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IRRIGATION RETURN FLOW

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ABSTRACT

In irrigation practices, certain portion of the applied water, over and above the consumptive use, infiltrates into the ground to reach either an aquifer as deep percolation or to a nearby stream flow as inter flow. This contributory replenishment from irrigation is referred to as irrigation return flow. It includes the subsurface flow resulting due to excess percolation during irrigation together with the seepage from the conveying canal system. Excess percolation from the irrigated field itself accounts as much as 20% - 40% of the volume of water applied for irrigation. The various factors affecting the irrigation return flow are namely the amounts of water diverted at the canal head for the purpose of irrigation, the hydrogeologic properties of the soils in the irrigated field, the conveyance and irrigation application efficiencies, the season of the year and the period of time through which the irrigation had been practised. Return flows from irrigation constitute a minor fraction in the hydrologic accounting of a watershed. However, the return flow is of great significance to the agriculturalist as well as to the economist. Return flows can be a valuable source of water supply for irrigation to water scarced areas. Additional project lands can be irrigated using the return flow . To the economist, return flow becomes an important

element in planning the multipurpose use of water. In the present report, efforts have been made to study the return flow from irrigation and to understand the various factors affecting it. Efforts have been made to collect and review different methods of quantifying return flows from irrigation. Attention has been focussed on the analytical methods of return flow assessment and a few important case studies have been described.

1.0 INTRODUCTION

In the management of groundwater resources, man intervenes with the hydrologic cycle in order to achieve beneficial goals. This intervention takes the form of modifications imposed on the various components of the water balance. In context with the groundwater regime of the hydrologic cycle, the movement of water towards an aquifer takes place in the following ways:

i) Groundwater inflow through aquifer boundaries and leakage from overlying or underlying aquifers
ii) Natural replenishment (infiltration) from precipitation over the area
iii) Return flow from irrigation
iv) Artificial recharge
v) Seepage from influent streams

In the present review report, attention has been focused exclusively on the return flow from irrigation. Efforts have been made to highlight different methods of quantifying the irrigation return flow resulting from different methods of irrigation and the quality of the return flow.

1.1 Definition

In irrigation practice, certain portion of the applied water, over and above the consumptive use, infiltrates into the ground to reach either an aquifer as deep percolation or to a nearby stream as interflow. This contributory replenishment from irrigation is referred to as 'Irrigation Return Flow' (Jensen, 1983, Hurley, 1968). Irrigation return flow is estimated to amount to as much as 20% - 40% of the volume of water applied for irrigation. It includes the subsurface flow resulting due to the excess percolation during irrigation together with the seepage from the canal bed and banks including the leakage at canal structures. Although irrigation return flow includes the surface runoff reaching the nearby stream through natural or artificial drainage courses including waste way discharges during conveyance of irrigation water, however, these have not been taken into account in the present report.

1.2 Development of Return Flow

During the early years of irrigation practice, excessive quantities of water are usually diverted and conveyed to the fields. Large portions of the excess deliveries percolates to groundwater storage gradually raising the levels of water tables. Subsequently the high levels of water tables causes interflow towards natural surface drainage courses. However, these high groundwater tables also lead to development of salt problems and cause large water losses due to excessive evaporation and transpiration through non-useful vegetation. As a remedial measure, artificial drainage systems are constructed to reclaim the water-logged areas and prevent further damages to the cropped areas. These improvements lead to further increase in return flows.

1.3 Factors Affecting Irrigation Return Flow

As stated earlier, irrigation return flow may amount to as much as 20% to 40% of the volume of water used for irrigation. This amount reaching the aquifer as return flow depends on the following factors:

i) Season during which the return flow is determined:
It is observed that maximum rates of return flow occur during the summer and fall months following the periods of irrigation and minimum rates during the winter and spring months, preceeding the periods of irrigation.

ii) Conveyance and irrigation efficiencies:
The rates of return flow are observed to decrease with increases in the conveyance and irrigation efficiencies as higher efficiencies lead to lesser water losses consequently lesser quantities of return flows.

iii) Amounts of water diverted for irrigation:
It is observed that as the amounts of water diverted for irrigation (over and above the required), is increased there is a corresponding increase in the rates of return flow.

iv) Periods of years the lands have been irrigated:
Irrigation return flow also depends on the history of irrigation practices.

v) Hydrological properties of the soil:
The individual and bulk properties of the soil and

the structure of soil strata influence the rates of return flow significantly. The antecedent soil-moisture conditions in the irrigated lands and the existing conditions of salts adhering to the soil also have a characteristic influence on the rates of return flow. The first irrigation during the cropping season leads to less quantity of return flow (as the soil is dry) however, this increases with the number of applications of irrigated water.

1.4 Significance of the Irrigation Return Flow

Return flows constitute a valuable source of water supply for additional arable lands that otherwise could not be utilised in crop production. Unused irrigated water can be stored for use during the subsequent seasons for additional purposes like domestic water supply other than the irrigation. Additional project lands can be irrigated by the irrigation return flow. Apart from the above, assessment of irrigation return flow from various spatial distributions of applied irrigation systems facilitates the evaluation of the efficiency of the system. This not only helps in the identification of a most efficient irrigation system but also plays an important rôle in its design as well as in the operation stage.

The significance of water saving measures might be exemplified by the result of the detailed water balance survey of the Vaksh irrigation system performed before its construction. The survey indicated that only about 21% of the total water intake was actually utilized within the crop field the remainder being lost to the system according to, the following tentative distribution among the above sources (in percentage of total water intake of the system) (U.N.Report No.75-41586).

. Water losses within the delivery system	39%
. Unused bypass waters	15%
. Deep percolation from the crop fields	20%
. Tail water from the crop field	5%

2.0 DETERMINATION OF IRRIGATION RETURN FLOW

2.1 Water Balance Approach

The term 'Water Balance' for a system refers to the mass balance between the inflow, outflow and the storage terms appropriate to the given system. In applying the water balance technique to a particular problem, the boundaries of the system must be clearly delineated. In the present context, hydrologic balance can be ascertained for the saturated zone beneath the irrigated lands from which irrigation return flow is determined. The saturated zone is divided into N number of sections along the length of the irrigated system. The hydrologic balance for any section is given as (vide Khan, 1980)

$$\sum_{i=1}^{N} QI_i + (1-\alpha) QI_{ir} + QI_g \;-\; \sum_{i=1}^{N} QO_i + QO_g = \frac{\Delta v}{\Delta t}$$

in which, (in terms of average flow rates taken over the period Δt)

$\sum_{i=1}^{N} QI_i$ = the total inflow into the section through precipitation, seepage from rivers and streams, artificial recharge, etc

α = the irrigation efficiency over the section

QI_{ir} = the total quantity of water used for irrigation

QI_g = the ground water inflow from adjacent sections

$\sum_{i=1}^{N} QO_i$ = the total outflow from the section through pumpage, consumptive use,etc.

QO_g = the groundwater outflow to the adjacent sections

Δv = the change in volume of water within the section during time Δt.

The term $(1-\alpha)QI_{ir}$, irrigation return flow, can be determined if all other elements of the above hydrologic balance equation are known.

In principle return flow from irrigation as the net balance of the changes in the horizontal and vertical distribution of flow quantities can be found on the basis of mass balance principle where in all the changes in the physical parameters with time can be taken into account. However, this approach would rarely give reliable results since all errors in measuring outflow, inflow and changes in storage are reflected directly in the computed values of irrigation return flow. Of the various element of the water balance, the determination of rainfall, artificial recharge, quantities of irrigation water applied and the water pumped do not pose major problems. Phreatophyte consumptive use, subsurface inflow and outflow quantities are difficult to be determined. Unless the problem is treated at process level model, the quality and quantity aspects of irrigation return flow cannot be ascertained realistically.

2.2 Process Level Models

The principal hydrologic processes in an irrigation return flow system, illustrated in Figure 1, include transpiration, evaporation, infiltration redistribution, and root extraction (Walker, 1978). Associated with each of these processes are a number of chemical and biological transformations affecting the dissolved and adsorbed constituents in the soil. The process level models are of two types: (1) infiltration-redistribution, and (2) unsaturated soil solute chemistry and transport. Other contributions to irrigation return flows which might be categorized as process level topics, namely irrigation uniformity, conveyance seepage, and field tailwater are generally not modeled independently. However irrigation uniformity has been recognized recently as an important input to irrigation return flow simulations.

Root extraction, transpiration, and evaporation do not appear separately in these modelling efforts. Combined transpiration-evaporation can be determined from climatic conditions or evaluation of the porous media physics. Process level models by themselves have only marginal utility in evaluating irrigation return flow systems unless they are used in the fabrication of new subsystem or system models. In process level models deep percolation represents a major component of return flow. Analysis of deep percolation or leaching depends on either determining a root zone mass balance or simulating the infiltration-redistribution process. The first approach requires more data, is more

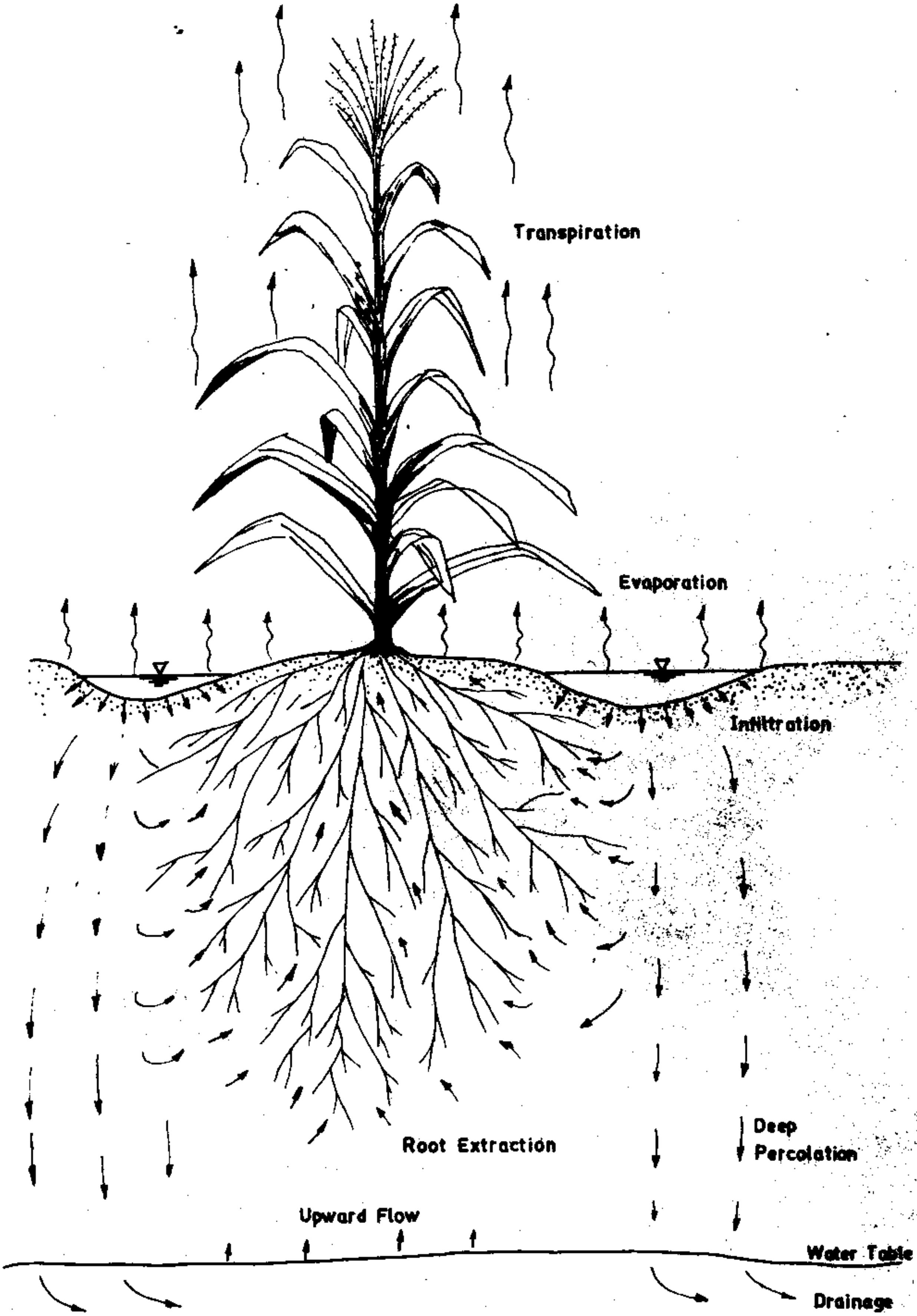


FIGURE 1 - SCHEMATIC PRESENTATION OF THE UNSATURATED ZONE IN AN IRRIGATED SYSTEM

applicable to large scale situations, and is often the most desirable. Evaluating infiltration-redistribution involves shorter time intervals, less data and yields a closer approximation to the actual event. Another point to be noted is that of the analysis of the chemical biological aspects of soils and soil solutes. Moisture flow is often better approximated by assuming steady-state conditions or that the transient nature may be represented by a series of steady-state conditions. In these cases, the quality aspects of modelling are somewhat independent of the moisture phase and can be accurately simulated by limiting the scope of the analyses. The output of a moisture flux simulation can be taken as input to chemical simulators thereby increasing the computational efficiency.

2.3 Subsystem Level Models

Subsystem level of modelling is defined as the combination of two or more process level simulations. The main subsystem for irrigation return flow studies is the field hydrology within the irrigated system itself. In a major watershed or river basin, there are other logical subsystems describing precipitation-runoff relations, reservoir operations, in-stream processes like dissolved oxygen behaviour, groundwater interflows. Within the irrigation system itself there may be a number of similar subsystems reflecting different soils, crops, and irrigation management practices.

Subsystem models vary in the scope and dimension of their mathematics. Some models deal with detailed treatments of a small part of the irrigated agriculture subsystem shown in Figure 1. Others are more macroscopic, large scale and time resolved treatments of the Figure 2 representation. The more detailed models involves basic physics and chemistry whereas the macroscopic approaches are generally mass conservation descriptions.

2.4 System Level Models

At the system level, there are two broad classes of models. The first is the models of the agricultural watershed, shown in Figure 2, in which one or more unsaturated zone subsystems are linked with a groundwater or drainage subsystem simulation to predict total irrigation return flow volumes and their time distributions. The second set of system models are those simulating river basin or sub basin hydrologies as shown in Figure 3. In these models, irrigated agriculture represents a small fraction of the actual land area and the emphasis is on evaluating the impact of irrigation on the system rather than quantifying its magnitude.

2.2.1 Infiltration redistribution process level model

2.2.1.1 Border irrigation

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

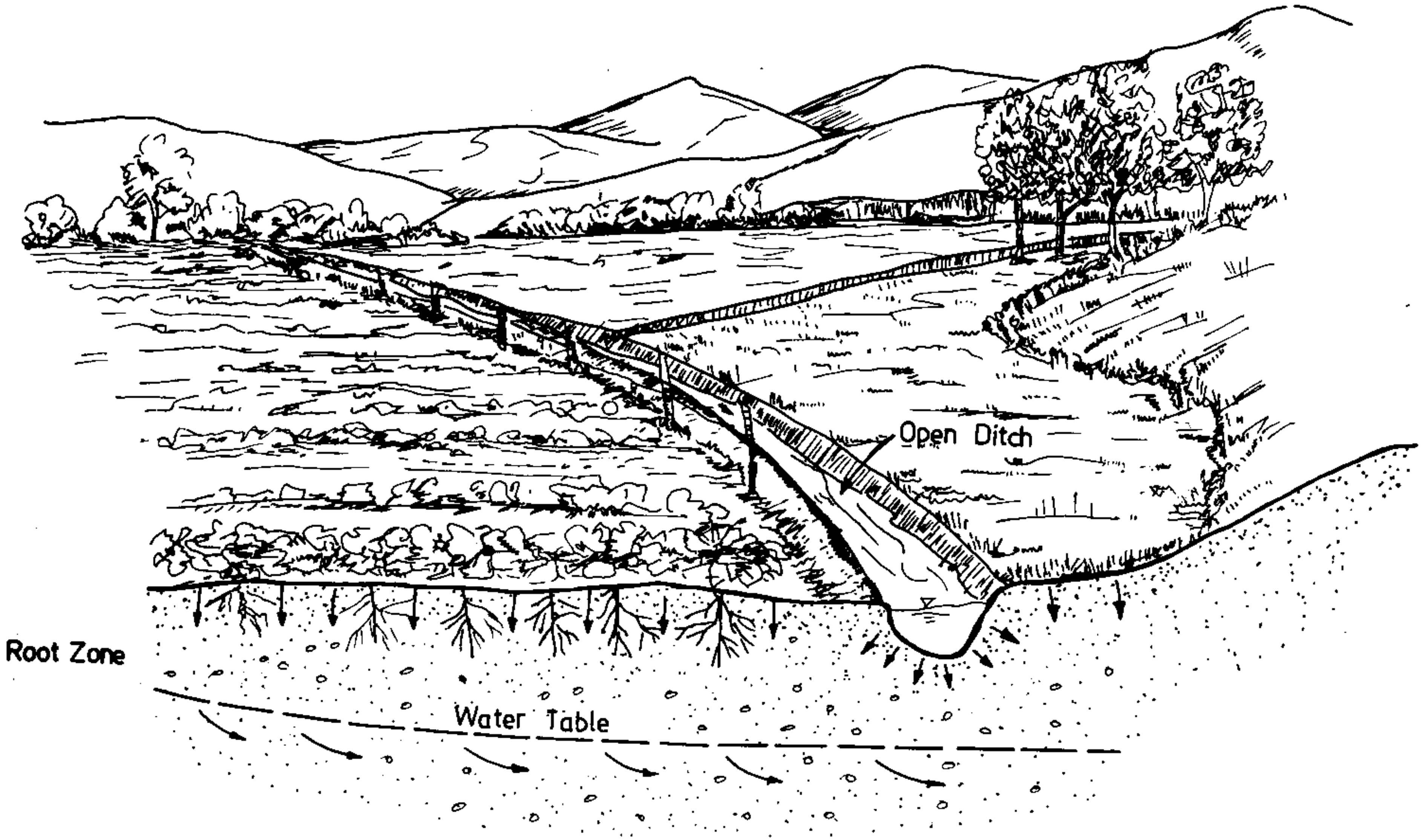


FIGURE 2 - VIEW OF A LARGE SCALE IRRIGATION RETURN FLOW SYSTEM

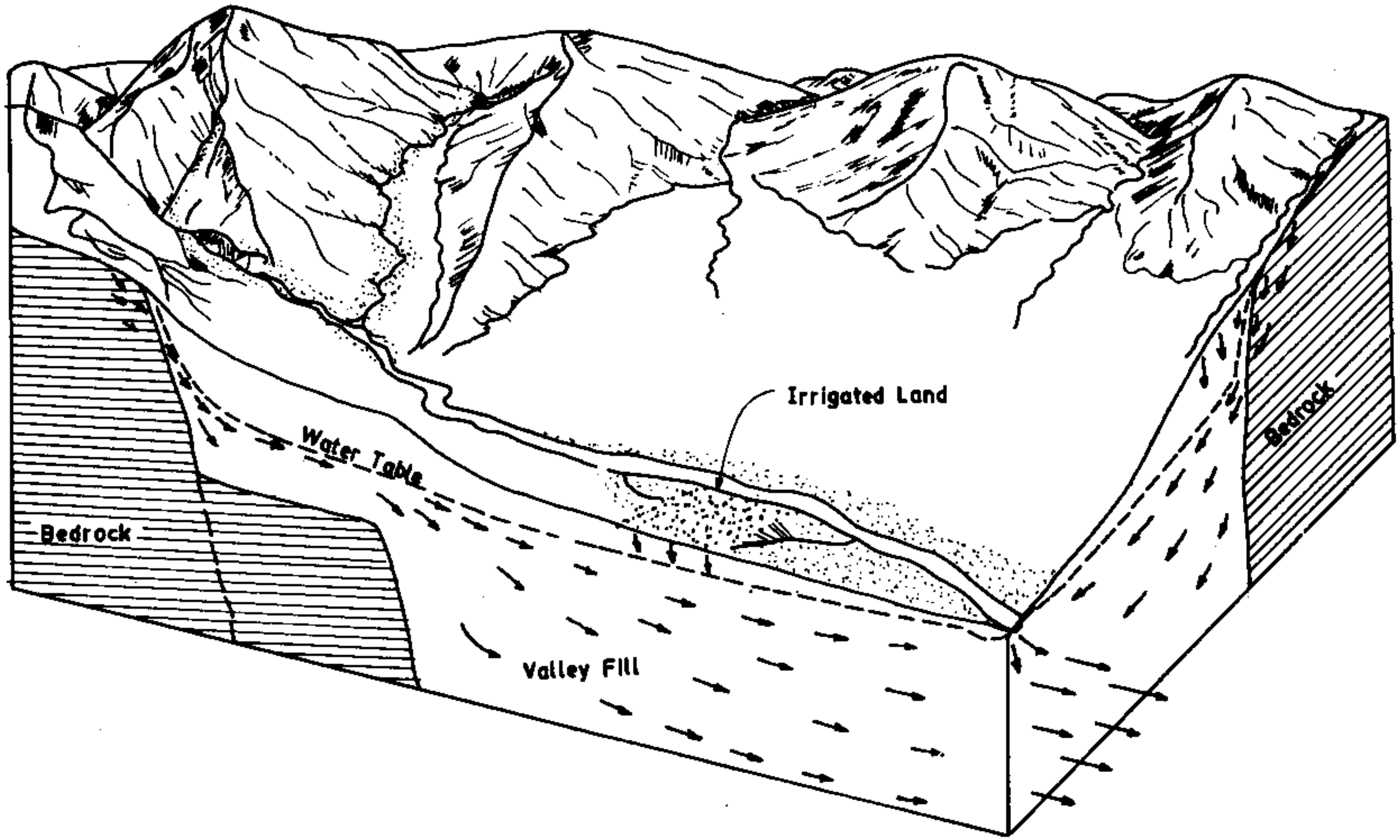


FIGURE 3 - AN ILLUSTRATION OF A WATERSHED WHICH INCLUDES AN IRRIGATED COMPONENT (EAKIN ET AL.(1976))

profile.

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 (Figure 4)or along an axis representing the length or width of the irrigated field (Figure 5). 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.

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(Figure 6). The cumulative frequency of actual depths of water can be represented in one of two ways:

i) "less" depths(Figure 6)for which p fraction of the area received a depth of water 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(Figure 7)for which p fraction of the area received a depth of water of y_p or

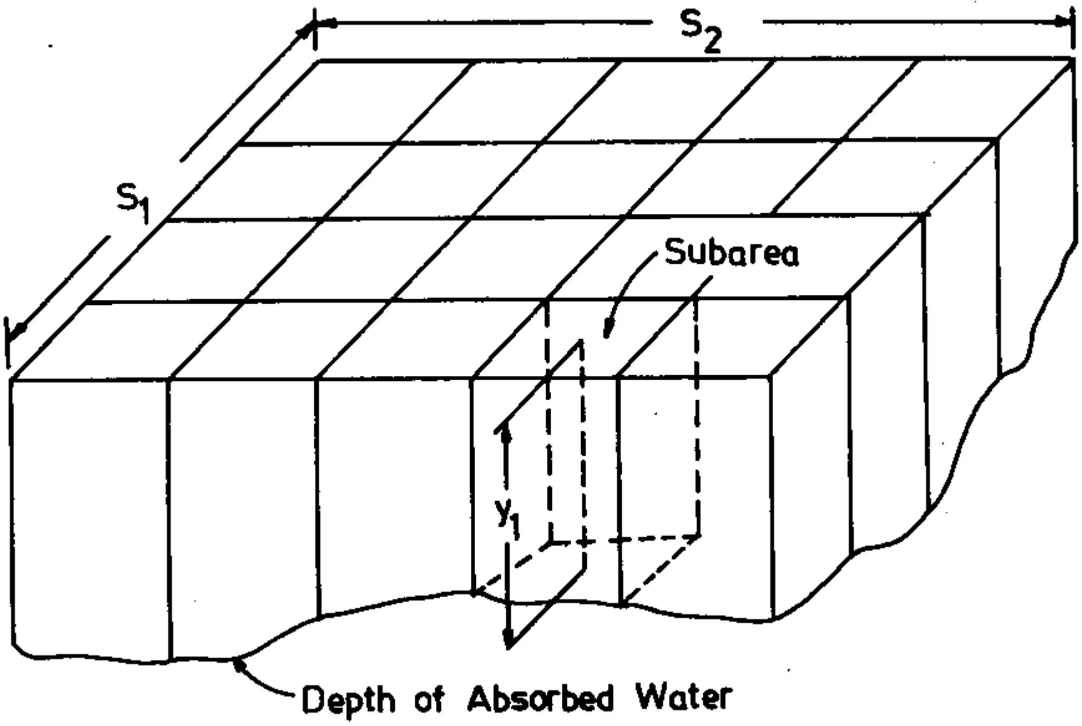


FIGURE 4 - DEPTH OF ABSORBED WATER OVER AN IRRIGATED AREA,ACTUAL FIELD WATER DISTRIBUTION

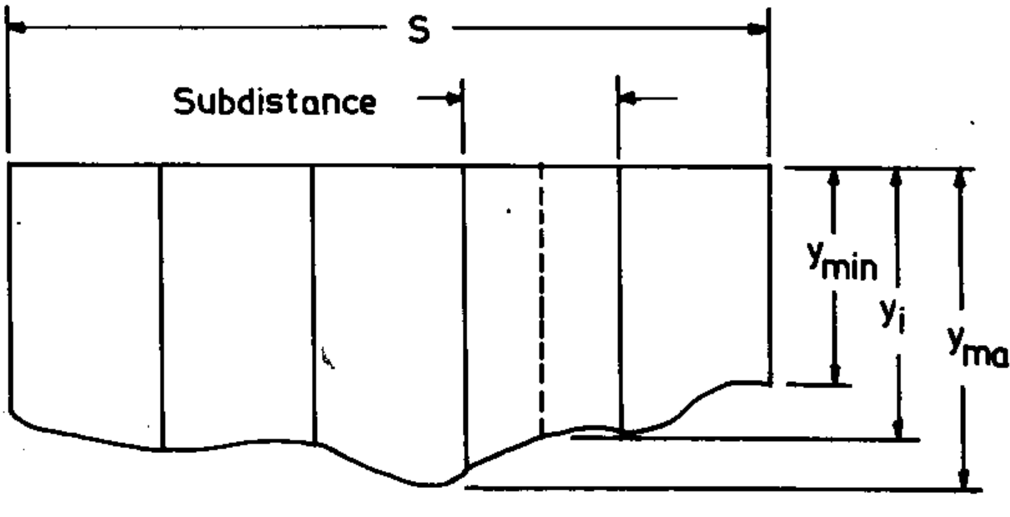


FIGURE 5 -DEPTH OF ABSORBED WATER ALONG AN AXIS, ACTUAL FIELD WATER DISTRIBUTION

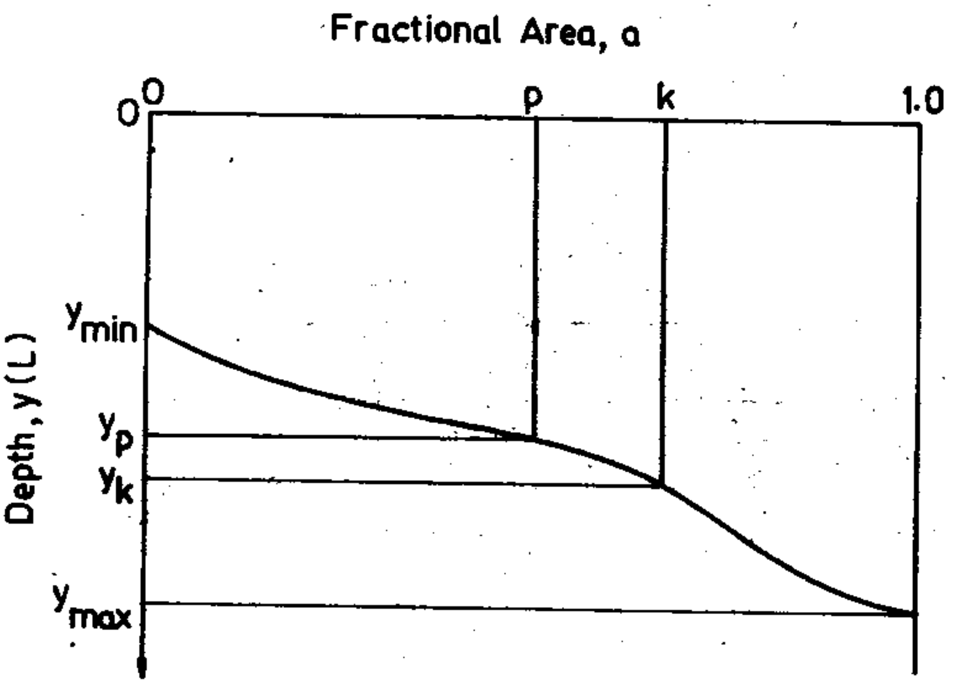


FIGURE 6 - 'LESS' DEPTH FREQUENCY DISTRIBUTION, CUMULATIVE FREQUENCY DISTRIBUTION OF ACTUAL WATER DEPTHS

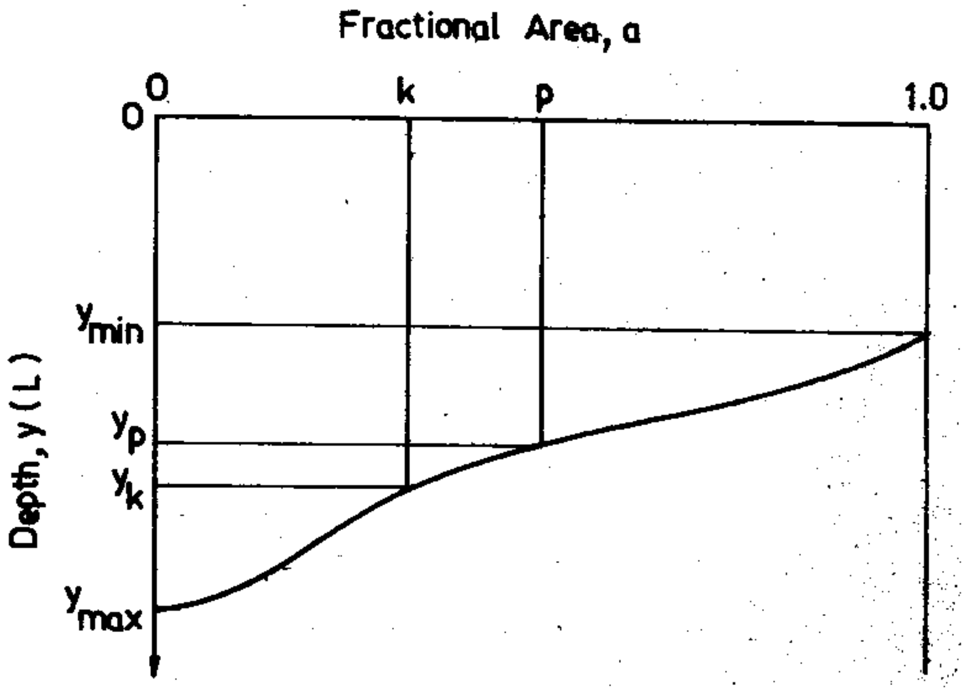


FIGURE 7 - 'GREATER' DEPTH FREQUENCY DISTRIBUTION, CUMULATIVE FREQUENCY DISTRIBUTION OF ACTUAL WATER DEPTHS

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 The nondimensional water depth is given by

$$H_i = \frac{y_i}{\bar{y}}$$

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

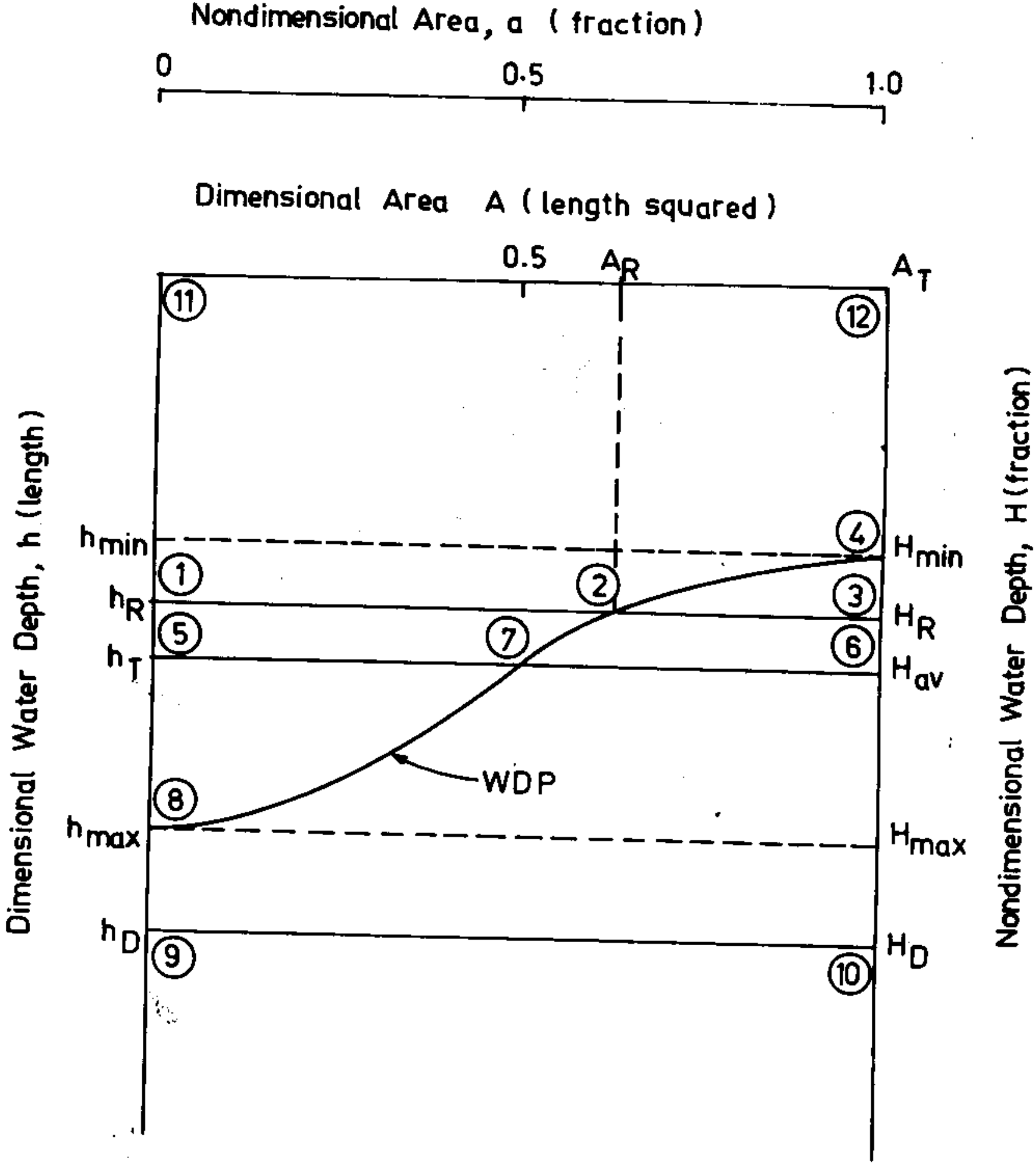
$$\bar{y} = \frac{1}{A} \sum_{i=1}^{n} A_i y_i,$$

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)

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

$$a_i = \frac{\sum_{j=1}^{i} A_j}{A}$$

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 (Figure 8). This type of representation of depths and areas is known as a Water Distribution Profile (WDP).



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

$T = F + R - B$

$T = D - W$

$H_T = \bar{y} = H_F + H_R - H_B$

$H_T = H_D - H_W$

FIGURE 8 - DEFINIATION SKETH FOR SYMBOLS

The efficiency and distribution of an individual irrigation have been described through the measurement of four independent quantities. Three efficiencies and one distribution parameter have been 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.

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

where R is the required 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

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

where T is the total quantity of water (L^3) applied to the field that infiltrated into the soil and B is volume of deficient water after an irrigation, measured from the required depth, h_R.

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, the losses to runoff (even if collected by a tail water reuse system), wind drift, evaporation, etc.

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

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. This is measure of the distribution of water over the field by the irrigation and so this term has been called the distribution uniformity, U_d.

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

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,

$$C = \frac{A_T}{2n} \sum_{i=1}^{n} | y_i - \bar{y} |$$

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 theoretical model for border irrigation:

Theoretical models for the prediction of water distribution patterns in basin irrigation have been developed and used (Peri et al., 1979) only for regular basins that are characterized by the following:

a. The basin is almost level with a uniform and smooth graded surface,

b. The water flows along the axis of the basin with a uniform water front across the basin,

c. The irrigation process includes four successive states:

i) Advance of water front along the basin: During this stage, the inlet stream flows and water advances until the basin is just covered.

ii) Ponding of water over the whole basin: In this stage the basin is already covered with water. The inlet stream flows with a flow rate much greater than the overall infiltration into the basin. Consequently, part of the water infiltrates and part is ponded within the basin.

iii) Depletion: In this stage no more inflow occurs. The ponded water infiltrates into the soil until the upper end of the basin surface exposed.

iv) Recession: The remaining water over the basin infiltrates while gradually exposing the basin surface.

The following basic assumptions have been made to develop a theoretical model that describe the basin water distribution pattern:

a. Recession is negligible with well leveled basins, however, when there is a slope in the basin, recession is a function of the depth of water over the surface, resulting from the slope.

b. The depth of water ponded over the surface does not affect infiltration. This assumption is especially true when large portions of the soil profile are already wetted.

c. Evaporation losses are negligible and there is no runoff. Consequently, all the water that has been delivered into the basin is absorbed by it.

A water distribution pattern model must provide a specific function for the depth of water infiltrated, $y_x(t)$, as related to the distance along the basin from the inlet end, x, at the time t. However, often the function is not required for all t, but may be required only for $t = t_r(x)$, where $t_r(x)$ is the time that water receded from point x, also known as the recession time. Thus, the final water distribution, y_x from which the distribution uniformity and irrigation efficiencies are calculated is:

$$y_x = y_x[t_r(x)]$$

The model must provide the water distribution pattern and efficiencies for a specific set of values for the system parameters studied. Then, when a change is desired, the parameters are changed, and a new set of results is obtained.

A General Model of y_x:

The depth of water infiltrated into the soil is obtained from infiltration equations. Several infiltration equations have been developed. One of the most commonly used infiltration equations is the well known modified Kostiakov equation, in which:

$$I = k\, t_{op}^{n} + C \qquad \ldots (1)$$

$$z = \frac{k}{n+1}\, t_{op}^{n+1} + C\, t_{op} = A\, t_{op}^{B} + C\, t_{op} \ldots (2)$$

where

I = infiltration rate (LT^{-1})

t_{op} = infiltration opportunity time (T)

C = basic infiltration rate, which is the infiltration rate for large t_{op} (LT^{-1})

k = constant (dependent on soil properties and units)

n = constant (dependent on soil properties) $-1 \le n \le 0$

A = constant, $A = \frac{k}{n+1}$

B = constant, $B = n + 1 \quad 0 \le B \le 1.0$

z = cumulative infiltrated depth of water (L)

Usually, irrigation takes place when the infiltration is mainly governed by the power term and C is neglected, so that

$$z = A\, t_{op}^{B} \qquad \ldots (3)$$

For basin irrigation, the opportunity time varies along the basin length, x, so that $y_x(t)$ is a function of x through the opportunity time. The opportunity time at any point at a distance, x, from the upper basin end is given by:

$$t_{op} = t_r(x) - t_a(x) \qquad \ldots (4)$$

where

$t_a(x)$ is the time water first arrived at point x. This is also called the advance time.

When recession can be neglected and it is assumed that the water disappears from the entire basin surface at the same time (an assumption which is accepted with level or almost level basins), the recession time is a constant expressed by

$$t_r(x) = t_b + t_{aL} \text{ for any } 0 < x \leq L \qquad \ldots (5)$$

where

t_b is the time for the infiltration of the water at the far end of the basin

$t_{aL} = t_a(L)$ is the advance time to the end of the basin.

Infiltrated depth at any point x is then given by

$$y_x = A[\,t_b + t_{aL} - t_a(x)\,]^B \qquad \ldots (6)$$

t_b is a function of the infiltrated depth at the lower end. For level basins and no recession, it is related to the minimum depth infiltrated which sometimes is taken as the required depth.

$t_a(x)$ amd t_{aL} are functions of the distance x or length of the basin L, the inlet stream size Q, the infiltration equation, and the hydraulic parameters (bed slope, roughness coefficient and flow cross section).

Assuming that $t_a(x)$ can be defined in terms of x and the other parameters, and t_b can be calculated for a known depth by Eq. 3, or taken as a known time, the water distribution profile can be expressed as a function of x and the other parameters. With y_x as given in Eq. 6, the following irrigation performance parameters can be derived.

The total volume of water infiltrated (per unit of basin width) is:

$$V = A_1 + A_2 = \int_{x=0}^{L} y_x dx \qquad \ldots (7)$$

$$A_2 = y_{min} L \qquad \ldots (8)$$

$$A_1 = \int_{x=0}^{L} y_x dx - y_{min} L \qquad \ldots (9)$$

$$A_3 = \bar{y}(L-x) - \int_{x=X}^{L} y_x dx \qquad \ldots (10)$$

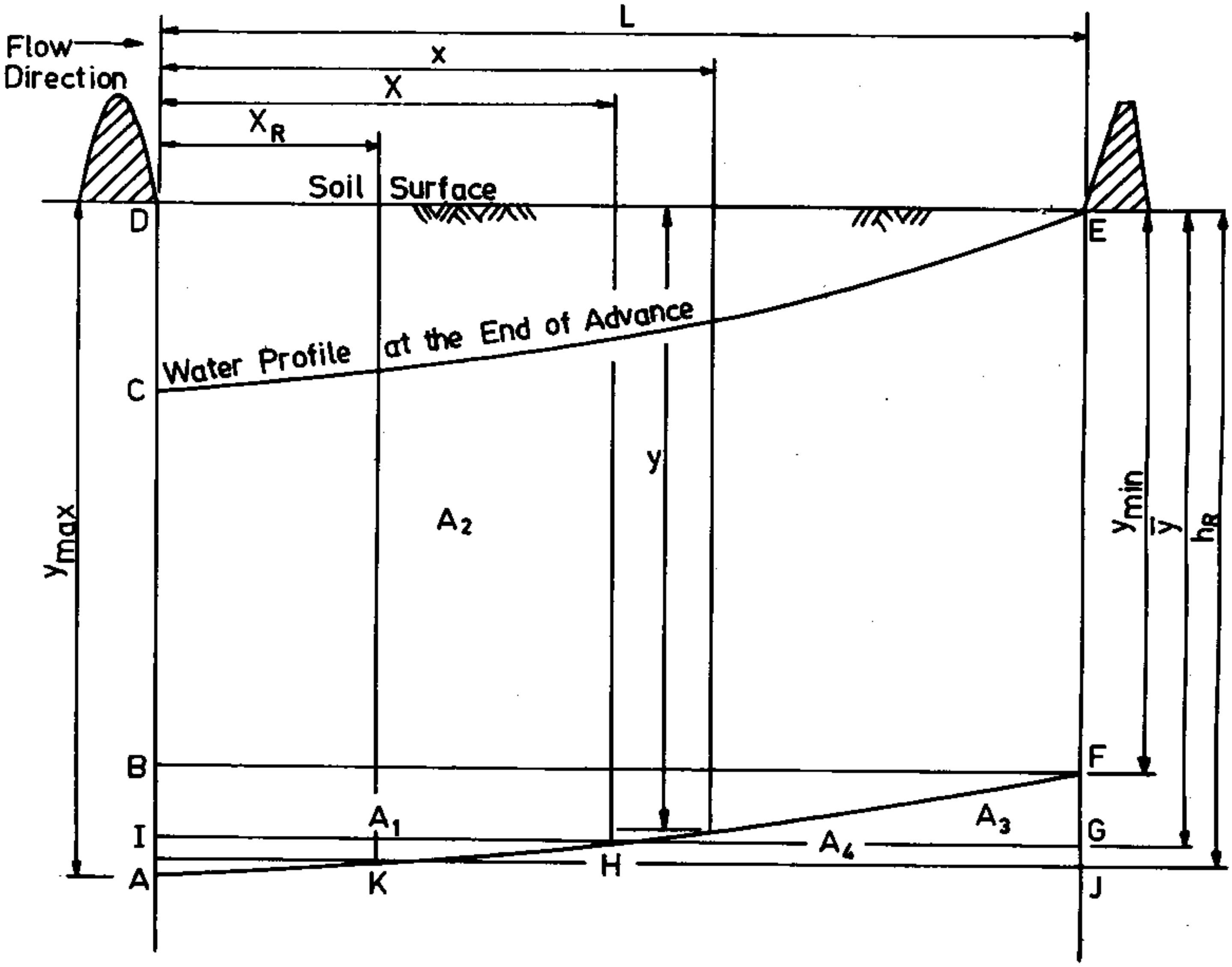
$$A_4 = h_R(L-X_R) - \int_{x=X_R}^{L} y_x dx \qquad \ldots (11)$$

$$\bar{y} = \frac{V}{L} = \frac{1}{L} \int_{x=0}^{L} y_x dx \qquad \ldots (12)$$

where

V = total volume of water infiltrated per unit of width

$A_1 + A_2$ = area confined by ADEFA (in Fig. 9)



A_1 = ABFHA

A_2 = BDEFB

A_3 = HFGH

A_4 = KFJK

h_R = Required Depth of Application

FIGURE 9 - WATER PROFILE UNDER REGULAR BASIN IRRIGATION

A_1 = area confined by ABFHA

A_2 = area confined by BDEFB

A_3 = area confined by HFGH

A_4 = area confined by KFJK

Since A_1, A_2, A_3, and A_4, are function of $\int y_x dx$, they are functions of all the parameters associated with y_x including the time terms t_b, t_{aL}, and $t_a(x)$.

The irrigation performance parameters can be derived from y_x as follows:

$$U_d = \frac{\bar{y} - \frac{A_3}{L}}{\bar{y}} \qquad \text{... (13)}$$

$$E_p = \frac{h_R - \frac{A_4}{L}}{\bar{y}} \qquad \text{... (14)}$$

$$E_S = \frac{h_R - \frac{A_4}{L}}{h_R} \qquad \text{... (15)}$$

2.2.1.2 Furrow irrigation

Modifications in the design or operation of surface irrigation systems to obtain different spatial distributions of applied irrigation waters can result in changes in return flow quality and quantity. The infiltration-redistribution process level model pertaining to furrow irrigation is discussed below:

The basic factors affecting the phases of water movement over and through the soil surface are:

i) soil infiltration characteristics
ii) slope of irrigated run
iii) geometric configuration and roughness of furrow
iv) length of run
v) volume inflow into furrow
vi) total time of irrigation.

In furrow irrigation, when infiltration rate is expressed as a depth per unit time, an equivalent depth is usually implied since movement is horizontal as well as vertical. This depth is obtained by dividing the volume rate of infiltration per unit of furrow length by the product of unit length and furrow spacing. In furrow irrigation, infiltration rate is commonly expressed as the volume absorbed by a unit length of furrow in a unit time ($L^3/(LT)$).

Besides physical soil properties the soil tillage can have a profound influence on the infiltration rate of the soil due to the physical disturbance of the soil surface by the tillage implements as well as compaction caused by the tractor and implement wheels. In furrow irrigation, the compaction caused by the tractor wheels may cause the furrow bottom to exhibit much lower infiltration characteristics than the uncompacted sides.

Another important factor which influences infiltration rate in furrow irrigation is channel characteristics. In furrow irrigation, the wetted perimeter (and therefore effective surface area of infiltration) is usually much smaller per unit of land area irrigated than it is for border irrigation. Wetted perimeter varies both with time and distance along the furrow since it is determined by the hydraulic conditions of shape, roughness, slope, and flow rate at any point in the furrow.

Theoretical approaches such as Philip, Green and Ampt and Kostiakov models which relate infiltration to basic factors affecting it cannot be used to establish the infiltration characteristics of an irrigated soil.

Factors which affect infiltration indicate that the same methods for assessing the infiltration characteristics may not be applicable to both borders and furrows. The methods used for assessing infiltration characteristics must be assessed for applicability to specific conditions.

Two techniques which have been used to determine infiltration rates in furrows are:

blocked furrow infiltrometer,

inflow-outflow measurements on segments of the furrows

The blocked furrow infiltrometer measures the infiltration of water into the soil profile over a short segment of furrow and from a ponded surface storage.

Advantages of this technique are:

i) A limited supply of water only is needed.

ii) The water level in the furrow can be set to represent actual depth during irrigation and variability in infiltration rate due to changes in depth of water in the channel may be assessed.

Disadvantages are:

i) The infiltrometer does not account for variability in soil characteristics along the furrow unless a large number of samples are studied.

ii) The infiltrometer does not account for the effects of changes in furrow cross section during irrigation or soil particle orientation and deposit caused by the flowing water.

The inflow-outflow method allows for determination of furrow intake rates by measuring the inflow and outflow from a reach of a furrow.

Advantages are:

i) The influence of flowing water on the infiltration characteristics is accounted for.

ii) A substantial portion of the furrow, usually 30-75 meters, provides a large sample area of infiltration.

Disadvantages are:

i) Most outflow-measuring devices generally obstruct the flow, causing it to back up in the furrow, thus increasing the cross sectional area of infiltration. This is especially true in fields with a small slope.

ii) The build up of surface storage between measuring devices is generally neglected and it is assumed that the difference between inflow and outflow is the intake rate for the portion of the furrow betweeen the two measuring devices. The error accompanying this is especially significant during early stages of measurement as the furrow surface storage build up is not reflected in the inflow and outflow measurements.

The water consumptively used which is in excess of that stored in the soil root zone above field capacity is assumed negligible. The following terms are defined by Hansen (1960) with reference to Figure 10.

i) Volume of water retained in the root zone of the plant after irrigation, VRZ (Area ABDGKA). This is the portion of applied water which remains available for plant use after an irrigation.

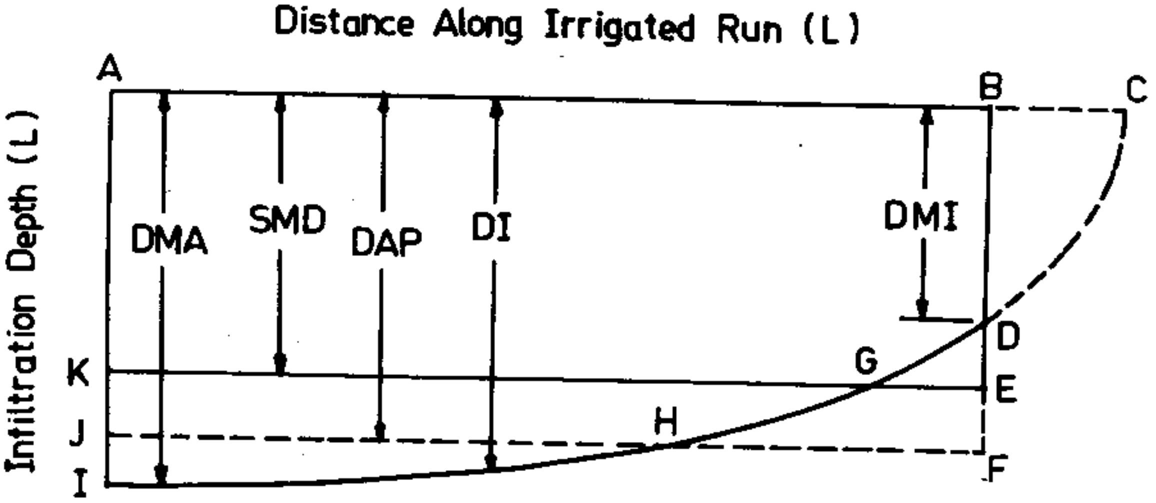
ii) Volume of soil moisture deficiency remaining after an irrigation, VDF (Area GDEG). This is the volume of of water required by the root zone after irrigation to reach field capacity.

iii) Volume of deep percolated water, VDP (Area KGHIK).

iv) Volume of tailwater, VTW (Area BCDB).

v) Volume of water delivered to irrigated field, VAP (Area ACDIA).

vi) Volume of water required in root zone to overcome total soil moisture depletion, VNW (Area ABEKA)



SMD -- SOIL MOISTURE DEFICIENCY BEFORE IRRIGATION (DEPTH)
DAP -- MEAN INFILTRATED DEPTH OF WATER
DI -- DEPTH OF INFILTRATION AT ANY DISTANCE ALONG IRRIGATED RUN
DMI -- MINIMUM INFILTRATED DEPTH ALONG RUN
DMA -- MAXIMUM INFILTRATED DEPTH ALONG RUN
GDEG-- SOIL MOISTURE DEFICIENCY AFTER IRRIGATION PER UNIT FIELD WIDTH (VDF)
KGHIK- VOLUME OF DEEP PERCOLATION PER UNIT FIELD WIDTH(VDP)
BCDB-- VOLUME OF TAILWATER PER UNIT FIELD WIDTH(VTW)
ACDIA- TOTAL VOLUME OF WATER APPLIED PER UNIT FIELD WIDTH(VAP)

FIGURE 10 - DISTRIBUTION OF INFILTRATED DEPTHS ALONG IRRIGATED RUN

vii) Total volume of infiltrated water, VIN (Area ABDGIA).

viii) Actual spatial distribution of infiltrated water, ASD (Line IHGD)

ix) Mean infiltrated depth of water, DAP (Line JHF)

Several concepts which describe irrigation efficiencies are summarized as follows:

Water Storage Efficiency: Water storage efficiency (E_s) as proposed by Hansen (1960) is defined as :

$$E_s = \frac{VRZ}{VNW} \times 100$$

Low E_s may be a result of nonuniform distribution of infiltrated water, due to design or operational factors, or inadequate supplies of water for fulfilment of crop water requirements.

Consumptive Use Efficiency: Consumptive use efficiency (E_u) envisaged by Hansén (1960) is defined as:

$$E_u = \frac{W_u}{W_d} \times 100$$

where W_u = crop consumptive use of water (transpiration and water retained in plant tissue)

W_d = net amount of water depleted from root zone.

The term W_d includes all the water evapotranspired, both beneficially and non-beneficially, and the water lost to deep percolation. The plant spacing, amount of foliage, height of ridges, and depth and uniformity of infiltration are factors in determining the consumptive use efficiency. Losses due to evaporation may be extremely difficult to isolate from consumptive plant use.

A Theoretical Model for Furrow Irrigation:

In this model the total inflow is determined from specified values of the inflow rate and the duration of irrigation. The infiltration at any point along the furrow is determined from knowledge of the intake opportunity time at different stations of the furrow and from measured infiltration data which is fitted to one or more empirical infiltration equations. The soil moisture deficiency is determined from knowledge of crop evapotranspiration through the season or from soil moisture samples taken the day before irrigation.

The advance curve is estimated using the Wilke-Smerdon technique. This technique is simple to apply and its use has been verified by several field investigations. The relationship between the variables affecting advance is given by:

$$\frac{qt}{c_m x} = 1 + P\,\frac{At^B}{c_m}$$

where q = furrow inflow

t = time of advance of distance x

c_m = average cross-sectional area of flow during the advance phase of irrigation

x = distance of advance

P = a constant depending only on the exponent of the infiltration equation B

A, B = constants of Kostiakov infiltration equation.

The constant c_m in equation is predicted from empirical relationships such as those developed by Wilke and Smerdon (1956):

$$d_0 = 0.075 \left(\frac{q}{s^{1/2}}\right)^{0.4}$$

$$c_m = 2.75\ d_0^{5/3}$$

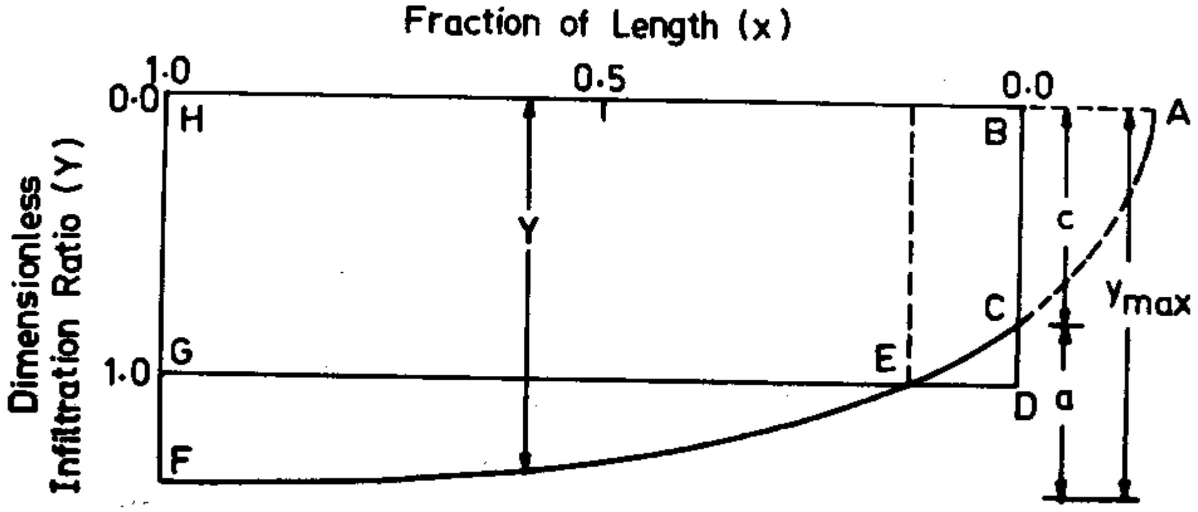
where d_0 is the upstream depth in the furrow. The upstream depth, d_o, may be computed using the Manning's equation and an estimate of surface roughness. A relationship which relates c_m to Manning's roughness factor (M_n), inflow (q), slope (s), and geometry of the furrow is

$$c_m = \text{SSF} \times \text{STC} \times \left(\frac{M_n q}{s^{.5}}\right)^{\text{STE}}$$

where STC, STE = constants depending only on furrow geometry

SSF = an empirical coefficient which is the ratio of mean surface storage area to the surface storage at the head of the furrow, assumed constant. Wilke and Smerdon (1969), Davis and Fry (1963), and others have used SSF factors ranging from 0.75 to 0.77.

Karmeli (1977) described the distribution of infiltrated water over an irrigated field by a dimensionless curve. A typical curve is illustrated in Figure 11 for a furrow irrigation system with monotonically decreasing depth of infiltration along the run. The infiltrated depth of water is



$Y = c + aX^b$

Y--DIMENSIONLESS INFILTRATION RATIO = DEPTH INFILTRATED/MEAN SOIL MOISTURE DEFICIENCY

a--$Y_{max} - Y_{min}$

b--EXPONENT OF DISTRIBUTION

HAFH--DIMENSIONLESS TOTAL APPLIED VOLUME

GEFG--DIMENSIONLESS VOLUME OF DEEP PERCOLATION

DCED--DIMENSIONLESS VOLUME OF SOIL MOISTURE DEFICIENCY REMAINING AFTER IRRIGATION

BACB--DIMENSIONLESS RUNOFF VOLUME

FIGURE 11 - POWER FIT CURVE OF DIMENSIONLESS DISTRIBUTION FOR SURFACE IRRIGATION

nondimensionalized by dividing it by the mean soil moisture deficiency (SMD). The distance along the run is nondimensionalized by dividing it by the total length of run (L). The X coordinate is measured from the end of the irrigated run.

The usefulness of the dimensionless representation ($Y \cdot = c + aX^b$) used by Karmeli is that:

i) The uniformity of irrigation and relative amounts of deep percolation or underirrigation are evident from simple visual inspection

ii) From the representative equation ($Y = c + aX^b$), E_s and C_u may be established through graphical means or by integration and manipulation of the representative equation. If a tailwater reuse system is part of the irrigation system, E_a may also be obtained.

Recognizing that deep percolation and tailwater may have significantly different environmental and economic impacts, Karmeli (1977) also proposed that two efficiencies which relate to tailwater and deep percolation be used to describe an irrigation system. These are the tailwater efficiency (ETW) and the deep percolation efficiency (EDP). With reference to Figure 11, these are:

$$ETW = 1 - \frac{VTW}{VAP}$$

$$EDP = 1 - \frac{VDP}{VAP}$$

It may be noted that the percent of total applied water which is tailwater (PTW) and the percent of total applied water which deep percolates (PDP) are simply:

$$PTW = (1 - ETW) \times 100 = \frac{VTW}{VAP} \times 100$$

$$PDP = (1 - EDP) \times 100 = \frac{VDP}{VAP} \times 100$$

All the irrigation efficiencies discussed above may be computed without resorting to actual field measurement if the following are known:

i) rate of advance of the irrigation front
ii) rate of infiltration of water into the soil
iii) inflow into furrow
iv) total time of irrigation
v) times of recession of water from the soil surface
vi) soil moisture deficiency before irrigation

The distribution of infiltrated water in the soil profile may be computed if times of advance and recession of the water from the soil surface and rate of infiltration of water into the soil profile are known. Inflow and duration of irrigation are specified or measured. Soil moisture deficiency can be established from field measurement or knowledge of crop water use and soil moisture history.

2.2.1.3 Sprinkler irrigation

The distribution of water in a field under sprinkler irrigation is primarily a function of design, operational, and climatic factors. Effects of soil characteristics on the distribution are considered negligible.

Various factors affect the uniformity of application in sprinkler irrigation. Some of these are:

i) Climatic (wind speed and direction)

ii) Design (sprinkler and lateral spacing, lateral diameters, nozzle type and size, user height, and design operating pressure)

iii) Operational (operating pressure and maintenance condition)

Insight into the performance of an irrigation system can be obtained if the pattern (distribution) of water application can be established for a specific set of conditions.

If the water application pattern of a single sprinkler is known for a given set of climatic, design,,and operational conditions, then the overlapped patterns of several sprinklers can be established analytically for different lateral and sprinkler spacings. The distribution of water in the overlapped patterns may usually be described by fitting the distribution to one of several functional relationships, e.g., normal, gamma, exponential. The performance of an irrigation system (quality of an irrigation including percolation losses can be assessed if the distribution is known.

The typical water distribution pattern in sprinkler irrigation is shown in Figure 12. Figure 13 depicts a schematic representation of histogram of application depth versus area irrigated. Figure 14 portrays a normalised non-dimensional water distribution profile for sprinkler irrigation.

It is recognized that there exists a need for a single, easily usable and accurate method that will enable the establishment of the sprinkler system distribution pattern and also supply other irrigation quality parameters.

A model is suggested (Karmeli, 1977) whose properties enable the characterization of precipitation patterns of sprinklers, mainly in reference to efficiency and other irrigation parameters.

The model is based upon the dimensionless cumulative frequency curve of the infiltration depth (Y) and the fraction of area (X), which is represented by the linear regression function (Figure 15).

$$Y = a + bX$$

where Y = dimensionless precipitation depth

X = fraction of area

a,b = linear regression coefficients (constants).

The least squares method is used to fit a straight line to the frequency curve. Example of actual cumulative frequency curve and its normal and linear fits are given in Figure 16.

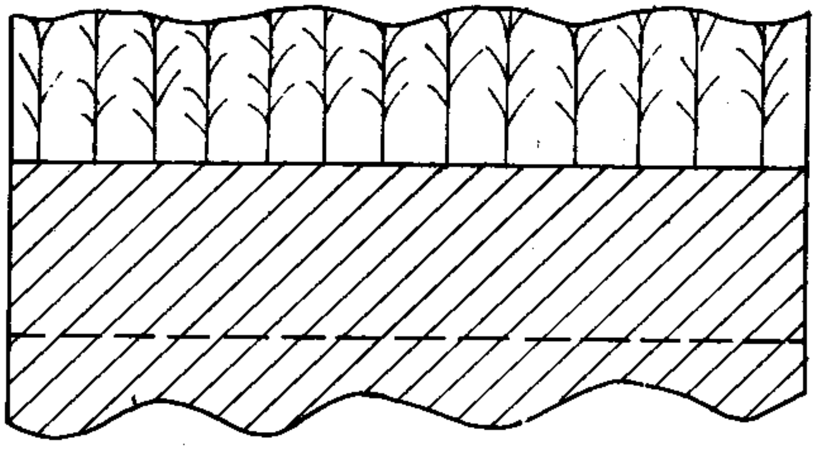


FIGURE 12 - TYPICAL EFFECTS OF WATER DISTRIBUTION PATTERNS ON A CROP UNDER IRRIGATION ASSUMING NO RUNOFF

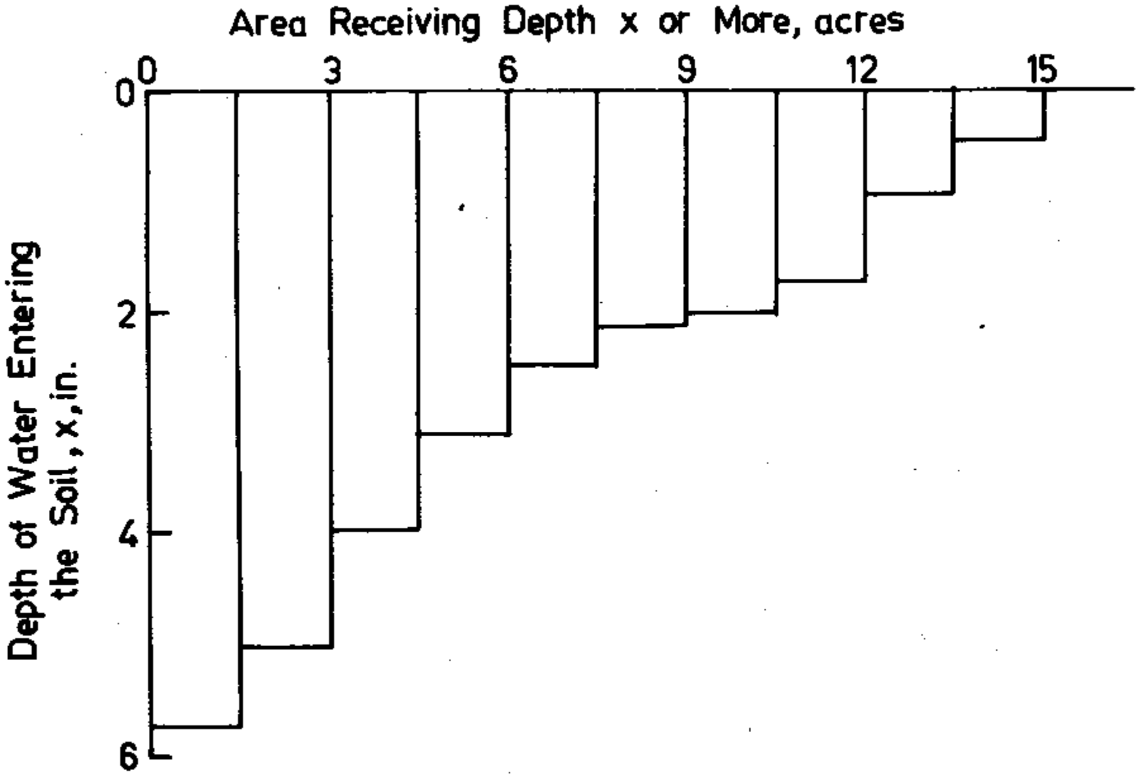


FIGURE 13 - HISTOGRAM OF APPLICATION DEPTH VS AREA IRRIGATED

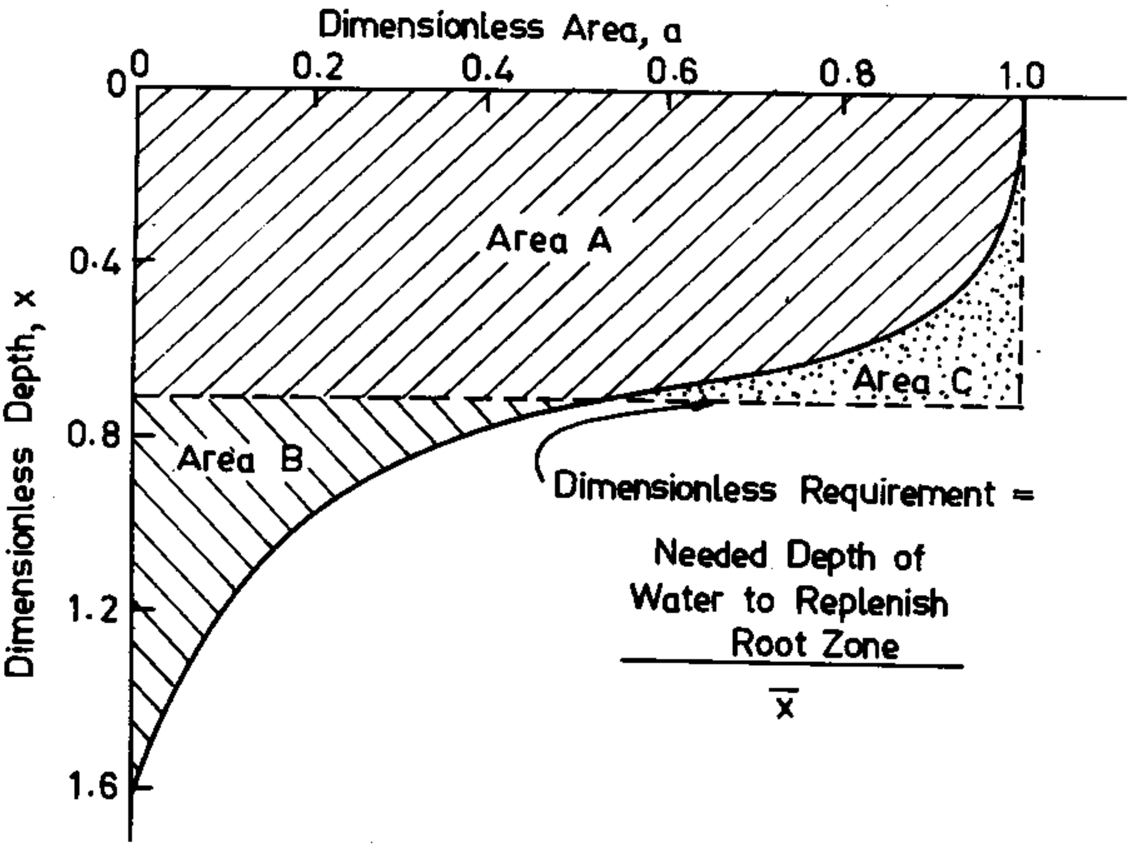


FIGURE 14 - NORMALISED NONDIMENSIONAL FRECUENCY CURVE

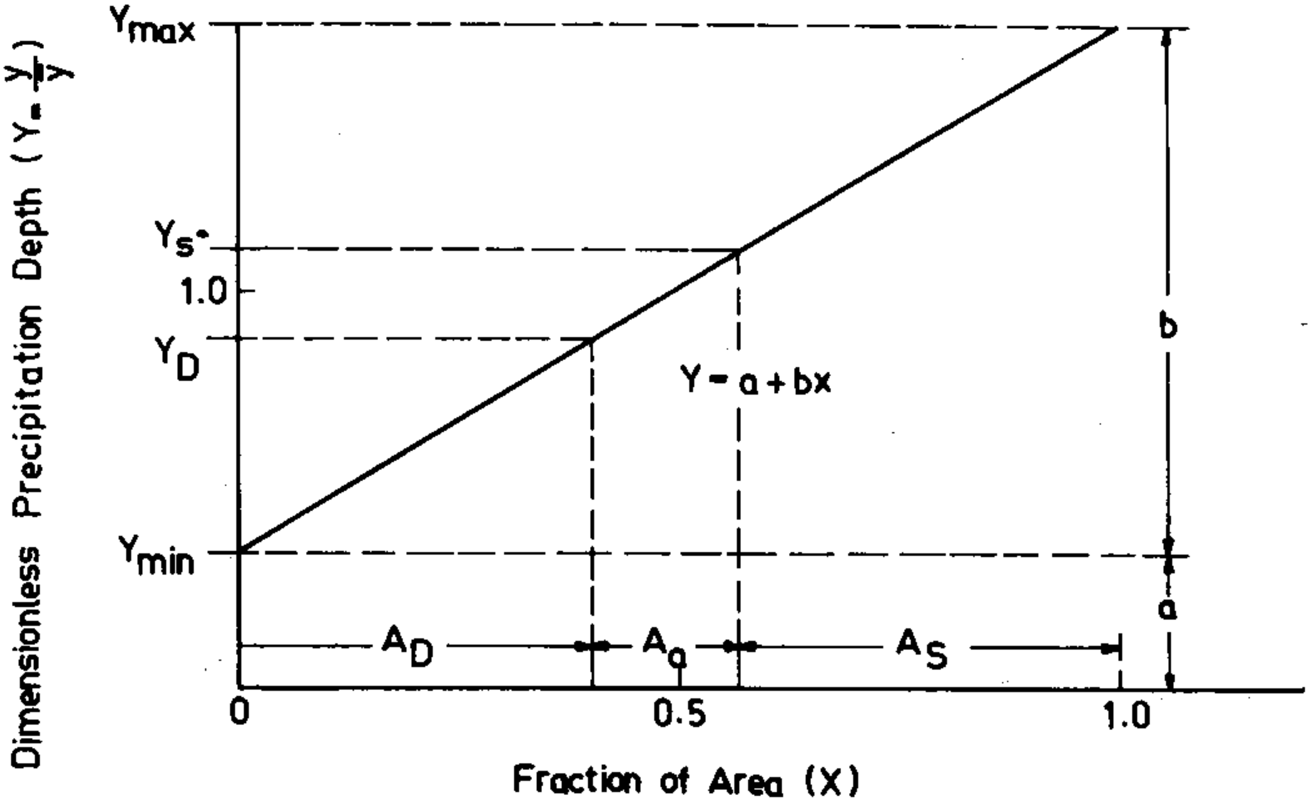


FIGURE 15 - LINEAR REGRESSION FIT OF A NONDIMENSIONAL DISTRIBUTION CURVE FOR SPRINKLER PATTERNS

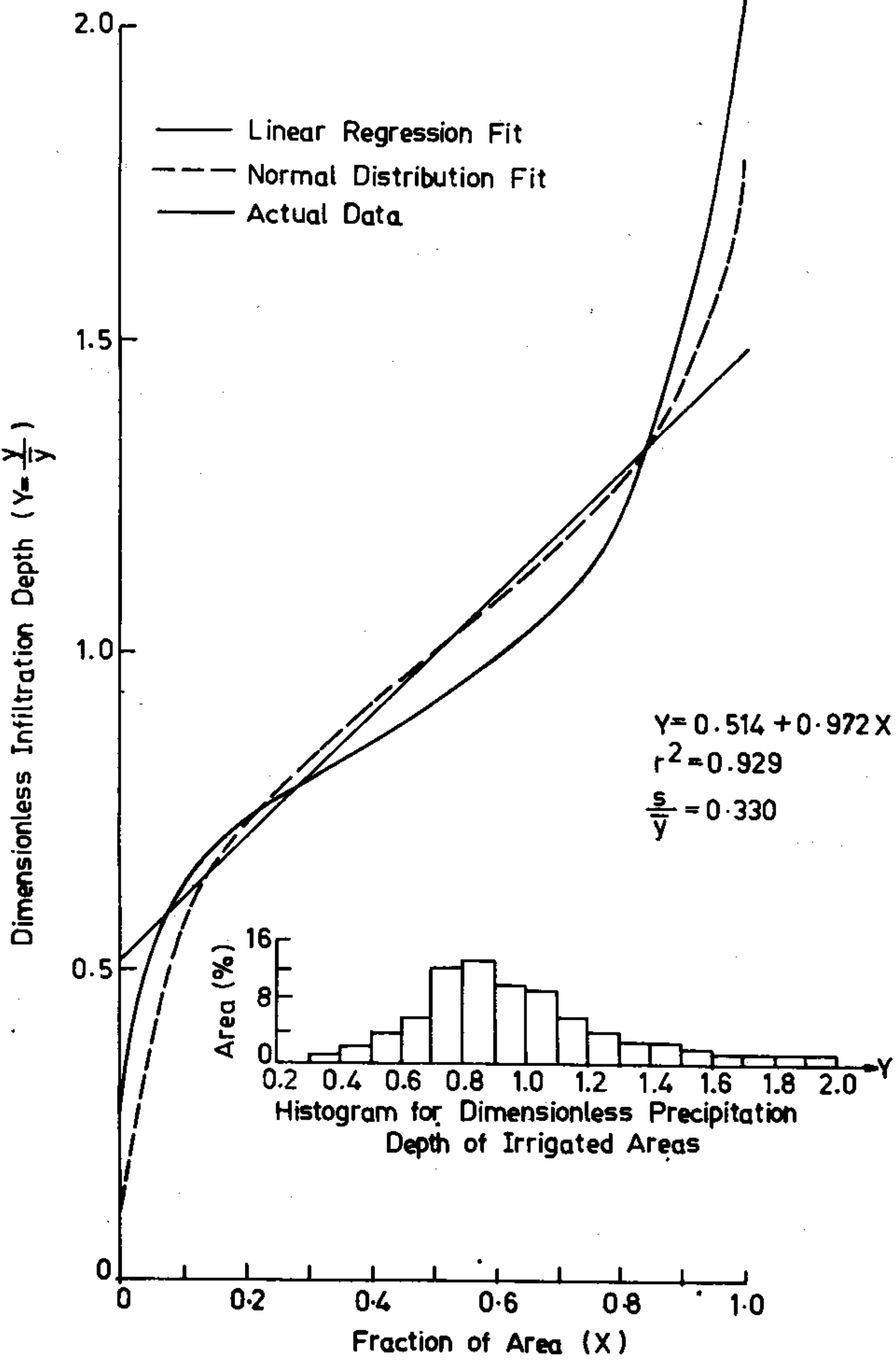


FIGURE 16 - FITS OF ACTUAL DATA INTO NORMAL AND LINEAR REGRESSION DISTRIBUTION IN SPRINKLER IRRIGATION

The dimensionless sprinkler frequency curve usually takes the "S' shape, as the distribution pattern usually tends towards a normal distribution. The s/y has a relatively small value when the pattern is highly uniform and most of the distribution is about the mean. However, when the pattern tends to be less uniform, s/y would increase as the deviation from the mean is larger, and the "S" shape of the distribution curve would stretch out to behave more like a straight line.

It may be hypothesized that the normal fit would be most suitable for distributions where s/y tends to be small. However, the linear fit may be just as good, as most of the distribution curve would tend to concentrate around the mean, and errors at both extremes of the frequency curve would be relatively limited. For distributions where the s/y is larger (less fitted to normal), the linear fit would better predict the overall distribution pattern, as errors on both extremes of the frequency curve would be of smaller magnitude.

The suggested model, based on the linear regression fit has some basic properties where for $Y = 1.0$ (average precipitation depth entering the soil profile = depth designed to replenish soil moisture deficiency), $X = 0.5$ (half of the area irrigated). The regression coefficient, b (slope of the line) represents $Y_{max} - Y_{min}$ (difference between minimal and maximal wetting zones of the field). The regression coefficient, a, is the estimated minimal precipitation depth

(Y_{min}) and also $Y_{min} = 1 - 0.5b$ as $[a + (a+b)]/2 = 1.0$. The estimated maximal precipitation depth (Y_{max}) equals a + b and also $Y_{max} = 1 + 0.5b$.

The use of the model allows reaching additional information regarding deficient and surplus volumes.

Area deficiently irrigated, $A_D = \dfrac{Y_D - a}{b} = X_D$

where Y_D = maximal depth in the area irrigated deficiently (Figure 17).

The fraction of deep percolation, D_p, represents the fraction of the total water applied that percolated past the root zone.

If $Y_r = 1.0$, the case where the desired application is equal to that amount to completely overcome deficit in the root zone, then

$$D_p = \frac{b}{8}$$

The irrigation return flow is very much connected with the actual volume of water applied which in turn depends on the water requirement. Water requirement for various types of crops grown in India are given in the following tables (Pai and Hukkeri, 1979).

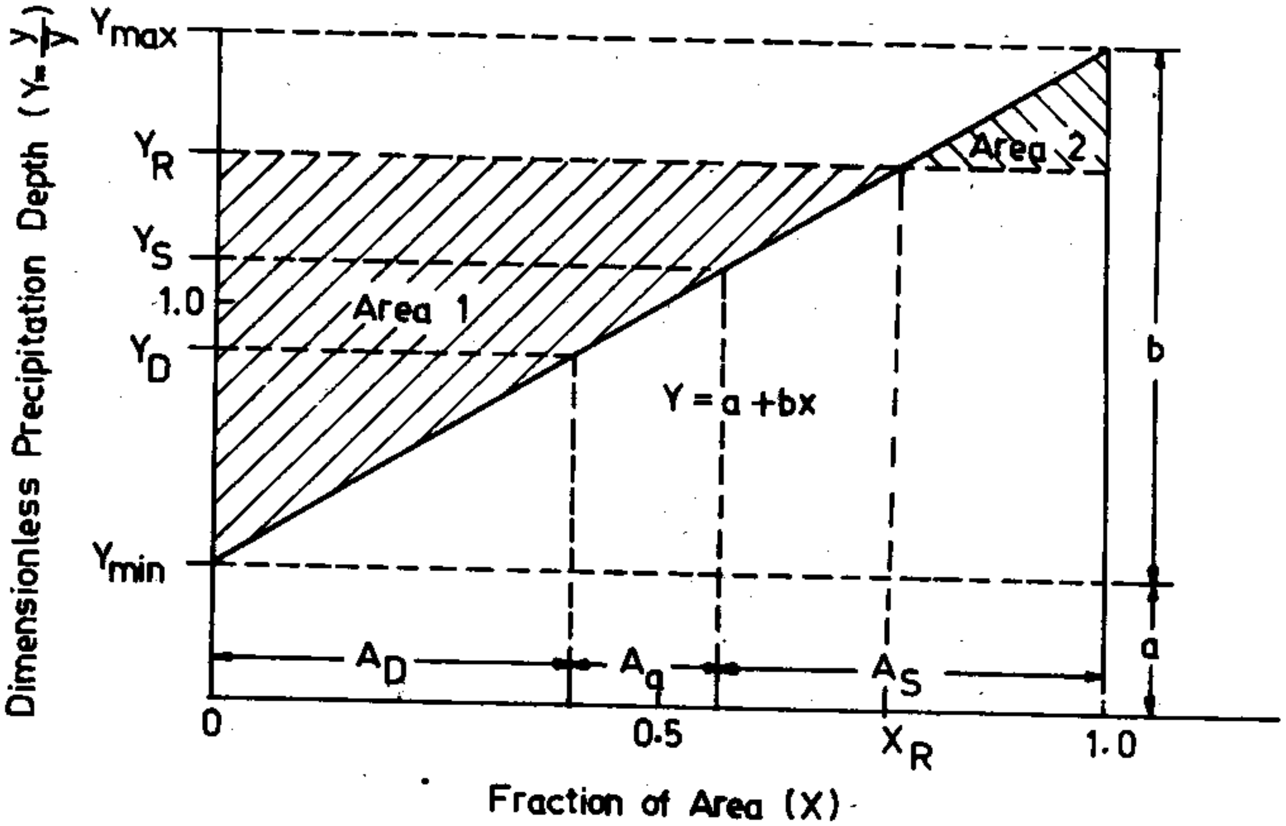


FIGURE 17 - THE PROPOSED MODEL WITH Y_R THE DIMENSIONLESS REQUIREMENT

TABLE 1

Water and Irrigation requirements of rice at different Locations

Place	Soil type	Water requirements (mm)	Irrigation* requirement (mm)	Season
(1)	(2)	(3)	(4)	(5)
Kharagpur (West Bengal)	Sandy-clay-loam	1850	N.A.	May/April-June/July
		1890	1440	July/Aug.Nov./Dec.
		2150	N.A.	Dec/Jan-Mar/April
Cuttack (Orissa)	Clay-loam	1300	790	June-September
		1190	980	Jan-April
Chakuli (Orissa)	Sandy-loam	N.A.	1100	Jan-May
		N.A.	330	July-October
Bhubaneshwar(Orissa)	Clay-loam	1440	780	June-September
		1650	1630	Sept.-December
Pantnagar(U.P.)	Loam	N.A.	500	June-Oct.
Roorkee(U.P.)	Loam	1620	750	June-Oct.
Hyderabad(AP)	Clay-loam	N.A.	780	March-June
Coimbatore(TN)	Do	1680	N.A.	July/Aug-Dec/Jan
Madurai(TN)		N.A.	900	July-November
		N.A.	830	July/October
Pattukottai(TN)	Sandy-loam	2006	N.A.	June-September
Chalakudy(Kerala)	Sandy-loam	N.A.	1620	Feb.-May
Delhi	Sandy-loam	2400	1600	June-October
Ludhiana(Pb).	Do	N.A.	1240	June-October

N.A. - Not available

*Actual number and interval of irrigation will depend on rainfall distribution and water table situation

TABLE 2

Irrigation requirements after sowing of maize, sorghum and bajra at different places in India

Crop	Place	Soil type	Season	*Irrigation requirements	
				(Nos.)	Amount (mm)
Maize . .	Delhi	Sandy loam	Kharif	2-3	100-150
	Hissar(Haryana)	Sandy loam	Kharif	5-6	300-360
	Pantnagar(UP)	Loam	Kharif	4	225-275
	Udaipur(Raj.)	Sandy loam	Kharif	4	300
	Arabhavi (Karnataka)	Clay loam	Kharif	3	150
	Siruguppa (Karnataka)	Black clay	Summer	10	510
	Bhubaneshwar (Orissa)	Loam	Kharif	2	100-150
			Rabi	11	500-600
	Madurai(TN)	Sandy Clay Loam	Summer	18	900
			Kharif	6	860
	Bhavanisagar(TN)	Loamy	Summer	25	1250
	Hyderabad(AP)	Black clay	Kharif	2	120
	Ludhiana(Pb)	Loamy sand	Kharif	2	150
Sorghum . .	Dharwar (Karnataka)	Loam to clay	Kharif	5	360
	Siruguppa (Karnataka)	Black clay	Summer	1-2	75-150
	Hyderabad(AP)	Sandy loam	Rabi	4	300
	Coimbatore(TN)	Clay loam	Summer	4	300
	Madurai(TN)	Sandy clay loam	Summer	8	600
	Delhi	Sandy loam	Kharif	4	250
Bajra . .	Siruguppa (Karnataka)	Black clay	Kharif	2	150
	Hissar(Haryana)	Sandy loam	Kharif	3-4	225-300
	Delhi	Sandy loam	Kharif	2	150
	Anand(Gujarat)	Sandy loam	Summer	10	500
	Jobner(Raj.)	Sand	Kharif	2	180

*Pre-sowing irrigation not included.

TABLE 3

Irrigation requirement after sowing *gram* in different parts of country.

Place	State/Union Territory	Season		Soil Type	Optimum regime	Irrigation requirements	
		Sowing	Harvesting			Nos.	Amount (mm)
Indore	M.P.	Mid October	1st week of March	Clay loam	Stages*	3-4	180—420
Parbhani	Maharashtra	Mid October	End of Feb.	Clay loam	Stages *	2	150
Siruguppa	Karnataka	Mid October	3rd week of Feb.	Meduim Heavy Black Clay	0·8 IW/CPE (6cm)	6—7	360—420
Dharwar . . .	Karnataka	Mid October	3rd week of Feb.	Clay	0·8 IW/CPE (6cm)	6	360
Kota	Rajasthan	Mid Nov.	1st week of April	Clay	Stages*	1	100
Delhi	Delhi	1st week of Oct.	2nd week of March	Sandy loam	Stages*	1	75
Hissar	Haryana	Mid. Oct.	1st week of April	Sandy loam	Stages*	2	140
Jabalpur	M.P.	1st week of Oct.	4th week of Feb.	Clay loam	Stages*	3	225
Navsari	Gujarat	1st week of Dec.	Mid March	Clay	Stages*	4	300
Chikhli	Gujarat	1st week of Dec.	3td-week of March	Clay	Stages*	2	150

*Based on the stage of growth, 1, 2, 3 and 4 irrigations are given at initiation of flowering, initiation of podding, active branching and pod development in that order of priority.

TABLE 4

Irrigation requirement after sowing of *Groundnut* in different parts of India.

Place	State/Union Territory	Season		Soil Type	Optimum Regime	Irrigation requirement	
		Sowing	Harvesting			No.	Amount (mm)
Bhavanisagar	T.N.	(Kh.) Mid of August	1st week of Dec.	Red sandy loam	75% depletion of ASM ASM	7	280
		(Rabi) Mid of Feb.	1st week of June	Red sandy loam	50% depletion of ASM	15	475
Hyderabad	A..P.	Mid of Jan.	Mid of May	Red sandy loam	25% depletion of ASM	10	650
Yeminiganur	Karnataka	Mid of Oct.	Mid of March	Red sandy loam	50% Do.	6—7	300—350
Parbhani	Maharashtra	Mid of Feb.	Mid of May	Clay loam	100 mm CPE	8	500
Kanpur	U.P.	July	October	Sandy loam	50% depletion of ASM	2	150
Hissar	Haryana	July	October	Sandy loam	75% Do.	4	300
Ludhiana	Punjab	June to early July	Oct. to Nov.	Loamy sand	50% Do.	5-6	250-300
Chakuli	Orissa	Mid of Nov.	1st week of April	Loamy sand	25% Do.	10	690
Dharwar	Karnataka	1st week of July	3rd week of Oct.	Black clay	50% Do.	5	360
Kharagpur	W.B.	1st week of Feb.	4th week of June	Sandy clay loam	0·8 IW/CPE (8cm)	6	440
Madurai	T.N.	1st week of Feb.	4th week of June	Sandy loam	0·9 IW/CPE (6cm)	7	420
Jabalpur	M.P.	4th week of June	4th week of Oct.	Black clay	50% Depletion of ASM	3	225

IW = Amount of irrigation water (given in parenthesis)

CPE = Cumulative pan evaporation

ASM = Available soil moisture

TABLE 5

Irrigation requirement of wheat after sowing at different places in India.

Place	State/Union Territory	Season		Soil Type	Optimum regime	Irrigation requirement	
		Sowing	Harvesting			No.	Amount (mm)
Jobner	Rajasthan	2nd week of Nov.	2nd week of April	Sandy to loamy sand	0·9 IW/CPE (4·5 cm)	9	405
Hissar	Haryana	Do.	1st week of April	Sandy loam	0·9 IW/CPE (6 cm)	5	300
Ludhiana	Punjab	1st week of Nov.	Do.	Do.	0·9 IW/CPE (7·5 cm)	5	360
Karnal	Haryana	Do.	Do.	Do.	0·9 IW/CPE (6 cm)	5	300
Delhi	Delhi	Do.	Do.	Do.	0·9 IW/CPE (6 cm)	5	300
Roorkee	U. P.	Do.	Do.	Do.	0·9 IW/CPE (6 cm)	6	360
Bikramganj	Bihar	2nd week of Nov.	Do.	Loam	0·9 IW/CPE (6 cm)	5	300
Ranaghat	West Bengal	4th week of Nov.	Mid March	Clay loam	0·8 IW/CPE (7 cm)	3—4	210—280
Kharagpur	West Bengal	Do.	3rd week of March	Sandy-clay loam	0·9 IW/CPE (8 cm)	5	400
Chakuli	Orissa	2nd week of Nov.	1st week of March	Sandy-loam	0·9 IW/CPE (8 cm)	5	400
Hyderabad	Andhra Pradesh	Mid Nov.	End of Feb.	Sandy clay loam	0·9 IW/CPE (6 cm)	5	300
Jabalpur	Madhya Pradesh	2nd week of Oct.	2nd week of March	Clay to clay loam	1·0 IW/CPE (7·5 cm)	5	375
Indore	Do.	Do.	End March	Medium black clay	1·05 IW/CPE (8 cm)	6	480
Navsari	Gujarat	2nd week of Oct.	Mid March	Black clay	0·8 IW/CPE (8 cm)	6	480
Dharwar	Karnataka	1st week of Nov.	1st week of March	Loam to clay	6 stages	6	300
Siruguppa	Do.	Do.	Do.	Clay	1·05 IW/CPE (6·5 cm)	7	450

IW = Amount of irrigation water (given in parenthesis)
CPE(= Cumulative pan evaporation.
ASM = Available soil miosture.

TABLE 6

Irrigation requirement after sowing of *Mustard* in different parts of India

Place	State/Union Territory	Season		Soil Type	Optimum Regime	Irrigation requirement	
		Sowing	Harvesting			No.	Amount (mm)
Jobner	Rajasthan	2nd week of Sept.	End of March	Sandy to loamy sand	0·55 IW/CPE	4	180
Ludhiana	Punjab	2nd week of Oct.	4th week of March	Loamy sand	3-4 weeks after sowing	1	80
Karnal	Haryana	1st week of Oct.	2nd week of March	Sandy loam	75% depletion of ASM	1	60
Hissar	Haryana	1st week of Oct.	3rd week of March	Sandy loam	0·2 IW/CPE (8cm)	1	80
Chakuli	Orissa	3rd week of Oct.	4th week of Jan.	Sandy loam	0·9 IW/CPE (6cm)	3	180
Kharagpur	W.B.	1st week of Dec.	1st week of Feb.	Sandy clay loam	0·4 IW/CPE (8cm)	1	80
Phulia	W.B.	2nd week of Oct.	2nd week of Feb.	Sandy loam	75% depletion of ASM	2-3	130—195
Pantnagar	U.P.	2nd week of Oct.	1st week of March	Sandy loam	80% depletion of ASM	2	160
Kota	Rajasthan	2nd week of Oct.	1st week of March	Black Clay	Branching and pod formation stages	2	150
Madhipur	Bihar	3rd week of Oct.	3rd week of Jan.	Sandy loam	3rd week of after sowing	1	75
Navasari	Gujarat	Mid Oct.	End March	Clayey	40% depletion of ASM	6	420
Cuttack	Orissa	4th week of Oct.	1st week of Feb.	Sandy loam	Branching and flowering.	2	100

IW—Amount of irrigation water (given in parenthesis)

CPE—Cumulative pan evaporation

ASM—Available soil moisture.

TABLE 7

Irrigation requirement of *Safflower* after sowing in different parts of India

Place	State/Union Territory	Season		Soil Type	Optimum regime	Irrigation requirement	
		Sowing	Harvesting			No.	Amount (mm)
Karnal	Haryana	4th week of Sept.	1st week of May	Sandy loam	0·2 IW/CPE (6 cm)	2	120
Delhi	Delhi	4th week of Sept.	1st week of May	Sandy loam	Rosette & flowring Stages	2	150
Indore	Madhya Pradesh	4th week of Sept.	2nd week of April	Black clay	0·4 IW/CPE (8 cm)	2	160
Dharwar	Karnataka	1st week of Nov.	4th week of March	Black clay	0·6 IW/CPE (6 cm)	5	300
Siruguppa	Karnataka	1st week of Nov.	4th week of March	Black clay	0·4 IW/CPE (8 cm)	4	285
Pantnagar	Uttar Pradesh	4th week of Nov.	1st week of May	Silty clay loam	7 weeks after sowing	1	80

IW=Amount of irrigation water (given in parenthesis)

CPE=Cumulative pan evaporation

TABLE 8

Irrigation requirement after sowing of *cotton* in different parts of India

Place	State/Union Territory	Season		Soil type	Optimum regime	Irrigation requirement	
		Sowing	Picking period			No.	Amount (mm)
Hissar	Haryana	May	Sep.-Oct.	Sandy loam	25% depletion of ASM	4	350
Ludhiana	Punjab	May	Sep.Oct.	Sandy loam	*Stages	5	300
Delhi	Delhi	May	Sep.-Oct.	Sandy loam	50% depletion of ASM	3	210
Bhavanisagar	Tamil Nadu	February	June	Red Sandy loam	Do.	11	725
Coimbatore	Do.	(*i*) 3rd week of Aug.	Feb.	Clay loam	75% depletion of ASM	5	300
		(*ii*) February	June	Clay loam	80% depletion of ASM	6	360
Siruguppa	Karnataka	Mid of August	March	Clay	75% depletion of ASM	6	640
Dharwar	Do.	August	March	Clay	Do.	5	640
Rahuri	Maharashtra	July	February	Clay	Do.	2	150
Akola	Do.	Do.	January	Clay	—	2	200
Hyderabad	Andhra Pradesh	Sept.	April	Black clay	0·8 IW/CPE	11	640

ASM = Available soil moisture

IW = Amount of irrigation water (given in parenthesis)

CPE = Cumulative pan evaporation

*Stages = 2 irrigation during pre-flowering, 2 during flowering and 1 during post flowering.

TABLE 9

Irrigation requirement after planting of *sugarcane* in different parts of India.

Place	State/Union Territory	Season		Soil Type	Optimum Regime	Irrigation requirement	
		Sowing	Harvesting			No.	Amount(mm)
Delhi	Delhi	Ist week of March	Jan. to February	Sandy loam	0·7 atm. at 22·5 cm soil depth.	12	860
Ludhiana	Punjab	Do.	Do.	Do.	0·75 IW/CPE (7·75cm)	8	620
Roorkee	Uttar Pradesh	Feb. to March	Dec. to January	Do.	40% depletion of ASM	11	660
Karnal	Haryana	1st week of March	January	Do.	50% depletion of ASM	8	600
Madhipura	Bihar	February	Dec. to January	Do.	30% depletion of ASM	10	500
Bikramganj	Do.	Do.	Do.	Loam	—	7	450
Padegaon	Maharashtra	January (June for adsali)	January	Clay loam	0·4 bar at 30-45 cm soil depth	25	*2150
Anakapalle	AP	Do.	Dec.	Do.		10	700
Coimbatore	Tamil Nadu	Dec. to January	Nov.—Dec.	Clay loam		14	1000
Navsari	Gujarat	January	February	Clay	40% depletion of ASM	13	1300

*The irrigation requirement is for one year crops.

2 For *adsali* crop, the irrigation requirement will be more.

Return flows from irrigation in Messilla Valley have been predicted analytically and compared with measured drain discharge by Harley (1968). The findings of the study by Harley are presented in Table 10 and 11. Deep percolation has been assumed to be equal to sum of diversion and effective precipitation minus the waste and consumptive use. The return flow has been calculated using Glover's solution.

TABLE 10-DEEP PERCOLATION CALCULATIONS AND RESULTS, BY MONTHS FOR 1940 AND 1941, IN 1,000 ACRE FEET

Year (1)	Month (2)	Measured Divers-ion (3)	Measured Waste (4)	Effective Precip-itation (5)	Estimated Consum-ptive Use (6)	Calculated Deep perc-olation (7)	Measured Drain Discharge (8)	Calculated Return Flow (9)	Variation (8)-(9) (10)
1940	January	1.5	1.0	0.5	5.7	0.0	10.9	7.7	3.2
	February	6.4	2.2	3.2	5.7	1.7	9.8	6.2	3.6
	March	41.7	5.4	0.1	11.5	24.9	14.6	11.5	3.1
	April	65.9	5.5	1.1	19.8	41.7	19.8	20.2	-0.4
	May	49.2	5.1	3.2	21.4	25.9	22.4	21.8	0.6
	June	61.1	6.6	8.7	30.6	32.6	24.3	24.6	-0.3
	July	74.5	5.9	7.2	42.0	33.8	27.3	27.1	0.2
	August	70.[illegible]	6.3	3.4	40.2	27.4	27.2	27.1	0.1
	September	50.9	6.1	8.5	27.2	26.1	25.6	26.7	-1.1
	October	8.3	2.2	3.6	14.0	0.0	18.8	19.1	-0.3
	November	4.0	0.9	3.1	5.7	0.5	13.2	13.7	-0.5
	December	0.8	0.2	2.9	5.7	0.0	11.6	11.0	1.6
1941	January	0.0	0.0	6.7	5.7	1.0	10.2	7.6	2.6
	February	3.5	1.1	1.9	5.7	0.0	8.3	5.6	2.7
	March	33.2	5.2	6.3	11.4	22.9	11.3	10.5	0.8
	April	66.5	8.0	5.1	19.6	44.0	18.4	20.1	-1.7
	May	45.5	6.4	3.6	21.2	21.5	21.1	20.6	0.5
	June	63.1	4.4	4.5	30.3	32.9	22.6	23.7	-1.1
	July	74.8	6.6	11.6	41.6	38.2	26.3	27.8	-1.5
	August	61.5	11.2	11.3	39.8	21.8	25.9	26.0	-0.1
	September	37.7	6.2	36.4	26.8	41.1	25.1	30.0	-4.9
	October	8.1	3.0	4.8	14.8	0.0	19.3	21.7	-2.4
	November	5.3	2.3	1.5	5.7	0.0	14.1	15.2	-1.1
	December	5.5	2.2	2.4	5.7	0.0	13.1	11.1	

TABLE 11 ANNUAL SUMMARY OF RESULTS, IN 1,000 ACRE-FEET

Calendar Year (1)	Calculated Deep Percolation (2)	Measured Drain Discharge (3)	Calculated Return Flow (4)	Variation, (3) - (4) (5)
1933	213.3	205.3		
1934	212.9	217.9	217.7	0.2
1935	135.7	167.2	138.7	28.5
1936	191.7	185.1	184.3	0.8
1937	178.7	180.3	184.1	- 3.8
1938	185.5	185.9	182.6	3.3
1939	222.2	217.4	218.3	- 0.9
1940	214.6	225.5	215.8	- 9.7
1941	223.4	215.7	220.0	- 4.3
1942	235.1	235.8	229.9	5.9
1943	266.7	256.8	265.9	- 9.1
1944	264.9	262.4	263.7	- 1.3
1945	280.8	225.3	276.7	-51.4

3.0 WATER QUALITY ASPECT OF IRRIGATION RETURN FLOW

3.1 Reuse of Irrigation Return Flow

Multiple use of irrigation return flow offers significant opportunities for increasing the efficiency of water use in irrigation if proper attention is paid to water quality constraints. The profitability of reusing agricultural drainage water for crop production depends on the salt tolerance of the crop being grown, the salt concentration of the drainage water. Salt concentration of typical irrigation and drainage water in some vallies in USA are given in Table 12 (Knapp and Dinar, 1984).

3.2 Water Quality Effects of Irrigation Return Flows

Irrigation return flows degrade the quality of receiving waters in various ways. In USA, irrigation-related pollution is equal in importance to municipal and industrial waste categories, not in terms of pounds or gallons of pollutants, but in terms of degradation of receiving waters, characteristically in water short areas (Blackman et. al, 1977). Detriments include, increases in solids (suspended, settleable, and dissolved), nutrients, pesticides, and temperature. Where consumptive losses of water are attributable to high rates of evaporation and transpiration, increases in total dissolved solids (salinity) may be acute. In arid areas irrigation may cause increases in the salinity of streams by salt-loading and salt concentrating mechanisms. Salt loading results from leaching of mineral salts from irrigated soil. The irrigation

TABLE 12 SALT CONCENTRATIONS OF TYPICAL IRRIGATION AND DRAINAGE WATERS IN IMPERIAL VALLEY, COACHELLA VALLEY, AND KERN COUNTY, CALIFORNIA (meq/l)

	Coachella Valley	Imperial Valley	Kern County
Irrigation Water	14.0	13.73	7.1
Drainage Water	32.57	43.80	75.2

return flow quality problem as visualized by Radosevich and Skogerboe (1977) is shown in Figure 18.

Annual salt yields from irrigated lands in the Colorado River Basin range from 8.5 tons/acre (1.9 kg/m^2) in the Price River Valley to less than 0.1 ton/acre (0.022 kg/m^2) in the Green River Valley upstream of the New Fork River (Blackmal et.al, 1977). The variability of such yields is attributed to many factors, including soil composition, chemical composition of applied water, quantity of water applied, residence time of water in and on soils, depth of percolation to drainage, type of drainage, and evaporation rates.

Salinity in drinking water supplies having sodium as a constituent is a health hazard for a significant portion of the population, including persons suffering from hypertension, edema associated with congestive heart failure and women with toxemias of pregnancy. Diets for these individuals permit 20 mg/l sodium in drinking water and water used for cooking (Vide, Blackman et.al, 1977).. These concentrations are routinely exceeded in streams polluted by irrigation return flow.

Nutrients reach receiving waters by the discharge of tailwater, and through near-surface percolation and subsequent return as base flow or diffuse discharges. In many areas of the northwestern States, USA, natural phosphate sources are sufficient to stimulate nuisance aquatic growth when combined with nitrogenous form discharged by irrigation drains. The

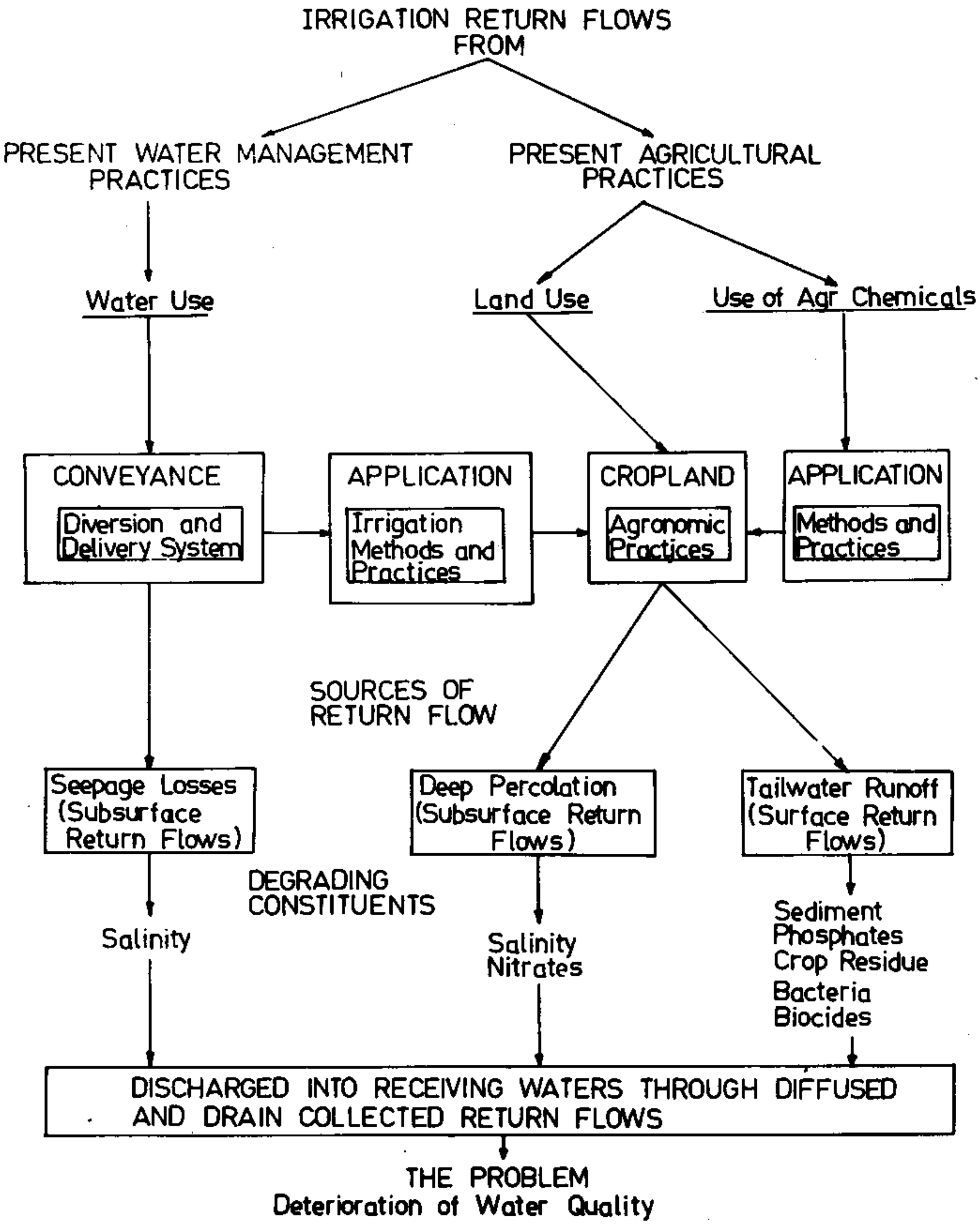


FIGURE 18 - THE IRRIGATION RETURN FLOW QUALITY PROBLEM

detriments associated with overenrichment of streams include accelerated eutrophication of lakes and reservoirs, impairment of fisheries, depressed oxygen concentrations, impairment of navigation, taste and odor in drinking water supplies, and interference with water treatment processes. Overenrichment has reached problem proportions in many receiving water bodies in the irrigated areas of the western USA. Among the more notable are the Snake River impoundments and the San Joaquin River.

Pesticides enter receiving waters as drift and overspray from aerial applications on and into canals, drains, and streams, in runoff from fields during storms, in subsurface drainage and tailwater from irrigated fields, from dumping of excess mixes and cleanup of application equipment in water ways and by direct application to control aquatic weeds, rough fish, and aquatic insect pests.

Pesticide pollution from irrigated areas occurs as random localized events, frequently manifested as fish kills caused by organo-phosphorous and organochlorine pesticides. The problem has been documented throughout the western USA but it has been more frequently observed in the arid Southwest part of USA where year-around cropping prevails. In 1971, 30% of the fish kills in Arizona, California, Nevada were pesticides-caused.

An enormous amount of research has been and is under-way to develop control and abatement mechanisms for IRF, and many of these mechanisms have been shown to be technically feasible

(Blackman et. al, 1977). These mechanisms include: Lining of conveyances, optimization of quantity of water applied, pump-back systems, optimization of type and quantity of fertilizer and pesticide applications, improved levelling and furrowing, scheduling, elimination of tailwater discharges,subsurface delivery systems, on-surface trickle systems, tile drainage systems, and ponding of drainage.

Reduction in concentrations and loads of important pollutants in irrigation return flow can be attained by optimizing the quantity of water applied and the frequency of application. If only that quantity of water necessary to meet the leaching requirement and satisfy plant requirements are applied: (1) Lesser quantities of salts would be leached from irrigated soils, (2) greater amounts of water could remain in receiving streams to dilute incoming pollutant loads, (3) solids (dissolved, suspended, and settleable), pesticides, and fertilizers carried to streams by tailwater discharges could be retained on fields, (4) losses from unlined coveyance channels, and leaching of soils by water thus lost could be reduced.

4.0 REMARKS

Irrigation return flow problems and appropriate solution to these problems are site specific. Quantification of irrigation return flow for different irrigation practice and for different crop in India is yet to be made through experimental research. Irrigation return flow in some basin can be as high as 71%. Quantification of return flow would indicate the state of irrigation water use in a basin. Uncared irrigation return flow creates water quality problems. Therefore, measures to retard irrigation return flow through improved irrigation practice should be given due consideration. Reuse of agricultural drainage water for crop production depends on the salt tolerance of the crop being grown and the salt concentration of the drainage water.

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