag{4-1}$$

$$DAR = \frac{RD}{AD} \tag{4-2}$$

where INR = the interval ratio, RI = recommended intervals between irrigations, AI = actual interval between irrigations, DAR = the depth ratio, RD = the recommended depth of application, and AD = actual depth of application.

Evaluation of these performance parameters is based on two irrigation scheduling parameters:

a. The date of irrigation, or the interval between two successive irrigations; and

b. The irrigation requirement, that is, how much to irrigate, or the depth of application.

These scheduling parameters are related and are a function of the crop, soil, and climatic conditions.

1. Factors involved in determining date and depth of an individual application.

Determination of date and depth of irrigation is mainly related to soil moisture content, evapotranspiration, the relationship between soil moisture content and stress, and the relationship between crop yield and soil moisture stress.

a. Soil moisture content.

Soil moisture content is defined by the level of moisture within the root zone. Two well known levels of soil moisture content are used in irrigation: moisture contents at field capacity (FC) and wilting point (WP). Based on these soil moisture levels, the available soil moisture capacity, AMC, of a soil profile having a depth of Z is given by:

$$AMC = \frac{(FC - WP)}{100} (1000Z\gamma_d) \tag{4-3}$$

where AMC = available soil moisture capacity in mm, FC = moisture content at field capacity in percent by weight, WP = moisture content at wilting point in percent by weight, γ_d = bulk density in g/cm^3, and Z = soil profile depth in meters. The total available moisture as a function of the wetted soil depth for different soils is given in Fig. 4-1. Irrigation usually takes place before all of the available water is consumed, that is, before the soil moisture content (SMC) drops to the wilting point.

If the soil moisture content at which irrigation takes place is denoted by CP (critical point) then

$$CP = WP + \frac{C^*}{100} (FC - WP) \qquad 0 \leq C^* \leq 100 \tag{4-4}$$

where C^*= percentage of available water above WP when irrigation is performed. Note that for C^*= 0, CP = WP and for C^*= 100, CP = FC.

The moisture deficiency by the time of irrigation, also known as the management allowed deficit, MAD, is given by:

$$MAD = FC - CP = (FC - WP) \left(1 - \frac{C^*}{100}\right) \tag{4-5}$$

where MAD is the moisture deficiency in percent by weight. The management allowed deficit, MAD, for a profile of depth Z expressed as

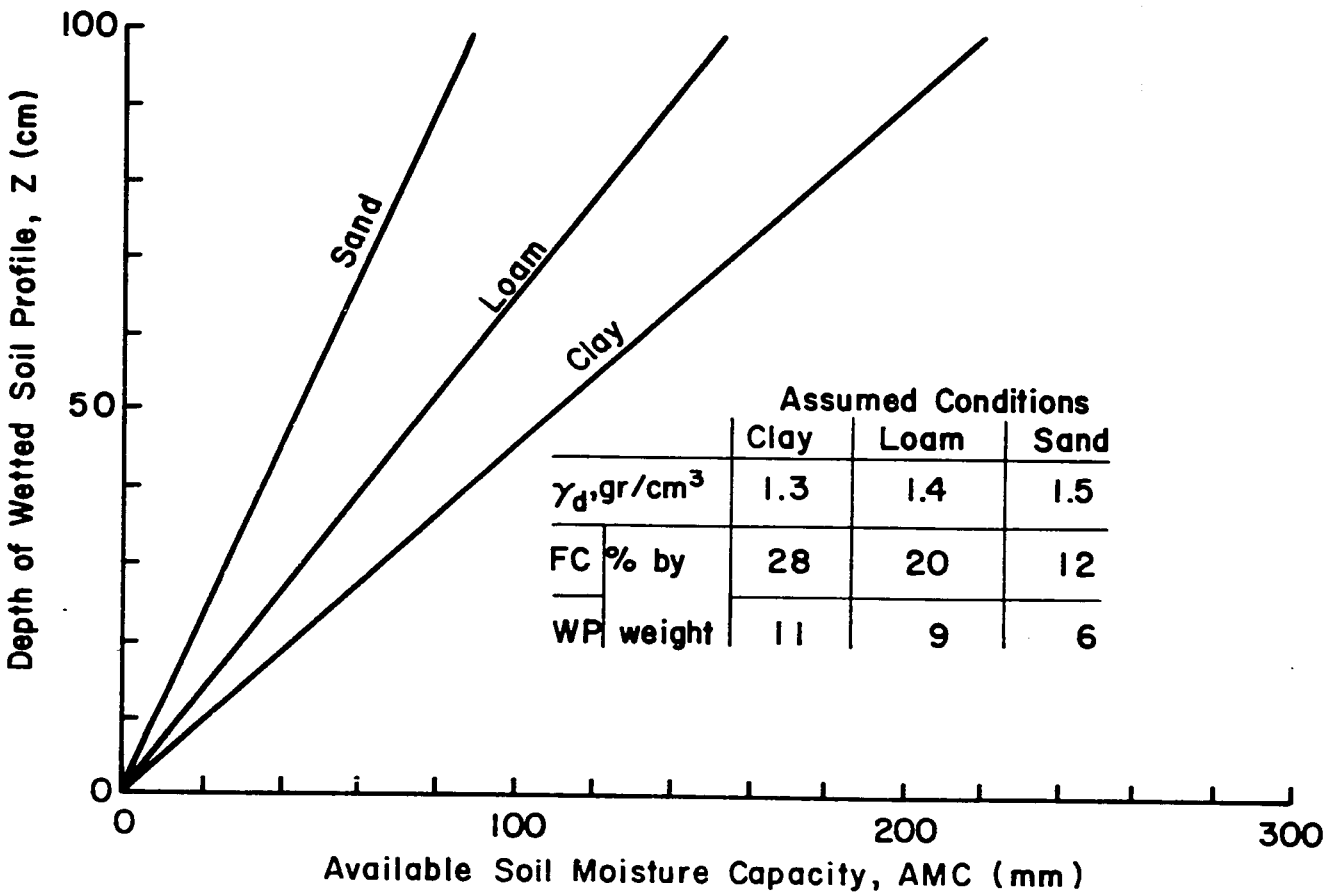


Fig. 4-1. Available moisture as a function of a uniform profile depth for three typical soil types.

depth of water is given by:

$$MAD = \left(\frac{FC - CP}{100}\right) (1000\ Z\gamma_d) \qquad (4\text{-}6)$$

where MAD is the soil moisture deficiency in mm. The moisture depletion as a function of CP is shown in Fig. 4-2.

As the percentage of available water at the time that irrigation is performed, C*, increases, the critical point, CP, also increases, reaching the value of the field capacity, FC, when C* = 100. The increase in the critical point means a lower management allowed deficit, MAD, at the time of irrigation (Fig. 4-2).

The maximum allowable moisture deficiency can be calculated for a known critical point, CP, and given soil with known moisture content at field capacity, and wilting point, bulk density and an effective root zone depth.

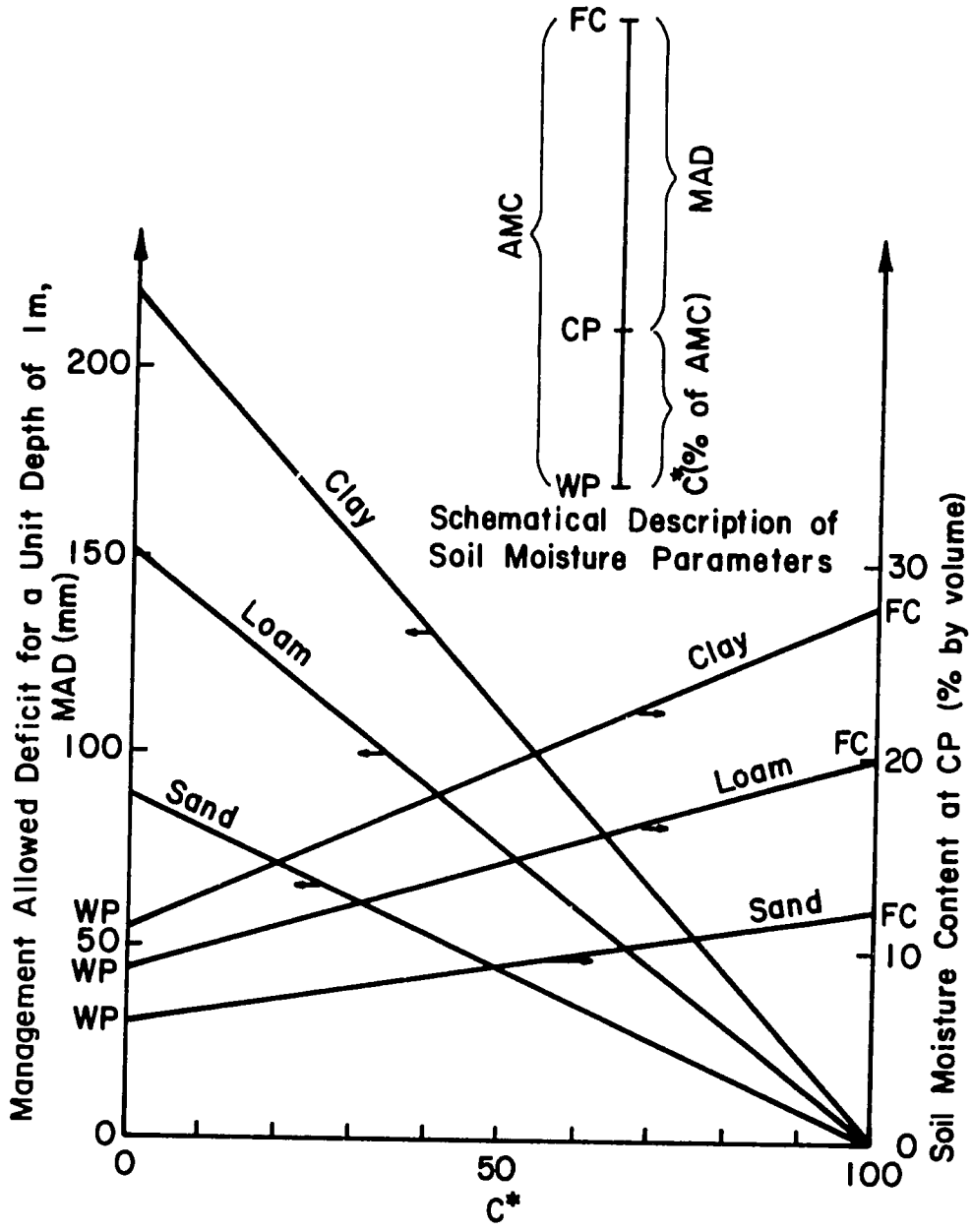
b. Relationships between soil moisture content and stress.

The soil moisture content, SMC, is related to the soil moisture stress by the soil moisture retention function. In general, a decrease in SMC is associated with an increase in the soil moisture stress. Typical retention curves are shown in Fig. 4-3. As the clay content increases (Fig. 4-3a), the retention curve "shifts" towards the right and its slope is more moderate.

For irrigation purposes, the retention curve is expressed in two forms as shown in Fig. 4-3:

(i) Soil moisture stress - as a function of the soil moisture content (Fig. 4-3a); and

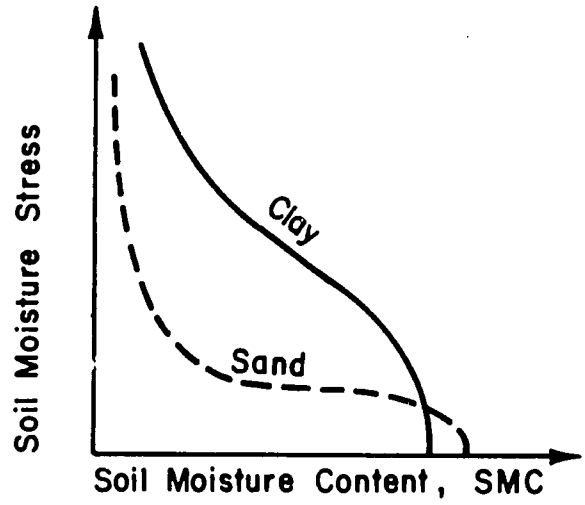
(ii) Soil moisture stress - as a function of available water deficiency (Fig. 4-3b).



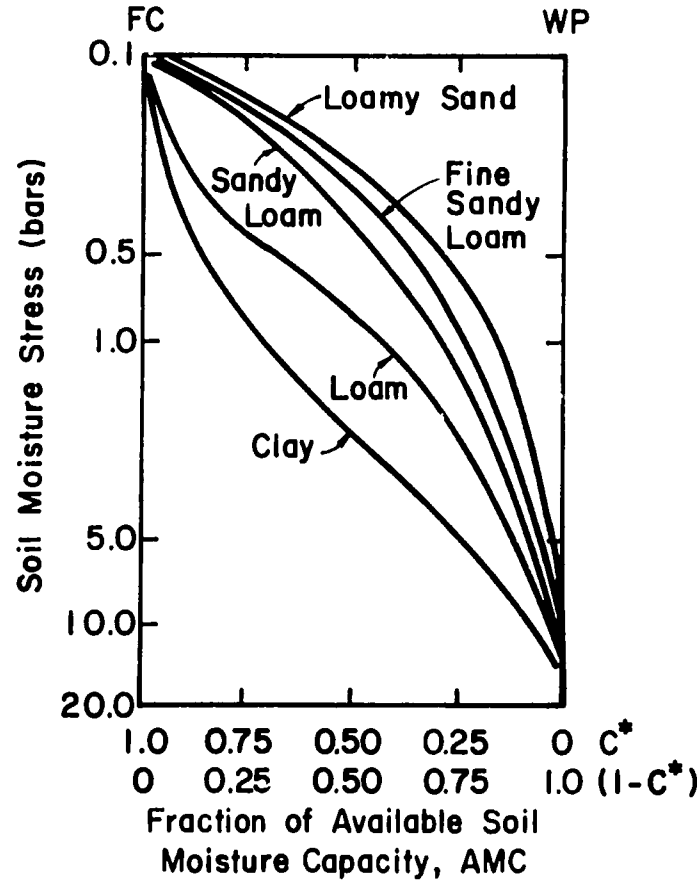
C*	1-C*	Clay (γ_d=1.3) MAD mm/m	Clay CP % by volume	Loam (γ_d=1.4) MAD mm/m	Loam CP % by volume	Sand (γ_d=1.5) MAD mm/m	Sand CP % by volume
0	1	221	11	154	9	90	6
0.1	0.9	199	12.7	139	10.1	81	6.6
0.3	0.7	155	16.1	108	12.3	63	7.8
0.5	0.5	110	19.5	77	14.5	45	9.0
0.7	0.3	66	22.9	46	16.7	27	10.2
1.0	0	0	28	0	20	0	12

Note: for C* = 0 CP = WP
for C* = 1.0 CP = FC

Fig. 4-2. The management allowed deficit, MAD, and the critical point for irrigation, CP, as a function of the percentage of available water above the wilting point, WP, for three major soil types.



a) Soil Suction as a Function of SMC



b) Soil Suction as a Function of Available Soil Moisture Capacity, AMC

Fig. 4-3. Retention curve for various types of soils.

For known soil properties (FC, WP), the calculation of MAD provides the soil moisture content and consequently, the soil moisture stress can be determined from a known retention curve. The soil moisture stress is commonly used as an indicator to determine the irrigation date.

c. Relationship between yield and soil moisture stress.

To obtain a reasonable or optimal yield, the soil moisture is not allowed to drop as far as the permanent wilting point. Consequently, irrigation should take place at a moisture content level above wilting point. The recommended level for the critical point is dependent mainly on the crop and its growth stage. Usually, recommended levels of soil moisture stress are given in terms of the fraction of available water above the wilting point (C*) that remains, or as the fraction that has been depleted (1-C*). Recommended maximum allowable moisture stress levels are used to determine the maximum allowable moisture deficiency for optimal yields (Table 4-1).

Unfortunately, there are no specific functions that define the relationship between yield and soil moisture stress. Therefore, results such as those in Table 4-1 that are based on experimental results, are used as a guide for best crop response.

d. Evapotranspiration.

Water consumption by an irrigated field is a result of water loss directly from the soil surface (evaporation) and water loss from the plants (transpiration). The total water loss from an irrigated field as a result of soil evaporation and plant transpiration is known as evapotranspiration. The evapotranspiration of an irrigated field is a function of:

Table 4-1. Soil water suction at which water should be applied for maximum yields of various crops grown in deep, well drained soil, fertilized and managed for maximum production (from Taylor, 1965).

Crop	Soil Suction, Bars
	Vegetative Crops
Alfalfa	1.50
Beans (snap, lima)	0.75 - 2.00
Cabbage	0.60 - 0.70
Canning peas	0.30 - 0.50
Celery	0.20 - 0.30
Grass	0.30 - 1.00
Lettuce	0.40 - 0.60
Tobacco	0.30 - 0.80
Sugar cane	0.25 - 0.30
Sweet corn	0.50 - 1.00
	Root Crops
Onions, early	0.45 - 0.55
Onions, bulbing	0.55 - 0.65
Sugar beets	0.40 - 0.60
Potatoes	0.30 - 0.50
Carrots	0.55 - 0.65
Broccoli, early	0.45 - 0.55
Broccoli, postbud	0.60 - 0.70
Cauliflower	0.60 - 0.70
	Fruit Crops
Lemons	0.40
Oranges	0.20 - 1.00
Deciduous fruit	0.50 - 0.80
Avocadoes	0.50
Grapes, early	0.40 - 0.50
Grapes, mature	1.00
Strawberries	0.20 - 0.30
Cantaloupe	0.35 - 0.40
Tomatoes	0.80 - 1.50
Bananas	0.30 - 1.50

NOTE - The soil suction can be used with the soil retention curve (e.g., Fig. 4-3) to obtain C*, which is the fraction of the available soil moisture capacity, AMC, at which irrigation should occur.

(i) meteorological factors,

(ii) nature of crop and its canopy, and

(iii) crop growth stage and the drought resistance for each stage.

Since the actual evapotranspiration, ET_a, depends on many crop properties which are difficult to measure and define theoretically, it is estimated from potential evapotranspiration, ET_p, which can be either measured or calculated theoretically.

The most common equation to estimate ET_a is given by:

$$ET_a = K \cdot ET_p \tag{4-7}$$

where ET_a = actual evapotranspiration from the irrigated field, ET_p = potential evapotranspiration, and K = a crop coefficient depending on the crop, stage of growth and soil suction. The potential evapotranspiration can be calculated by:

(i) Theoretical or empirical equations using various meteorological and climatic factors, or;

(ii) Direct pan evaporation measurements.

Expressing ET_a and ET_p by daily evaporation, the total amount of water consumed by the irrigated field between two successive irrigations is given by:

$$D_I = \sum_{i=1}^{T_I} ET_{ai} = \sum_{i=1}^{T_I} K_i ET_{pi} \tag{4-8}$$

or assuming K is constant during the interval

$$D_I = \sum_{i=1}^{T_I} ET_{ai} = K \sum_{i=1}^{T_I} ET_{pi} \tag{4-9}$$

where D_I = depth of water consumed during T_I days in mm, T_I = number of days between two successive irrigations, ET_{ai} and ET_{pi} = daily actual and potential evapotranspiration, respectively in mm/day.

The crop coefficient, K, is dependent on the stage of growth of the crop and the geographical location. Numerous experimental results have been utilized in establishing crop coefficients, K, for various crops in various locations and various stages of growth. Fig. 4-4 provides several typical examples, where the stage of growth is represented as a percentage of the total growing season.

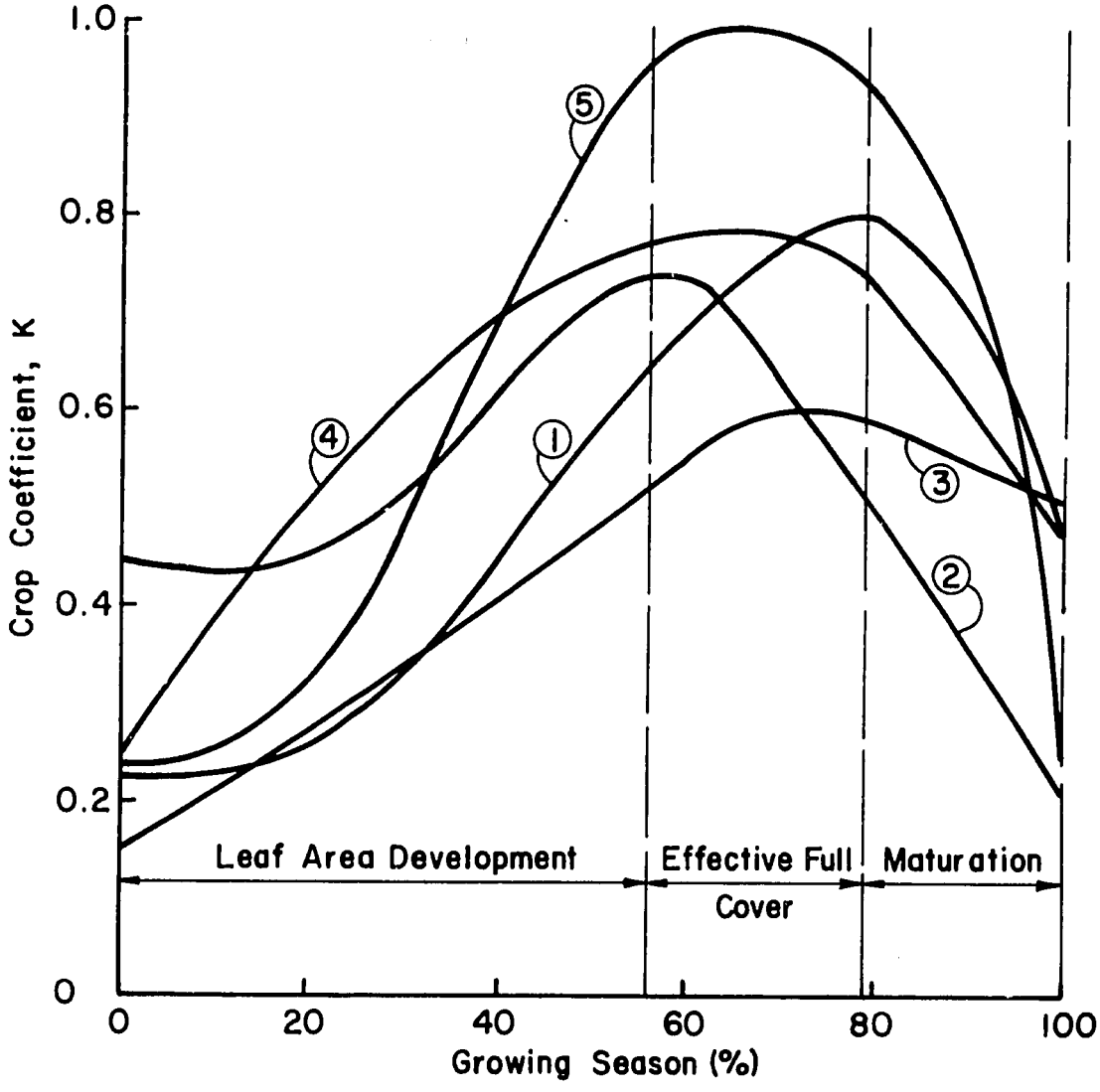
When experimental data for determining K are not available, the crop coefficient can be estimated by energy balance equations; for example, the equation suggested by Jensen, Robb and Franzoy (1970):

$$K = \frac{1 + \beta_o}{1 + \beta} \frac{(R_n + G)}{(R_{no} + G_o)} \tag{4-10}$$

where $\beta = A/ET_a$, R_n = net radiation, A = sensible heat flux to or from the air, G = sensible heat flux to or from the soil, where subscript $_o$ designates concurrent values for a reference crop in the immediate vicinity.

2. Procedure for determining the irrigation regime parameters.

The irrigation regime parameters for an individual application are concerned with the date and the depth of application. A qualitative approach is based on human sensing and identifying the proper time for irrigation by correlating various soil, crop and climatic performance parameters to the crop demand. Feeling the soil dryness, watching for plant color as a measure of stress, counting days since last irrigation, etc., are among the most qualitative activities in human sensing and identification of irrigation needs. Although, in some individual cases, such a procedure may be efficient and successfully applied, in general it leads to many improper decisions, such as irrigating too



1. Summer sorghum
2. Winter wheat
3. Spring cotton
4. Summer peanuts
5. General

Fig. 4-4. Examples of crop coefficient as a function of stage of growth.

early or too late and with depths of application that are too low or too high; with the latter being the most frequent case. Procedures are needed for decisions that are based on other measured or calculated parameters. With the four main factors affecting irrigation date and depth of application (soil moisture content, soil moisture stress, yields as a function of soil moisture stress, and evapotranspiration) the determination of the irrigation date and depth of application is carried out by one of three common procedures.

a. Irrigation scheduling by soil moisture stress.

Determination of date and depth of application by soil moisture stress characteristics. To determine the date and depth of application the following information should be known:

(i) soil properties (FC, WP, γ_d);

(ii) retention curve;

(iii) recommended minimal soil moisture content, or stress, or optimal allowable soil moisture depletion; and

(iv) effective root zone depth, Z.

With this information, the management allowed deficit, MAD, is calculated as given by Eq. 4-6. The depth of application equals the management allowed deficit, MAD.

The soil moisture stress or moisture content is measured daily (starting at least several days before irrigation is expected) by any of the available methods (tensiometers or gypsum blocks for soil suction; gravimetric, neutron probes or gamma rays for soil moisture content). The time of irrigation is determined to be when the soil moisture stress or moisture content reaches the recommended level. To summarize, the date of the upcoming irrigation is calculated to take place when the

soil moisture content or stress drops to the recommended level, CP. The depth of application is equal to the soil moisture depletion at that level, which is also the calculated management allowed deficit, MAD.

b. Irrigation scheduling by evapotranspiration for date and soil moisture stress for irrigation depth.

In this procedure, the interval between two successive irrigations or the number of days until the upcoming irrigation is determined by evapotranspiration, while the depth of application is calculated in the same way as in procedure a (irrigation scheduling by soil moisture stress). The following information should be known:

(i) soil properties (FC, WP, γ_d);

(ii) retention curve;

(iii) recommended minimal soil moisture content, or stress; and

(iv) effective root zone depth, Z.

With the known information, the management allowed deficit, MAD, is calculated and determined by means of Eq. 4-6. The interval between the two successive irrigations is calculated by:

$$T = \frac{\text{depth of application}}{\text{daily average } ET_a} = \frac{MAD}{ET_a} \qquad (4\text{-}11)$$

where $ET_a = K\ ET_p$ (Eq. 4-7). ET_p is measured (pan evaporation) or calculated by any of the appropriate formulas. K is known by experiments, or calculated from energy balance equations. When the number of days before the next irrigation is to be determined with reference to any present time after the last irrigation has been terminated, the calculation is as follows. Estimate the remaining available moisture at the

present time by:

$$RAM = MAD - WD \tag{4-12}$$

where RAM = remaining available moisture (mm), MAD = management allowed deficit (mm) and WD = accumulated moisture depletion from last irrigation to present time (mm). WD can be determined by measuring the present soil moisture content (PMC) and calculated by:

$$WD = \frac{(FC - PMC)}{100} (1000\ Z\gamma_d) \tag{4-13}$$

where PMC is the present moisture content in percent by weight (all other dimensions as defined in Eq. 4-3). The evaluation of WD by soil moisture measurements is not accurate; therefore, it is recommended that WD be calculated by evapotranspiration as follows:

$$WD = \Sigma ET_a - \Sigma R_e \tag{4-14}$$

where ΣET_a = the sum of actual evapotranspiration from the end of last irrigation to the present time, ΣR_e = the sum of effective precipitation during the time from the end of the last irrigation to the present time. After the remaining available moisture (RAM) is calculated, the number of days to the next irrigation is given by:

$$N = \frac{RAM}{ET_a} \tag{4-15}$$

where N = number of days to the next irrigation from the present time, ET_a = predicted average daily evapotranspiration for the N coming days. ET_a can be calculated on the basis of past data, or as suggested by Jensen (1970) as an average for the three preceding days and the three forecast days. Note that for WD = 0 (just after one irrigation is terminated and the next coming irrigation is considered), RAM = MAD and consequently, $N = T_I = \frac{MAD}{ET_a}$.

c. Irrigation scheduling by soil moisture stress for date and evapotranspiration for irrigation depth.

For this method, the recommended minimal soil moisture content or stress should be known. The soil moisture content or stress is measured daily at least several days before irrigation. The time of irrigation is determined when the level of the soil moisture content or stress reaches the recommended level. The depth of application is calculated by (Eq. 4-8):

$$D_I = \sum_{i=1}^{T_I} ET_{ai} = \sum_{i=1}^{T_I} K_i ET_{pi} \qquad (4\text{-}16)$$

where T_I is the number of days between the irrigations. ET_p and K are obtained by calculations or direct measurements as discussed previously.

3. Summary.

The evapotranspiration cannot provide the sole source for both date and depth of application; therefore, the recommended critical point, CP, must also be known. Consequently, at least one term (date or depth) is determined by soil moisture stress and only the remaining term can be determined by evapotranspiration.

Three procedures for determining the preirrigation decisions are described together with the required data and the possible ways to obtain this data. Presently, the use of current techniques for estimating evapotranspiration is recommended for the determination of date and depth of the upcoming irrigation. Determination of the irrigation date on the basis of evapotranspiration (procedure b) and determination of the depth of application based on evapotranspiration (procedure c) are recommended and should be used where data and knowledge are available.

Chapter 5

EVALUATION OF THE PERFORMANCE OF THE SYSTEM--INDIVIDUAL APPLICATION

1. Introduction.

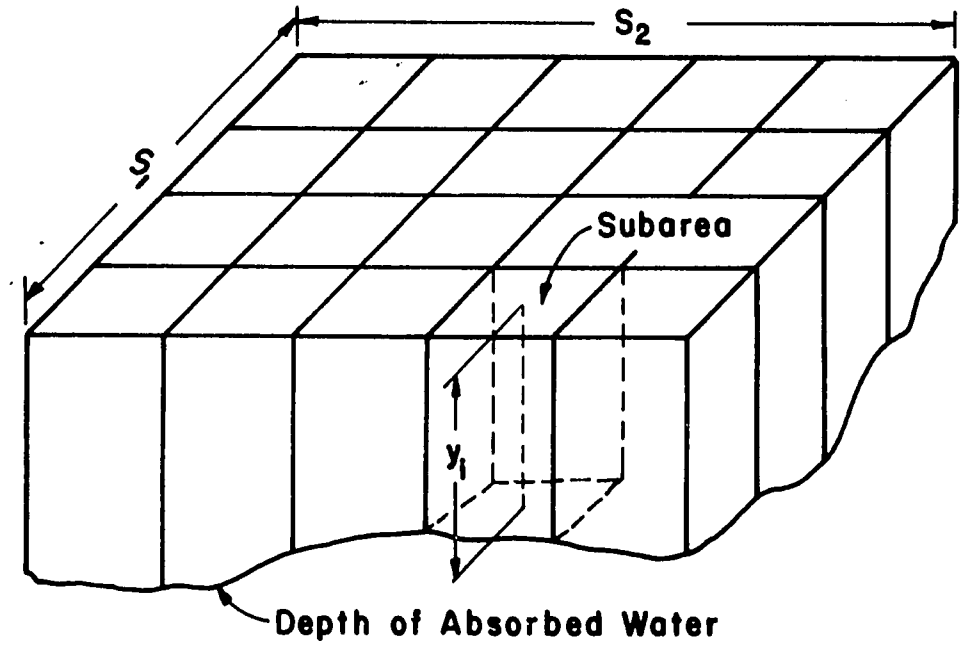
Evaluation of performance of an individual application is based on the water distribution profile after irrigation. Efficiencies and coefficients that describe the irrigation performance are derived directly from the water distribution profile. Based on these efficiencies, the irrigation performance is determined and classified into the appropriate performance categories and subsequently, the need for improvement and types of improvements are determined.

2. Water Distribution Profile After Irrigation.

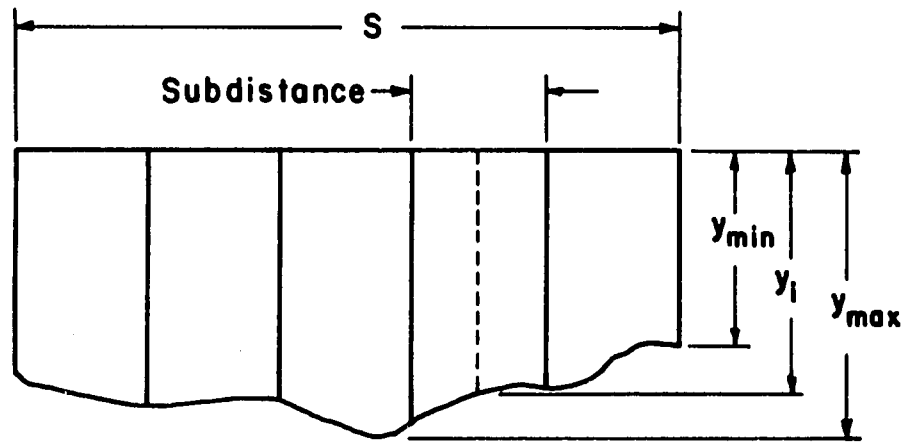
The water distribution profile after irrigation is expressed by one of three common methods.

a. Actual water distribution in the field.

The depth of water, y_i, is given for a set of points over the irrigated surface area. The set of points can be over the whole irrigated area (Fig. 5-1a) or along an axis representing the length or width of the irrigated field (Fig. 5-1b). The area of axis is usually divided into equal increments, although this is not necessary, and the chosen value of y_i is the average depth absorbed in that area. Graphical representation of the discrete water depths usually provides a continuous distribution of water depths. In either system, a maximum depth, y_{max}, and a minimum depth, y_{min}, may be identified. The main advantage of this representation is that the water depths are related to specific locations, and thus can also be related to the irrigation operating conditions (stream size, infiltration, spacing of sprinklers, pressures, soil variability, etc.).



(a) Depth of Absorbed Water Over an Irrigated Area



(b) Depth of Absorbed Water Along an Axis

Fig. 5-1. Actual field water distribution.

b. Cumulative frequency distribution of actual water depths and areas.

The actual depths of water are arranged as a cumulative distribution, where the abscissa is a fraction of the total area (Fig. 5-2). The cumulative frequency of actual depths of water can be represented in one of two ways:

(i) "less" depths (Fig. 5-2a) for which p fraction of the area received a depth of water of y_p or less and a k - p fraction of the area received a depth ranging between y_p and y_k.

(ii) "greater" depths (Fig. 5-2b) for which p fraction of the area received a depth of water of y_p or greater and p k fraction of the area received a depth ranging between y_k and y_p.

c. Cumulative frequency distribution of nondimensional water depths.

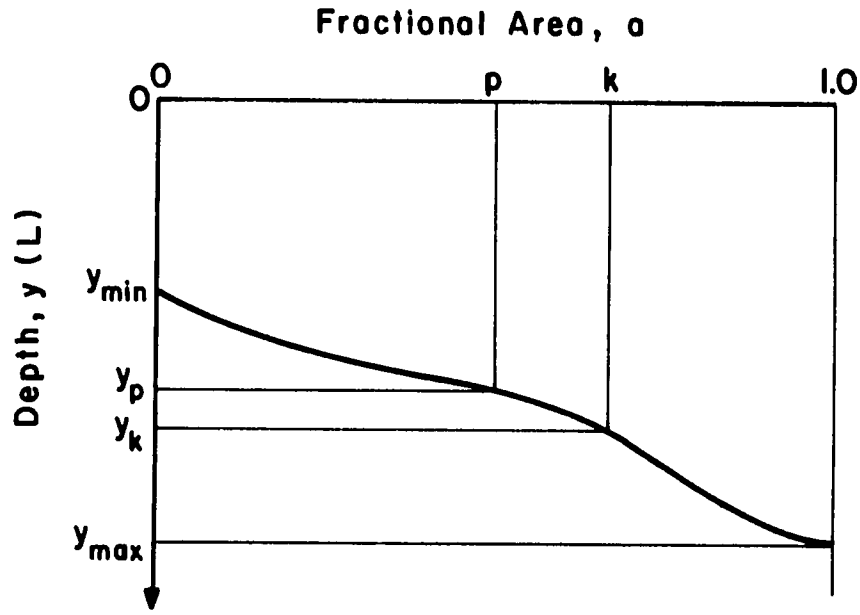
Each water depth, y_i, is transformed into a nondimensional water depth, $H_i (L\ L^{-1})$.

$$H_i = \frac{y_i}{\bar{y}} \tag{5-1}$$

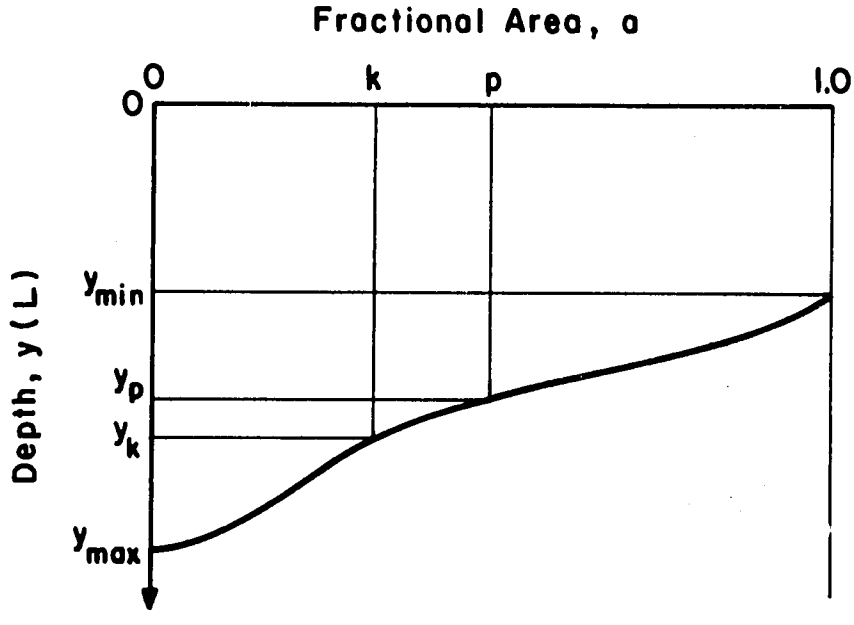
where y_i is the actual water depth (L), and $\bar{y}$ is the average water depth (L). The average water depth is

$$\bar{y} = \frac{1}{A} \sum_{i=1}^{n} A_i y_i, \tag{5-2}$$

where n is the number of water depth observations, A_i is the field area (L^2) associated with y_i and A is the total field area (L^2).



(a) "Less" Depth Frequency Distribution



(b) "Greater" Depth Frequency Distribution

Fig. 5-2. Cumulative frequency distribution of actual water depths.

The field area is also nondimensionalized by dividing by the total field area. That is,

$$a_i = \frac{\sum_{j=1}^{i} A_j}{A}, \qquad (5\text{-}3)$$

where a_i is the dimensionless area ($L^2\ L^{-2}$) equal to the sum of all dimensional areas, A_j (L^2) up to and including $A_i(L^2)$. It is usual to relate a_i's and H_i's in a "greater" frequency distribution (Fig. 5-3). This type of representation of depths and areas will be referred to as a Water Distribution Profile (WDP).

3. Parameters related to the water distribution profile.

Each water distribution profile, no matter what its method of representation, can be described by a set of parameters. These parameters can be defined in terms of water volumes or in terms of water depths. These depths may be dimensional or nondimensional. The system of symbols used in this work are described below.

a. Scheme for symbols.

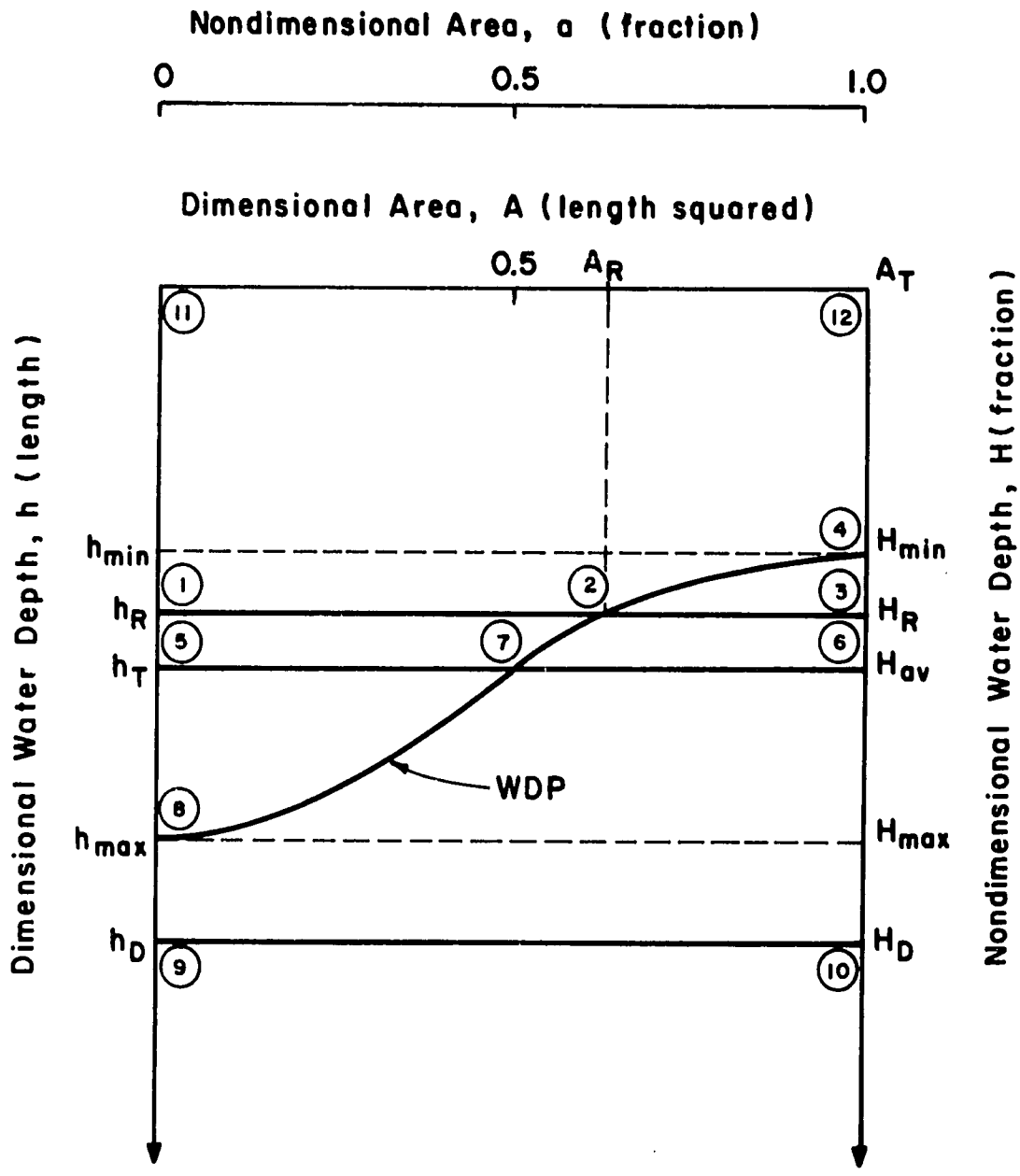
The scheme for designating water quantities and depth is as follows:

(i) The symbol A_T (L^2) is reserved for the area of the field;

(ii) Actual infiltrated depths, at points in a field, are designated by the letter y, with or without a subscript, as described below;

(iii) Volumes of water are designated with capital letters (R, T, etc.);

(iv) Derived dimensional depths, determined by dividing a volume by the field area, are given the letter h, with or without a subscript, as described below;



B = 2, 4, 3, 2

C = 7, 2, 4, 6, 7

D = 9, 11, 12, 10, 9

E = 1, 8, 7, 2, 1

R = 1, 11, 12, 3, 1

F = 5, 8, 7, 5

T = 8, 11, 12, 4, 8 = 5, 11, 12, 6, 5

W = 8, 9, 10, 4, 2, 7, 8

$T = F + R - B$

$T = D - W$

$H_T = y = H_F + H_R - H_B$

$H_T = H_D - H_W$

Fig. 5-3. Definition sketch for symbols.

(v) Dimensionless depths, determined by dividing the dimensional depth by the mean depth ($\bar{y}$) are identified by the letter H, with or without a subscript, as described below (these dimensionless depths may be derived from actual infiltrated depths, such as y's, or from volumes which have been converted to depths, such as h's.

b. Symbols related to volumes (dimension of L^3) (refer to Fig. 5-3).

B = volume of deficient water after an irrigation, measured from the required depth, h_R.

C = volume of deficit (or excess) water after an irrigation, in relation to the mean depth applied. (Note that C = B when R = T.)

D = volume of water delivered to the irrigated area, including field runoff, evaporation and wind losses.

E = volume of water which infiltrated beyond the required depth, h_R.

F = volume of water which infiltrated beyond the average depth, $\bar{y}$.

R = volume of available root zone water storage at the time of irrigation (i.e., the requirement).

T = volume of water absorbed in the irrigated area.

W = volume of water which was delivered to the irrigated area but was not absorbed by it.

c. Symbols related to derived dimensional depths.

h_B = volume of deficient water after an irrigation, divided by the area irrigated = B/A_T.

h_C = volume of deficient water after an irrigation measured from the mean depth, $\bar{y}$, divided by the area irrigated = C/A_T.

h_D = volume of water delivered to the irrigated area, divided by the area irrigated = D/A_T.

h_E = volume of water that infiltrated beyond the required depth, h_R, divided by the irrigated area = E/A_T.

h_F = volume of water that infiltrated beyond the average depth, $\bar{y}$, divided by the irrigated area = F/A_T.

h_R = volume of available root zone water storage at the time of irrigation, divided by the area irrigated = R/A.

h_T = volume of water absorbed in the irrigated area, divided by the area irrigated = $T/A_T = \bar{y}$.

h_W = volume of water that was delivered to the irrigated area but was not absorbed by it, divided by the irrigated area = W/A_T.

d. Symbols related to nondimensional depths.

H_{av} = mean infiltrated depth divided by the mean infiltrated depth = 1.

H_B = $h_B/\bar{y}$.

H_C = $h_C/\bar{y}$.

H_E = $h_E/\bar{y}$.

H_F = $h_F/\bar{y}$.

H_{max} = maximum depth infiltrated divided by the mean depth infiltrated = $y_{max}/\bar{y}$.

H_{min} = minimum depth infiltrated divided by the mean depth infiltrated = $y_{min}/\bar{y}$.

H_R = average requirement divided by the mean depth (i.e., the available root zone water storage divided by the product of the mean depth infiltrated and the area irrigated) = $h_R/\bar{y}$.

H_T = $h_T/\bar{y}$ = 1 (= H_{av}).

e. Symbols related to infiltrated depths.

$\bar{y}$ = average depth infiltrated.

y_{max} = maximum depth infiltrated.

y_{min} = minimum depth infiltrated.

The nondimensional water distribution profile (WDP) has some features that should be noted. First, there is a minimum value of H, H_{min}, and a maximum value, H_{max}, corresponding to y_{min} and y_{max}, respectively. There is also an average value, H_{av}, corresponding to $\bar{y}$ which is always numerically equal to 1. Finally, there is a value, H_R, that corresponds to the quantity of available root zone water storage at the time of irrigation. These values are shown on Fig. 5-3. The area below the water distribution profile (WDP) and above H_{av}, and the area below H_{av} and above the WDP are, by the definition of the mean, equal. They are, respectively, H_F $[=F/(A_T\bar{y})]$ and H_C $[=C/(A_T\bar{y})]$. The values H_B and H_E are, respectively, the areas below the WDP and above H_R, and the area below H_R and above the WDP. They are equivalent, respectively, to $B/(A_T\bar{y})$ and $E/(A_T\bar{y})$. These are equal if and only if $H_R = H_{av}$.

A water distribution profile can also be plotted in terms of dimensional depths and areas, similar to that of Fig. 5-2. The water volumes that are derived from the dimensional water distribution profile are as follows:

$$T = \int_0^{A_T} y \, d\alpha, \tag{5-4}$$

where α is a dummy variable.

$$B = h_R (A_T - A_R) - \int_{A_R}^{A_T} y \, d\alpha \tag{5-5}$$

where h_R is the average requirement (i.e., R/A_T) and A_R is the area of the field that receives the requirement or more.

$$E = \int_{o}^{A_R} y \, d\alpha - A_R h_R \tag{5-6}$$

The above relationships and the dimensional water distribution profile both indicated that the following holds,

$$T - E = R - B \tag{5-7}$$

4. Efficiencies describing irrigation performance.

The efficiency and distribution of an individual irrigation can be described through the measurement of four independent quantities. Three efficiencies and one distribution parameter will be defined in terms of these four quantities.

a. Storage efficiency, E_s.

This parameter is the fraction of the available root zone water storage (at the time of irrigation) that is filled by the irrigation.

$$E_s = \frac{R - B}{R} = 1 - \frac{B}{R} = 1 - \frac{h_B}{h_R} = 1 - \frac{H_B}{H_R} \tag{5-8}$$

where R is the available root zone water storage (L^3) at the time of irrigation, and B is the available root zone water storage (L^3) after the irrigation has occurred. This is a measure of the adequacy of the irrigation.

b. Deep percolation efficiency, E_p.

This parameter is the fraction of the total water absorbed in the irrigated area which contributes to filling the available root zone water storage (at the time of irrigation). It is a measure of the water which is lost to deep percolation.

$$E_p = \frac{R - B}{T} = \frac{h_R - h_B}{h_T} = H_R - H_B \tag{5-9}$$

where T is the total quantity of water (L^3) applied to the field that infiltrated into the soil.

c. Delivery efficiency, E_d.

This parameter is the fraction of the water delivered to the irrigated area which is absorbed by the soil through infiltration. It is a measure of the water that is lost to factors other than deep percolation, i.e., the losses to runoff (even if collected by a tail-water reuse system), wind drift, evaporation, etc.

$$E_d = \frac{D - W}{D} = \frac{T}{D} = \frac{h_T}{h_D} = \frac{H_T}{H_D} \tag{5-10}$$

where W is all water lost (L^3) during an irrigation except that due to deep percolation, and D is the total quantity of water (L^3) delivered to the field.

d. Distribution uniformity, U_d.

This parameter is the fraction of the total water absorbed in the irrigated area that contributes toward filling the root zone or is lost to deep percolation. Although it is not immediately obvious, it will be shown later that this is a measure of the distribution of water over the field by the irrigation, and so this term will be called the distribution uniformity, U_d.

$$U_d = \frac{T - C}{T} = 1 - \frac{C}{T} = 1 - \frac{h_C}{h_T} = 1 - \frac{H_C}{H_T} \tag{5-11}$$

where C is the volume of deficit (or excess) of infiltrated water after an irrigation, in relation to the mean depth applied. In equation form,

$$C = \frac{A_T}{2n} \sum_{i=1}^{n} \left| y_i - \bar{y} \right|, \tag{5-12}$$

where y_i is the depth of absorbed water representative of the one n-th of the irrigated field and $\bar{y}$ is the mean of the n absorbed depths in the field. A_T is the total irrigated area.

A more common distribution measure is Christiansen's (1942) uniformity coefficient, U_{cc}, which is often expressed as

$$U_{cc} = 1 - \frac{\sum_{i=1}^{n} \left| y_i - \bar{y} \right|}{n\,\bar{y}} \tag{5-13}$$

This is equivalent to

$$U_{cc} = \frac{T - 2\,C}{T} \tag{5-14}$$

so

$$U_d = \frac{1 + U_{cc}}{2} \tag{5-15}$$

An examination of Eqs. 5-8 through 5-15 indicates that a total of five quantities (R, T, D, B, and C) were used to define the four parameters. However, since C is a special case of B, mathematically four quantities are sufficient to define the four parameters.

5. Analysis of irrigation performance measures.

The performance of an irrigation is determined by simultaneous analysis of the four quantities defined in Eqs. 5-8 through 5-15. Some typical cases that emphasize the need for a simultaneous analysis are the following:

a. Given a water distribution with $h_R \geq h_{max}$ (Fig. 5-4a). In this case, $E_p = 1$ because no deep percolation can exist. However, $E_s < 1$, which means that an inadequate irrigation has been applied. If the inadequacy is excessive, then the irrigation is not satisfactory.

b. Given a water distribution with $h_R \leq h_{min}$ (Fig. 5-4b). In this case, $E_s = 1$ because the entire requirement has been met. However, $E_p < 1$ because deep percolation occurs. If this is excessive, the irrigation is not satisfactory.

c. Given a water distribution with $h_{min} < h_R < h_{max}$ (Fig. 5-4c). In this case, E_p and E_s are both less than 1, but they may each be satisfactory. In such a case, both the level of adequacy and the deep percolation are acceptable.

The above examples can be extended to include an analysis of the distribution uniformity, U_d, and the delivery efficiency E_d.

The above discussion suggests a special case in which R = T, which means that the average requirement is equal to the average application. In such a case, B = C, and so

$$E_p = E_s = U_d \quad (R = T) \tag{5-16}$$

The above result can be generalized. It is noted from Eqs. 5-8 and 5-9 that for a <u>given</u> irrigation (that is, one having a specific distribution of y values) U_d and E_d take on specific values, and both E_s and E_p can be defined in terms of the dimensionless requirement (i.e., H_R).

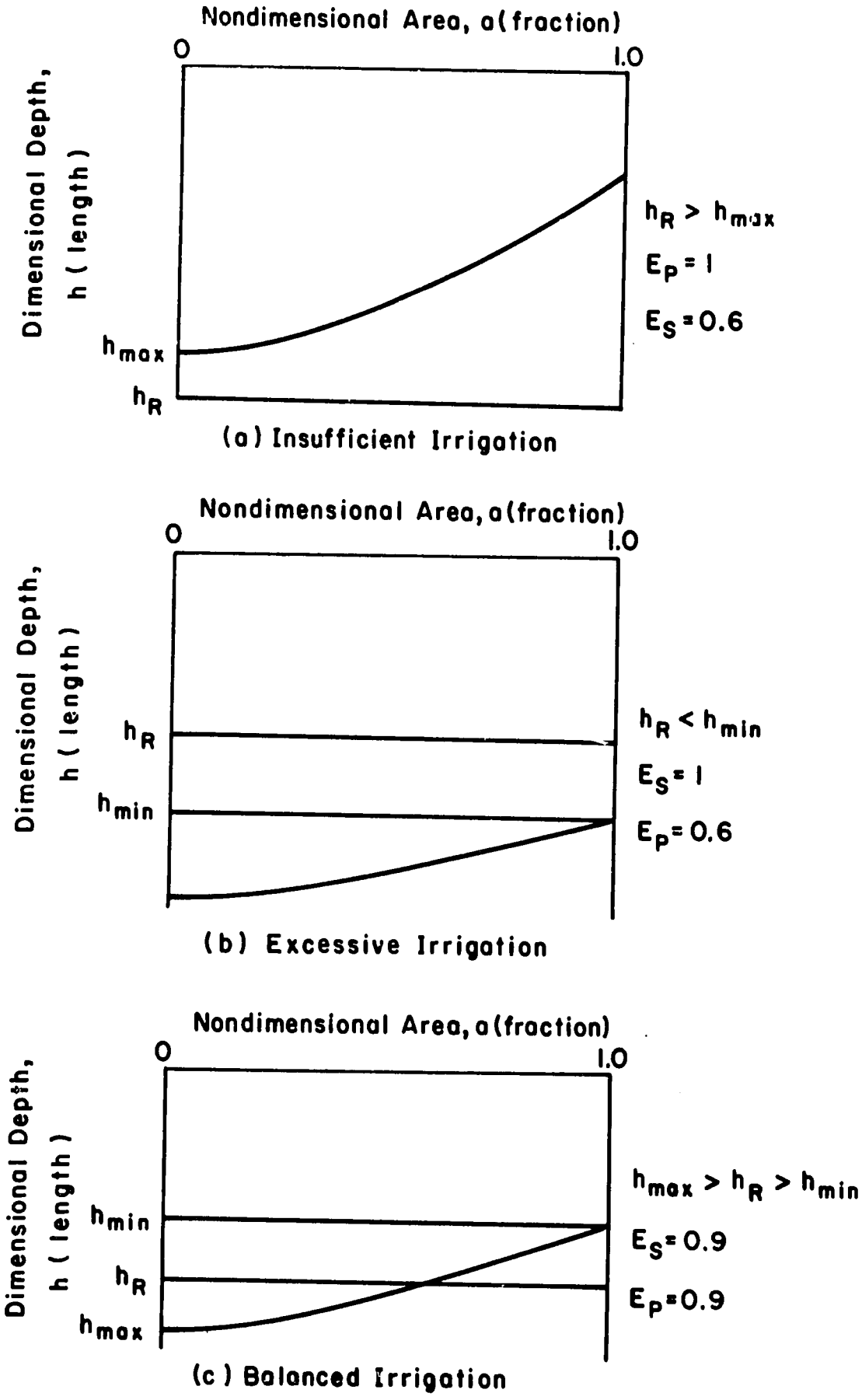


Fig. 5-4. Three possible water distribution profiles.

That is, E_p and E_s are dependent also on the required depth. Extending the example given in Fig. 5-4, E_s and E_p can be described as functions of the required depth. An example of this is shown in Fig. 5-5. The specific case plotted is for a normal distribution with $U_d = 0.9$ ($U_{cc} = 0.8$). Although the values of H theoretically range from $-\infty$ to $+\infty$, they have been arbitrarily cut off at 0.225 (H_{min}), corresponding to $E_s = 0.999$ and 1.775 (H_{max}), corresponding to $E_p = 1.000$.

Expressing E_p and E_s as a function of H_R (Fig. 5-5) enables further analysis of the irrigation performance as follows:

a. For a given water distribution profile, analysis of cases such as those given in Fig. 5-4 can be conducted.

b. For a given water distribution profile, both E_p and E_s can be determined simultaneously for any required depth of application, H_R.

c. For a given water distribution profile, the range of H_R can be determined so that a required combination of E_p and E_s is satisfied (for example, the range of H_R so that E_p and E_s will be greater than 0.85).

d. For a given water distribution profile, the effect of deviations in H_R, on the irrigation performance, can be determined.

e. If the given water distribution cannot be changed easily (due to stream sizes, dimensions, etc.) then the depth of application can be determined so that the irrigation performance is satisfactory. The interval between irrigations is then determined according to the depth of application, and the known daily crop requirement.

6. Acceptable levels of performance parameters.

The question arises as to what value of H_R (or h_R) is acceptable for a given irrigation. In Fig. 5-5, a minimum allowable value of E_s and

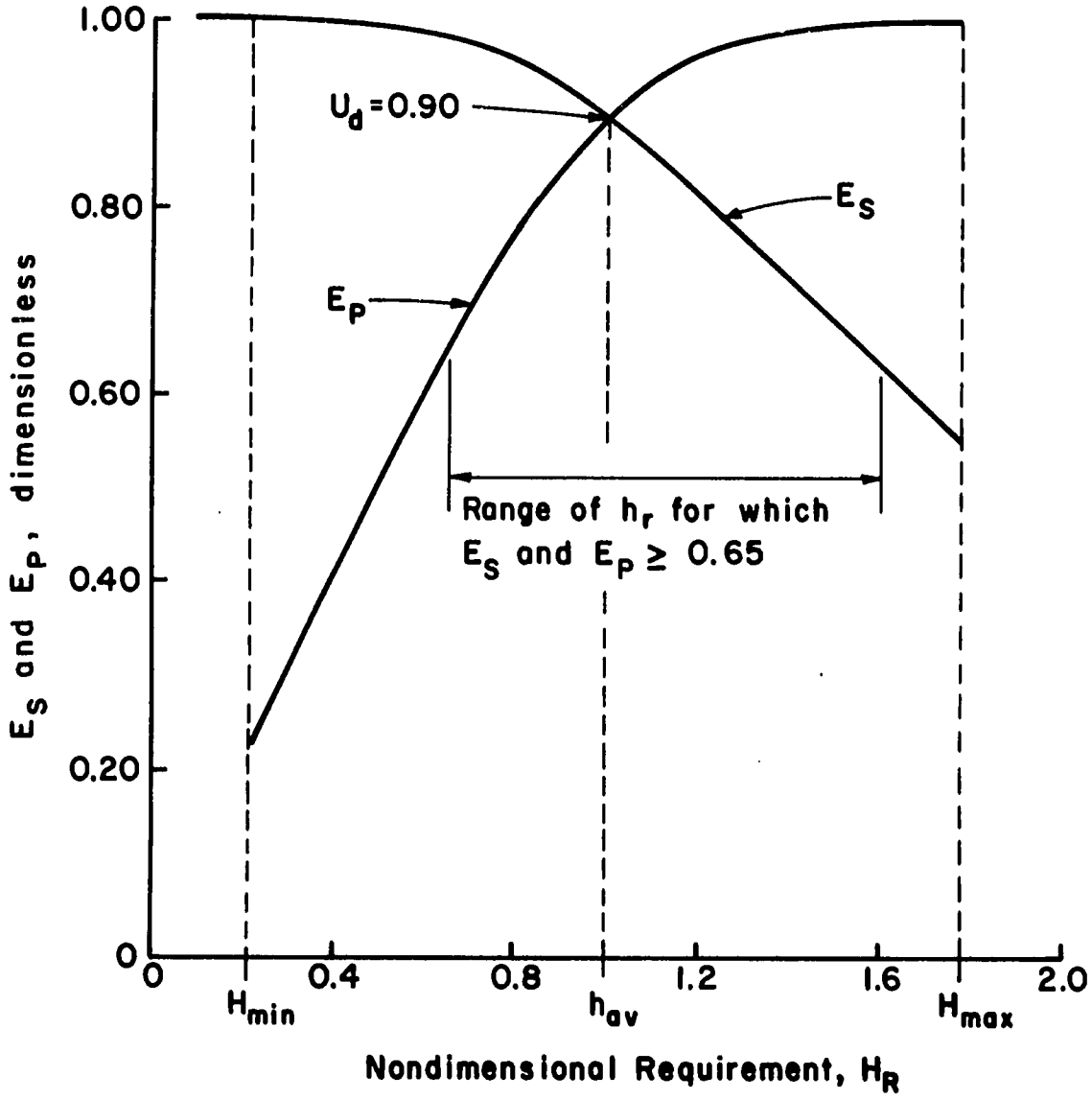


Fig. 5-5. Water storage efficiency (E_s) and deep percolation efficiency (E_p) as a function of H_R for a nearly normal distribution with U_d = 0.9 (U = 0.8).

E_p of 0.65 has been shown, and if this were accepted, the values of H_R could range from 0.66 to 1.56. This means that the average application would be between 0.66 and 1.56 times the requirement. Such a choice is entirely arbitrary, and a more comprehensive treatment of this would consider an objective function, Q_o, which included the three efficiencies and the distribution parameter, each with an associated weighting factor. Thus,

$$Q_o = C_1E_s + C_2E_p + C_3E_d + C_4U_d. \qquad (5\text{-}17)$$

The C_i's are weighting factors giving the relative importance of the four performance parameters. The coefficients C_1 and C_4 are directly related to yield and water quantity. The coefficient, C_2, is related to deep percolation and its cost (leaching of nutrients, waste of water and contribution to ground water problems). The coefficient, C_3, is related to the cost of water that is delivered but does not arrive on the field, or runs off the field. Unfortunately, specific values of C_i's are unknown in general, and although they may be set for specific crops, even this has not yet been done. Nevertheless, current knowledge of irrigation may suggest general ranges differing between the various sets of conditions. Three ranges of each have been listed--excellent, satisfactory and unsatisfactory. From this, six categories of irrigation performance can be developed. These are independent of the delivery efficiency, and apply only to absorbed water.

a. Category I.

The parameters E_s, E_p, and U_d are in the excellent range. No improvement in water distribution or depth of application is required.

b. Category II.

The efficiencies, E_s and E_p, are in the excellent range, but the water distribution is out of this range. The implication is that the water distribution should be improved for the same level of average application.

c. Category III.

The parameters, E_p and U_d, are in the excellent range, but the parameter E_s is less than excellent. This implies that the required amount of water, on the average, has not been absorbed by the soil. To meet the requirement, the average depth of application must be increased.

d. Category IV.

The parameters E_s and U_d are in the excellent range and the parameter E_p is out of this range. This implies that the distribution is good, and that the requirement has been absorbed by the soil. However, an excess amount of water has been absorbed. The total water applied should be reduced.

e. Category V.

The parameter U_d is not in the excellent range, and the parameters E_s and/or E_p are not in the excellent range, and $E_s < E_p$. Improved irrigation performance requires an improvement in distribution, and since E_s is deficient, then additional water must be applied in conjunction with the improved distribution.

f. Category VI.

The parameter U_d is not in the excellent range, and the parameters E_s and/or E_p are not in the excellent range and $E_s > E_p$. Improved performance requires that the distribution be improved, and that the total application be decreased.

The delivery efficiency, E_d, is then associated with each of the categories, to provide an additional level of performance. Fig. 5-6 summarizes the six categories, showing the relationships between the performance parameters, and the changes required to improve the irrigation, for each category.

7. Summary.

The performance of an irrigation system can be fully described in terms of four parameters--the fraction of the absorbed water that is stored in the root zone, the fraction of the requirement that is met, the fraction of the delivered water that is absorbed, and the distribution of the water over the field. Most of the commonly used terms can be derived from these four parameters. If limits of acceptability for these parameters can be established, then the analysis of an irrigation system can be conducted to evaluate the irrigation performance and to determine how the irrigation can be improved (i.e., improve distribution, reduce or increase total application).

The steps required to evaluate the performance of an individual application are:

a. Determine the water depths applied to the irrigated area and represent the water distribution profile in one of the three methods as described in Figs. 5-1, 5-2 and 5-3.

b. Determine the total amount of water that was delivered to the irrigated area, D, and the total amount of water absorbed by the irrigated area, T. This also provides the quantity of water lost to the outside of the field, W.

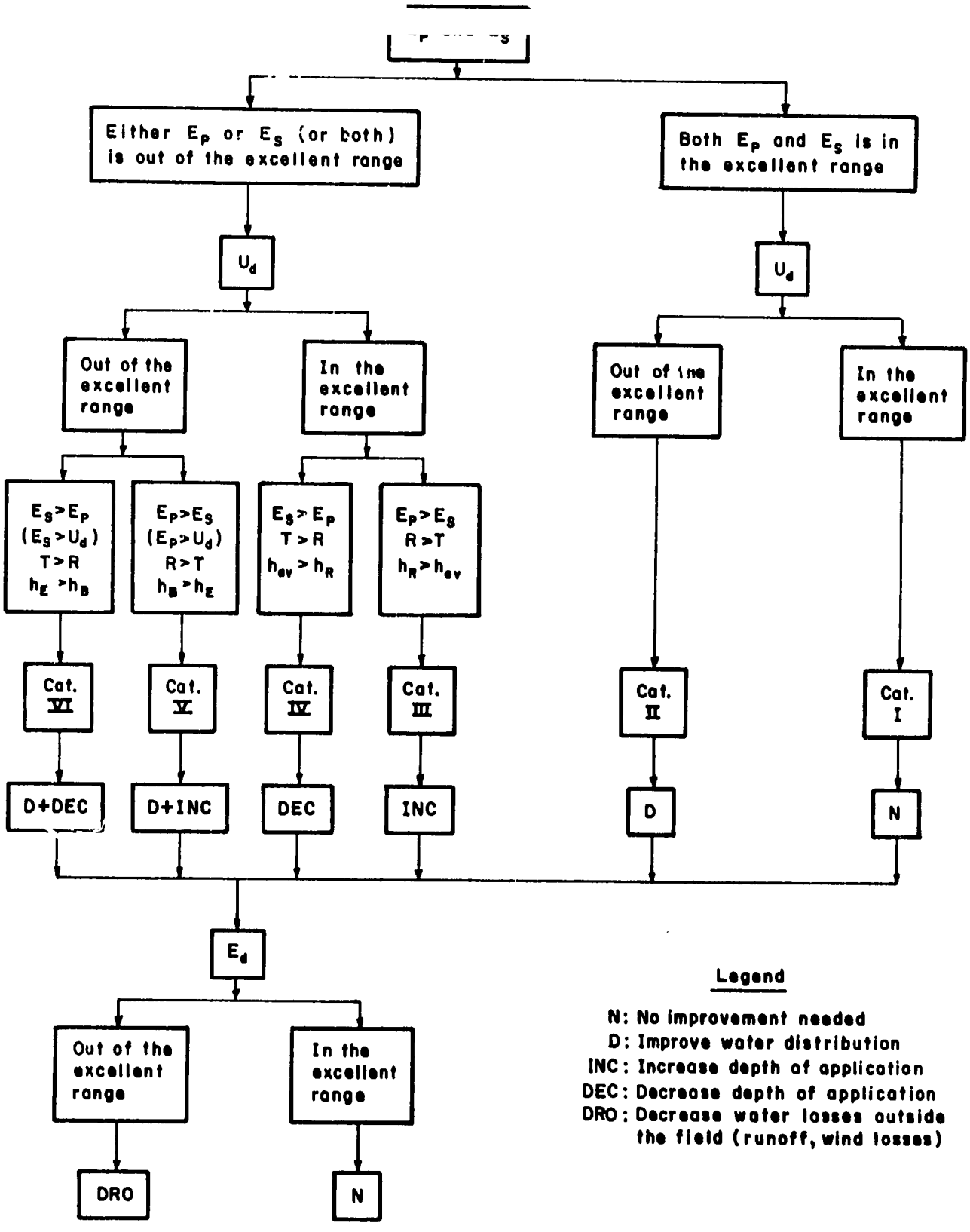


Fig. 5-6. Categories of irrigation performance for individual application.

c. For a given required depth of application, h_R, and using the water distribution profile, calculate the deficiency, h_B, and then (with the already known T, D, R, B) calculate the four efficiencies, E_p, E_s, E_d, and U_d (Eqs. 5-8 to 5-15).

d. For various values of the required depth, h_R, calculate the deficiency, h_B and the resulting E_p and E_s. Represent E_p and E_s as a function of h_R (Fig. 5-5). The effect of deviations in the required depth of application, on the irrigation performance, can be determined.

e. According to the levels of efficiencies, determine the irrigation category and the required improvement from Fig. 5-6.

Chapter 6

EVALUATION OF THE PERFORMANCE OF AN OVERALL IRRIGATION SEASON

The parameters for evaluating the performance of an overall irrigation season are crop yield, water efficiencies, and environmental and economic results. The levels of these parameters can be determined directly. However, for improvement decisions, the performance of the irrigation regime and the individual application should be considered.

1. Evaluation of seasonal irrigation performance by crop yield.

The obtained yield is one of the major indicators for defining irrigation performance. Although the yield of an irrigated field is greatly dependent on other factors apart from irrigation (climate, fertilizer, cultivations, socio-economics, etc.), it can be related to the irrigation performance, especially for known and given levels of the other factors. However, it should be noted that the yield may only partially reflect the effects of irrigation.

The evaluation of the performance of an overall irrigation season with respect to yield is associated with the simultaneous analysis of two terms:

a. The ratio of the actual yield per unit of area to the expected yield per unit of area:

$$C_a = \frac{Y_{act}}{Y_{exp}} = \frac{Y_{uoa}}{\bar{Y}_{uoa}} \tag{6-1}$$

b. The ratio of the actual yield per unit of water to the expected yield per unit of water.

$$C_v = \frac{Y_{uow}}{\bar{Y}_{uow}} = \frac{Y_{uoa}/V}{\bar{Y}_{uow}} \tag{6-2}$$

in which Y_{uoa} = actual yield per unit of area; $\bar{Y}_{uoa}$ = expected yield per unit of area; V = water quantity associated with the actual yield; Y_{uow} = actual yield per unit of water; and $\bar{Y}_{uow}$ = expected yield per unit of water. The expected yield per unit of area, and per unit of water is based on one of two common sources:

a. The average yield normally obtained in the area studied or in other areas with similar conditions (Fig. 6-1a) is given by:

$$\bar{Y}_{uoa} = \frac{1}{n} \times \sum_{i=1}^{n} (Y_{uoa})i \qquad (6\text{-}3)$$

in which (Y_{uoa}) = yield per unit of area for the ith season, and n = number of seasons observed. The expected yield per unit of water is given by:

$$\bar{Y}_{uow} = \frac{1}{n} \times \sum_{i=1}^{n} \frac{(Y_{uoa})_i}{V_i} \qquad (6\text{-}4)$$

in which V_i = applied water quantity in the ith season.

b. Optimal potential yield. Optimal potential yield data can be obtained from local experiments or by adaptation of relevant data from other sources. Yield is expressed by a function relating the yield to the seasonal total applied quantity of water (Fig. 6-1b).

The expected yield per unit of water is the ratio of the expected yield per unit of area (taken as the yield in the level somehow less than the maximum) to the water quantity associated with it:

$$\bar{Y}_{uow} = \frac{\bar{Y}_{uoa}}{\bar{V}} \qquad (6\text{-}5)$$

in which $\bar{V}$ = water quantity associated with the expected yield per unit of area, $\bar{Y}_{uoa}$.

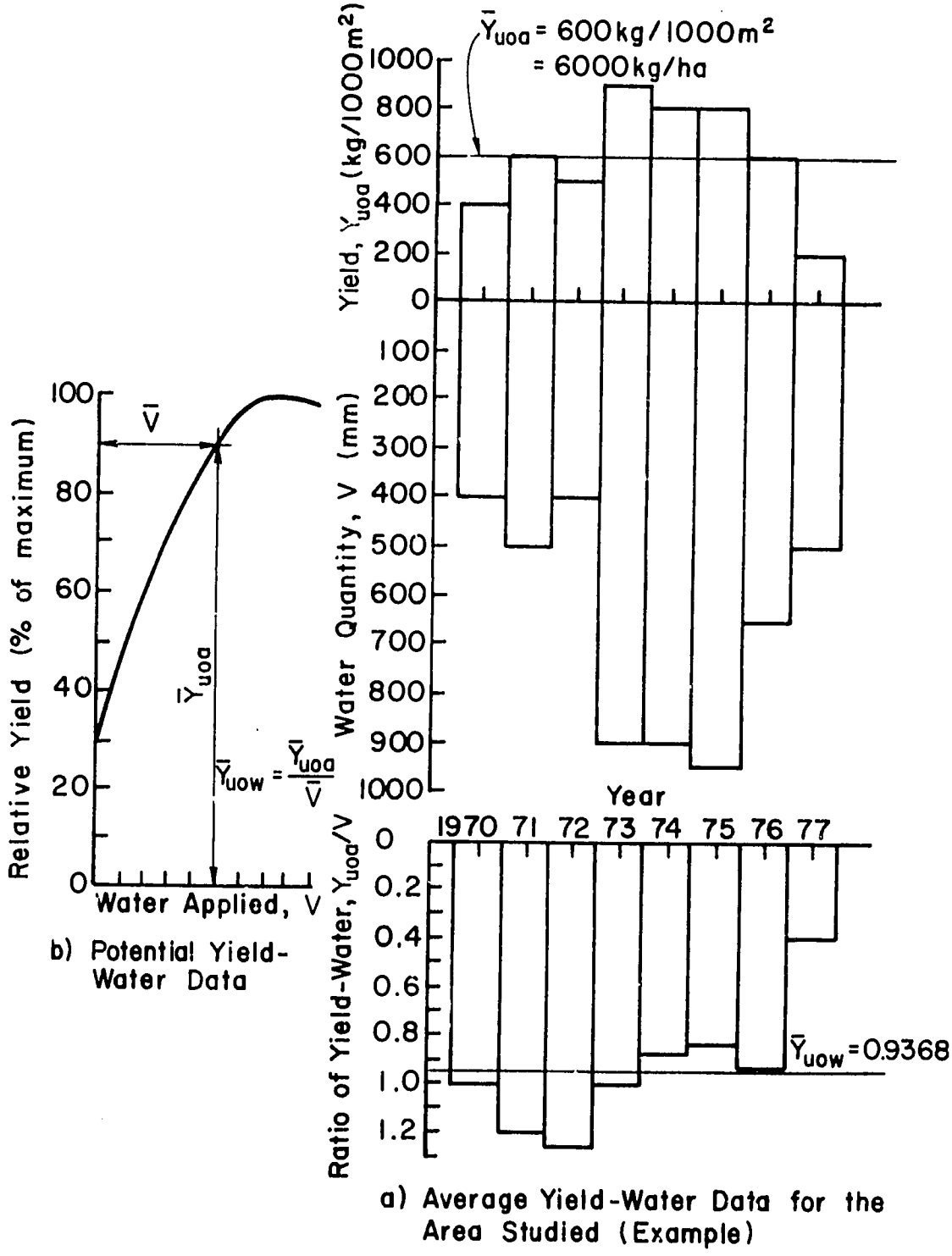


Fig. 6-1. Example of yield as a performance parameter.

Evaluation of the overall irrigation season is related to the simultaneous analysis of C_a and C_v (Eqs. 6-1, 6-2). The various possible combinations are illustrated in Table 6-1 and Fig. 6-2 and may be grouped into four categories:

Table 6-1. Yield categories as levels of the parameters of the performance of seasonal irrigation.

	$C_a \geq 1$	$C_a < 1$
$C_v \geq 1$	I	II
$C_v < 1$	III	IV

Category I: Where $C_a \geq 1.0$ and $C_v \geq 1.0$. Actual yields are higher than the expected ones for both units of area and water. The overall irrigation season is regarded satisfactory and this category is considered the most desirable.

Category II: Where $C_a < 1$ and $C_v \geq 1.0$. Actual yields are lower than the expected, although yields per unit of water are higher than expected. Consequently, the water use is rather efficient, but the total depth of application is too low, resulting in lower yields.

Category III: Where $C_a \geq 1$ and $C_v < 1$. Actual yields are higher than the expected ones, but actual yields per unit of water are low. The higher yield is a result of sufficient water but inefficient application. Additional

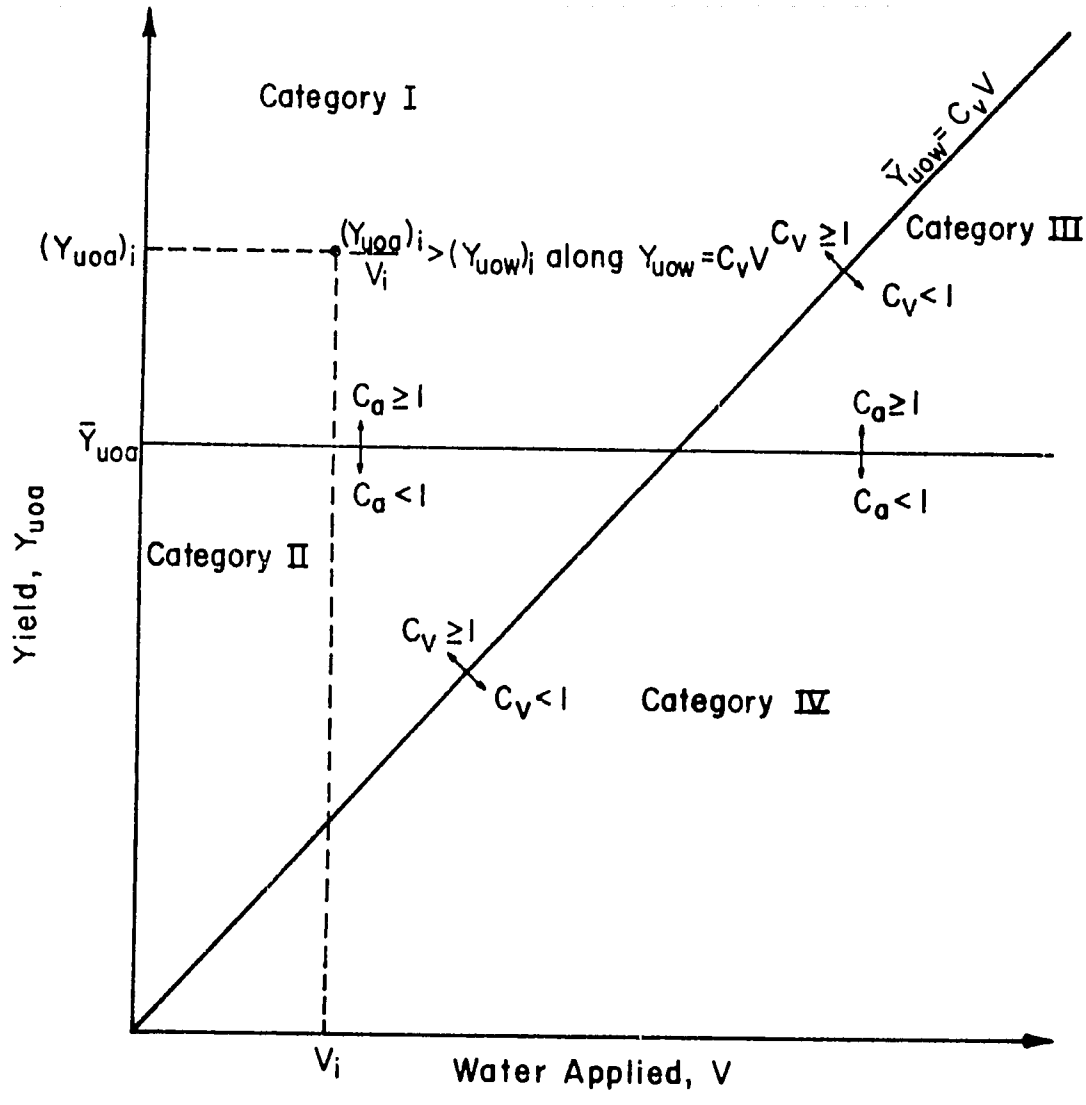


Fig. 6-2. Yield categories as parameters of the performance of seasonal irrigation.

relatively large quantities of water result in relatively small increases in yield; however, those yields are higher than the expected. This category may be an economically satisfactory result where high yields are the goal.

Category IV: Where $C_a < 1$ and $C_v < 1$. Large quantities of water result in yields lower than the expected, and water is used inefficiently Results are most unfavorable and yields indicate poor irrigation performance.

To illustrate the use of the concepts outlined, the following example (Table 6-2 and Fig. 6-3) is given. Average yields and water used obtained in a certain area under study are given. The optimal potential yield is known as 7800 kg/ha with 600 mm of irrigation and the optimal potential expected yield per unit of water, $Y_{uow} = \frac{7800}{600} = 13.0$ kg/ha-mm. Yield ratio values (C_a and C_v) for each year are calculated and the ratios arranged for both average and potential expected yield (Table 6-2 and Fig. 6-3).

From this example, it can be noted that since the optimal potential yields (Y_{uoa} and Y_{uow}) are higher than those based on average yield obtained, the seasonal performance is poorer when it is related to the potential yields. For example, data of 1971 (Y_{uoa} = 6000 kg/ha and V = 500 mm) result in a satisfactory performance, Category I, when local yield and water data are used. However, the same data (1971) will result in a poor performance, Category IV, when optimal potential yield and water data are used.

Table 6-2. Example of seasonal evaluation of irrigation performance based on yields.

Year		1970	1971	1972	1973	1974	1975	1976	1977	Average 1970-77	Expected yield per unit of area $\bar{Y}_{uoa}$	Expected yield per unit of water $\bar{Y}_{uow}$
Average yield, Y_{uoa}, obtained in the area (kg/ha)		4000	6000	5000	9000	8000	8000	6000	2000	6000		
Water used, V, for irrigation (mm)		400	500	400	900	900	950	650	500	650		
$Y_{uoa}V$		10.0	12.0	12.5	10.0	8.88	8.42	9.23	4.0	9.368		
Based on average yield	C_a	0.66	1.0	0.833	1.5	1.333	1.333	1.00	0.33			
	C_v	1.06	1.281	1.334	1.06	0.948	0.899	0.985	0.352		6000	9.368
	Category	II	I	II	I	III	III	III	IV			
Based on optimal potential yield	C_a	0.512	0.769	0.641	1.154	1.026	1.026	0.769	0.256			
	C_v	0.769	0.923	0.961	0.769	0.683	0.648	0.71	0.308		7800	13.0
	Category	IV	IV	IV	III	III	III	IV	IV			

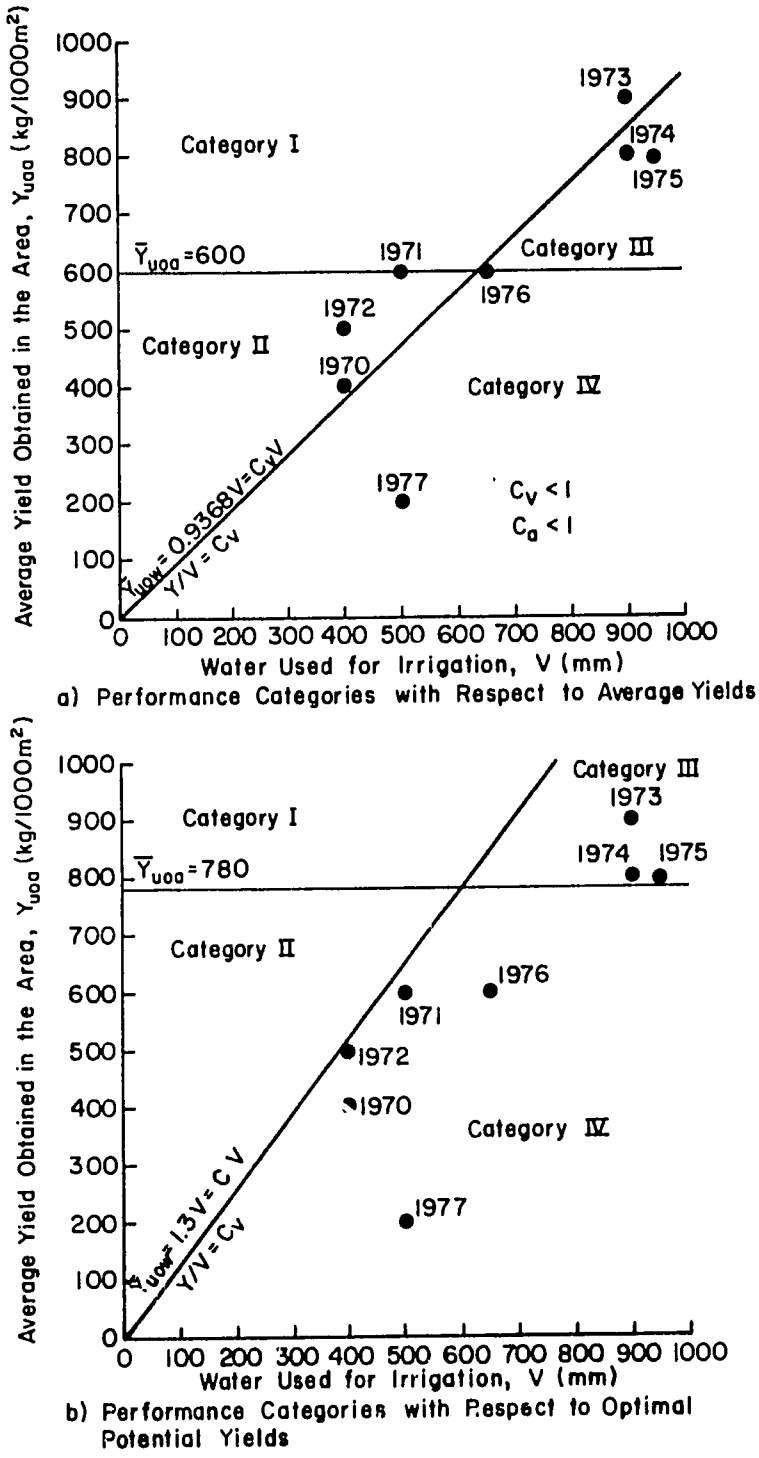


Fig. 6-3. Example of seasonal irrigation performance categories with respect to yield.

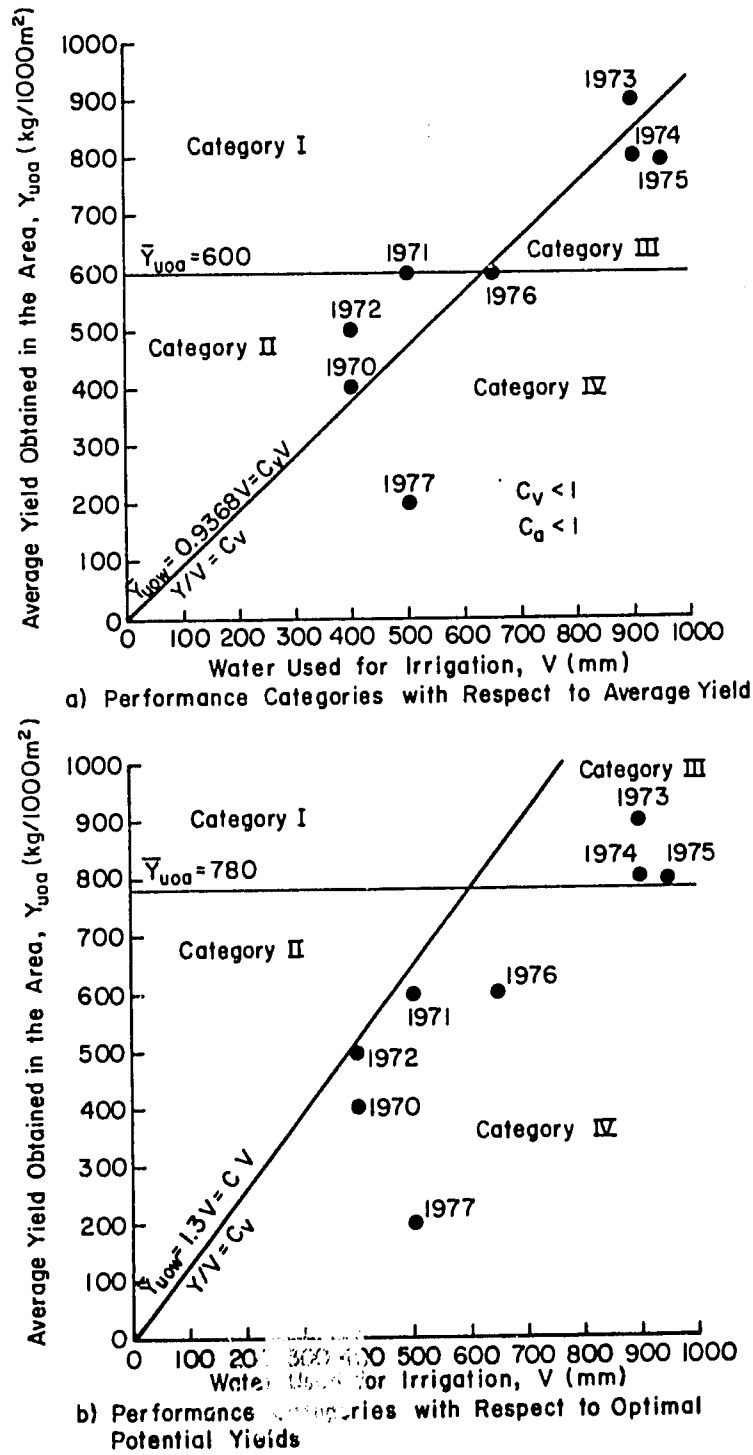


Fig. 6-3. Example of seasonal irrigation performance categories with respect to yield.

2. Evaluation of overall irrigation season performance by water application efficiencies.

Efficiency of water application is defined by:

$$IE = \frac{V_c}{V_d} \tag{6-6}$$

in which IE = efficiency of water application, V_c = amount of water beneficially consumed, and V_d = amount of water delivered.

The efficiency of water application can be applied to various sections of the irrigation system (the irrigated field, farm ditches, delivery system, reservoirs, etc.).

Since the layout of the on-farm irrigation system differs from case to case, a general definition of the possible efficiencies is given. When dealing with seasonal irrigation, all water quantities are seasonal quantities.

The on-farm irrigation system can be schematically described by a set of successive sections, where each section is characterized by the quantity of water which is delivered as compared with water losses (Figs. 6-4 and 6-5).

For the ith section of the irrigation system, the section efficiency can be defined as:

$$E_i = \frac{V_{ci}}{V_{di}} \tag{6-7}$$

and the water losses can be defined as:

$$L_i = V_{di} - V_{ci} \tag{6-8}$$

where V_{ci} = amount of water beneficially consumed in the ith section, and V_{di} = amount of water delivered into the ith section. (Definition of

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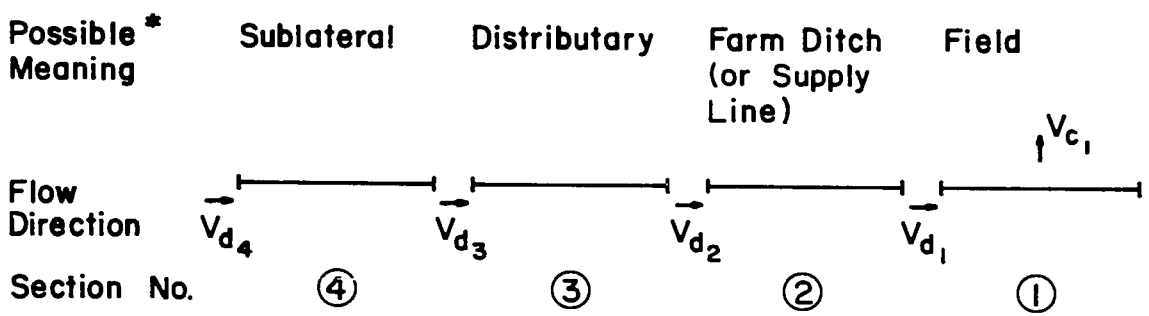

* For More Details See: "International Commission on Irrigation and Drainage" (1978)

Fig. 6-4. Schematic description of irrigation system sections.

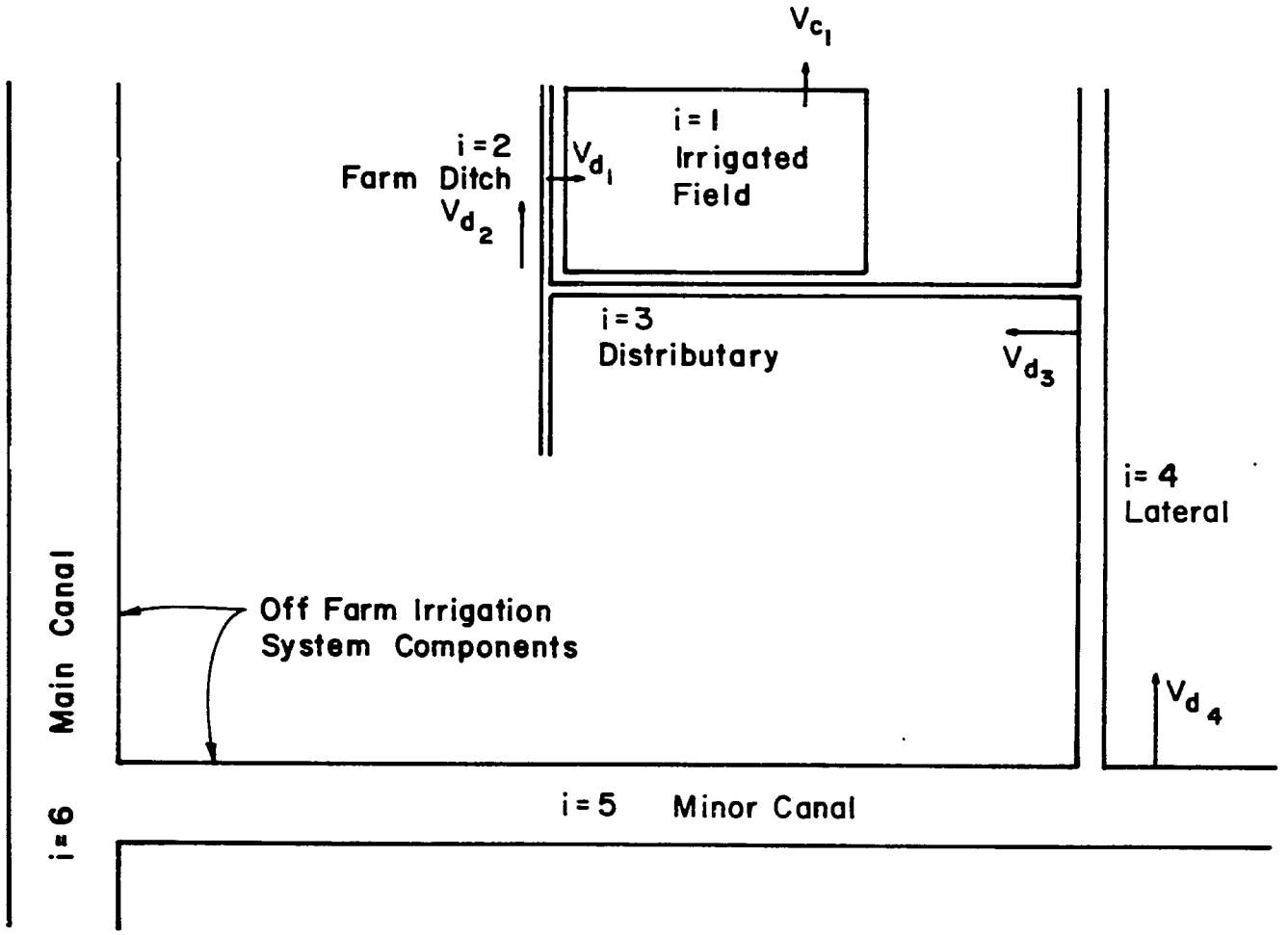

Fig. 6-5. Typical on-farm irrigation system sections.

the system sections and efficiencies is according to ICID, 1978, where possible, otherwise, similar definitions are derived.)

It should be noted that the first section (going upstream) is the irrigated field for which the beneficially consumed amount of water is the amount of water needed to maintain the soil moisture above the minimum level required for the crop.

The other sections of the irrigation system ($i \geq 2$) deal with the water delivery components (pipes, ditches, canals) for which:

$$V_{ci} = V_{di-1} \qquad i \geq 2 \qquad (6\text{-}9)$$

It is often useful to define an efficiency term that relates the water quantity consumed in the ith section to the water delivered into the jth section where $j > i$. This efficiency is denoted by:

$$E_{ij} = \frac{V_{ci}}{V_{dj}} = \frac{V_{di-1}}{V_{dj}} \qquad j > i \qquad (6\text{-}10)$$

From Eq. 6-10, it can be seen that:

$$E_{ij} = \prod_{i=1}^{j} E_i \qquad j > i \geq 2 \qquad (6\text{-}11)$$

The water losses from the j section to the ith section are expressed by:

$$L_{ij} = V_{dj} - V_{ci} = \sum_{i=1}^{j} L_i \qquad j > i \qquad (6\text{-}12)$$

While $i = 1$ is defined as the irrigated field, the other sections of the on-farm irrigation system are determined for each specific situation.

The water application efficiencies, as parameters of the performance of seasonal overall irrigation, are further analyzed in relation to the sections comprising the system as shown in Fig. 6-5.

Efficiency in the irrigated field is the field application efficiency (E_1) given by:

$$E_1 = \frac{V_{c1}}{V_{d1}} \qquad L_1 = V_{d1} - V_{c1} \tag{6-13}$$

where E_1 = field application efficiency, V_{c1} = volume of water beneficially consumed by the crop, V_{d1} = volume of water delivered to the field and L_i = water losses during or shortly after application. L_1 is usually composed of: runoff, deep percolation, evaporation during application, and wind drift.

Efficiency in the farm ditch (E_2) is given by:

$$E_2 = \frac{V_{c2}}{V_{d2}} = \frac{V_{d1}}{V_{d2}} \qquad L_2 = V_{d2} - V_{c2} = V_{d2} - V_{d1} \tag{6-14}$$

in which E_2 = farm ditch efficiency, L_2 = water losses in farm ditch, and V_{d2} = volume of water delivered into farm ditch. L_2 is usually composed of: seepage, bank leakage, channel spills, evaporation, and evapotranspiration by phreatophytes.

The consumed quantity in the field (section 1) in relation to the delivered quantity in the farm ditch (section 2) is the farm efficiency given by: (From Eqs. 6-10, 6-11).

$$E_{1,2} = \frac{V_{c1}}{V_{d2}} = E_1 \times E_2 \tag{6-15}$$

and the water loss in sections 1 and 2 from Eq. 6-12 is given by:

$$L_{1,2} = V_{d2} - V_{c1} = L_1 + L_2 \tag{6-16}$$

Efficiencies for the other sections (i = 3, 4) are defined similarly and presented in Fig. 6-6 as portions of the whole system.

For any efficiency $E_{i,j}$ where i=1 (efficiency that includes field application efficiency E_1) it is better to have the highest field

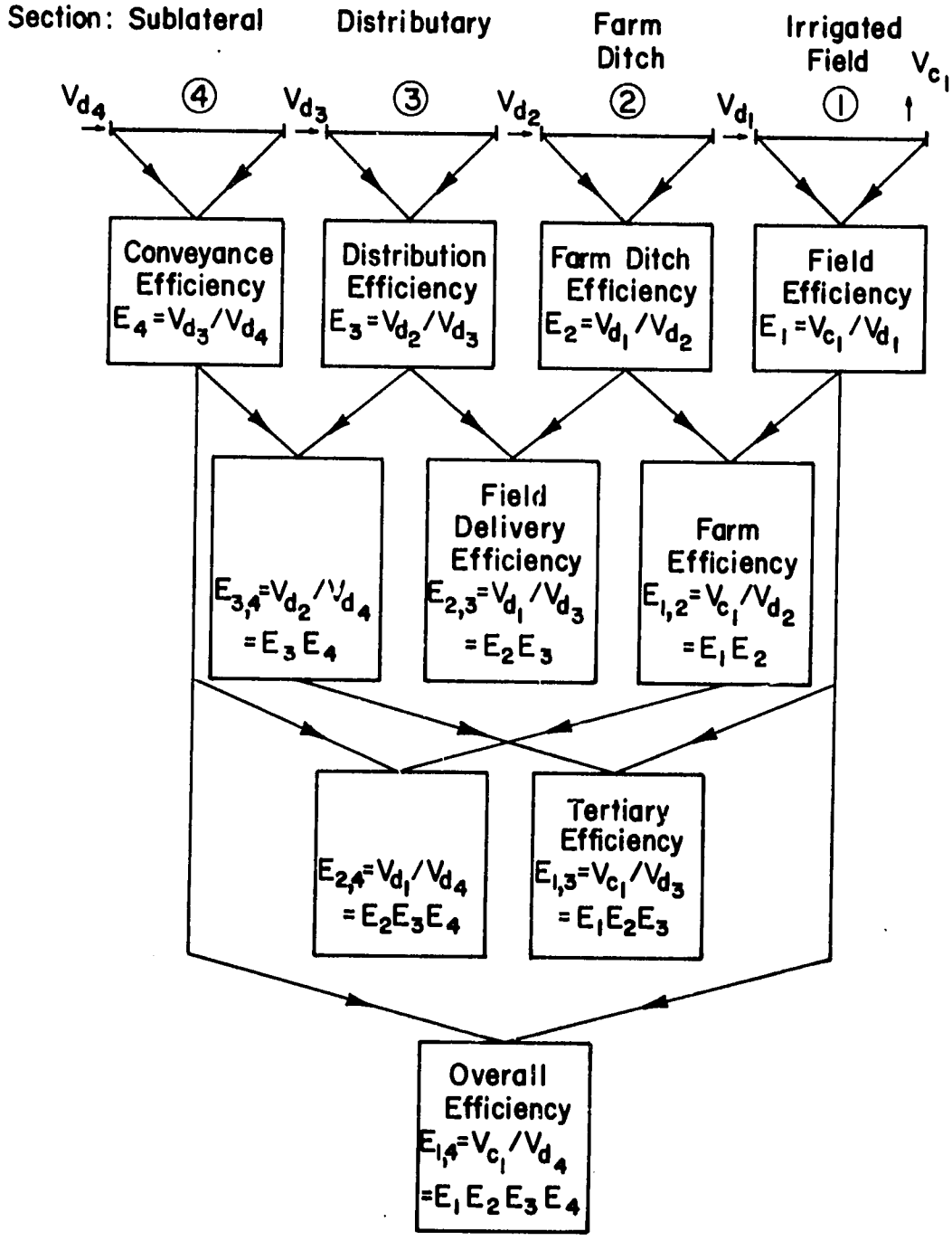

Fig. 6-6. Water application efficiencies for an on-farm irrigation system with four sections.

efficiency E_1 for a given E_{ij}, since it is accepted that E_1 is more important than any other efficiency, $E_{i>1}$. This can be demonstrated by the following example, where the analysis is concerned with two sections: the field and the farm ditch. The farm efficiency, $E_{1,2}$, is 0.667 for both cases:

Case 1: with $V_{c1} = 80$, $V_{d1} = 100$, $V_{d2} = 120$; $E_1 = 0.8$, $E_2 = 0.889$, $E_{1,2} = 0.667$

Case 2: with $V_{c1} = 80$, $V_{d1} = 90$, $V_{d2} = 120$; $E_1 = 0.89$, $E_2 = 0.75$, $E_{1,2} = 0.667$

Case 2 can be regarded as more favorable ($E_1 = 0.89$) although $E_{1,2}$ representing overall field efficiency is equal for both cases ($E_{1,2} = 0.667$).

When evaluating the seasonal irrigation efficiencies, the need for improvement can be defined in relation to the section where the efficiency is low. With on-farm irrigation, the improvement of the field application efficiency is associated with the individual irrigations as described in Chapter 5.

3. Evaluation of overall irrigation season performance by environmental effects.

The overall irrigation season performance can be related to environmental features such as the soil and groundwater.

a. Soils.

The following soil aspects should be considered.

(i) Soil erosion. Soil erosion is mainly a result of water flow over the soil surface, but may also be caused by wind. Irrigation systems such as surface methods and sprinkler are most likely to cause erosion.

(ii) Infiltration rate. The infiltration rate may decrease during the irrigation season to an unfavorable level. Formation of an impermeable crust (mainly in silty textures) decreases the water infiltration. Irrigation is likely to produce a surface crust which requires special treatment to allow further irrigation.

(iii) Deterioration of soil structure. The soil structure near the surface layer is subject to deterioration as a result of water movement over the surface. Impact of water drops also creates deterioration of the soil surface.

(iv) Salinity and nutrient balance. Irrigation may increase salinity levels by adding salts which are dissolved in the irrigation water. At the same time, the movement of the irrigation water may affect the soil nutrient balance by leaching required nutrients.

b. Groundwater.

The following groundwater aspects should be considered.

(i) Groundwater levels change and may rise with excessive irrigation, or lower where extensive pumping is required for irrigation.

(ii) Return flows from irrigated lands are likely to be one of the main sources of water pollution in both the groundwater and streams.

c. Weed and natural vegetation.

Irrigation encourages the spread of weeds by providing water for the natural vegetation.

4. Evaluation of overall irrigation season performance by level of economic inputs.

Evaluation of economic performance of an overall irrigation season refers to the economic inputs expressed in annual terms. The economic inputs expresses the actual cost required to maintain the irrigation at a given level.

The inputs of an on-farm irrigation system include capital investment and operating cost.

a. The capital investment for an irrigation system is represented by an annual cost allocated to equipment, installation and major land preparation.

b. Operating cost is mainly allocated to labor, minor land preparation, energy, and water costs.

Both costs of the capital investment and operation are expressed in annual cost terms and are added together to provide the total economic input.

These components are interrelated and may be at a high, moderate, or low level. On the basis of these three input levels, irrigation methods can generally be classified into various major groups such as in Table 6-3. For each system, the quantity and cost of these components determine the total annual costs, which are the basis for the evaluation of the irrigation performance.

Table 6-3. Relative economic inputs for some irrigation methods.

Economic component	Irrigation method				
	Sophisticated with high pressure (center pivot, traveling guns, etc.)	Sophisticated with moderate pressure (solid set, center pivots)	Movable with moderate pressure	Drip	Labor oriented (surface)
Equipment or land preparation	high	high	moderate	high	moderate
Labor	low	low	moderate	low	high
Energy	high	moderate	moderate	moderate	low

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