High Frequency Basin Irrigation Design for Non-rice Crops in Ricelands

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Abstract

Rice soils are generally characterized by heavy textures, poor structures, low porosities and permeabilities, shallow traffic pans and slow rates of internal drainage. Growth and yields of non-rice crops in these soils are adversely affected because of restricted root aeration and development. Under these conditions, irrigation of non-rice crops poses serious problems because of further reductions in the air-filled porosity and the soil's tendency to waterlog.

A high frequency basin irrigation method for non-rice crops in rice soils was developed. It was based on a computer solution of the Lewis and Milne surface irrigation volume balance equation by numerically inverting the Laplace transform of the equation. The method provides an optimum design for the alleviation of soil-related adverse effects while enabling a high application efficiency and uniformity.

The method was rested in three different fields in Guimba, Nueva Ecija. Water depths of 0.330, 0.325 and 0.374 meter with design application efficiencies of 90.9, 92.4 and 93.7% were applied in 8, 7 and 10 low volume irrigations, respectively. The corresponding yields were 8.08, 6.14, and 9.17 t/ha, while farmer yields in the area average 2.0-2.5 t/ha.

Introduction

The potential of irrigated upland (non-rice) crops in crop diversification schemes is seldom realized for a number of reasons. These may include:

1. Inadequate or excessive water applications, due to lack of experience with non-rice crops and resulting in low application efficiencies and uniformities. Thus, yields are adversely affected and limited water, energy and financial resources are wasted.
2. Selection of crop inappropriate for the amount of available water and existing market price environment.

These problems are compounded by the physical constraints of rice soils when planted to upland crops. Puddling destroys the soil structure and results in high resistance to root penetration, low porosities and permeabilities and the formation of a shallow traffic pan which further impedes vertical water movement, thus reducing infiltration and percolation rates. The heavier soil textures usually associated with rice soils magnify these problems by restricting drainage and promoting waterlogging. Moreover, such soils tend to crust when irrigated. These conditions reduce root aeration, impede root development of upland crops and adversely affect crop growth and yields. Imgation of upland in rice soils poses formidable problems because of the aforementioned limitations and a much higher level of management is necessary to overcome these deficiencies.

Surface Irrigation Method Selection

Basin irrigation was selected as the most appropriate irrigation method for rice fields. Selection was based on the following considerations:

1. Rice fields are remarkably flat (at least within the paddies) because of the levelling effect of puddling.

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2. The maintenance requirements for basin irrigation are very limited as opposed to furrow irrigation. Operation of the irrigation system is easy and can be easily handled by a single person.
3. Minimal easily-removed modifications to the basic paddy geometry was desired to minimize labor and energy requirements and costs.
4. Previous socio-economic research bas shown that majority of the farmers rely on rented machinery for cultural operations and that the availability of capital is the most important constraint to agricultural production. The simple construction of a basin irrigation system is less expensive and may increase profitability.

The ensuing analysis is based on small, shallow-well (and usually privately owned) pump irrigation systems. These irrigation systems were selected because they allow total water control and management flexibility. However, if reliable water supply at the system level is available, the concepts of this research can be used in larger deep-well systems, as well as surface irrigation systems serving large command areas.

The Mathematical Model

Based **on** the work of Lewis and Milne (1938) and Davis (1961), the volume balance equation for basin imgation is

$$Q_u = C_s \cdot l + \int_0^l fz(t_{op})dx \tag{1}$$

where

$$Q_u = \frac{Q}{W} \tag{2}$$

Q = the inflow rate ($m' . sec^{-1}$);
Q_u = the stream size ($m^3 . sec^{-1}$);
t_l = the stream advance time to reach a distance l from the inlet (sec);
W = the basin width (m);
C_s = the surface storage (m);
$fz_{(t)}$ = cumulative infiltration function (m);
t_{op} = the infiltration opportunity time (see);

and

$$t_{op} = t_l - t_x \tag{3}$$

where tx is the advance time to distance x from the inlet (Figure 1).

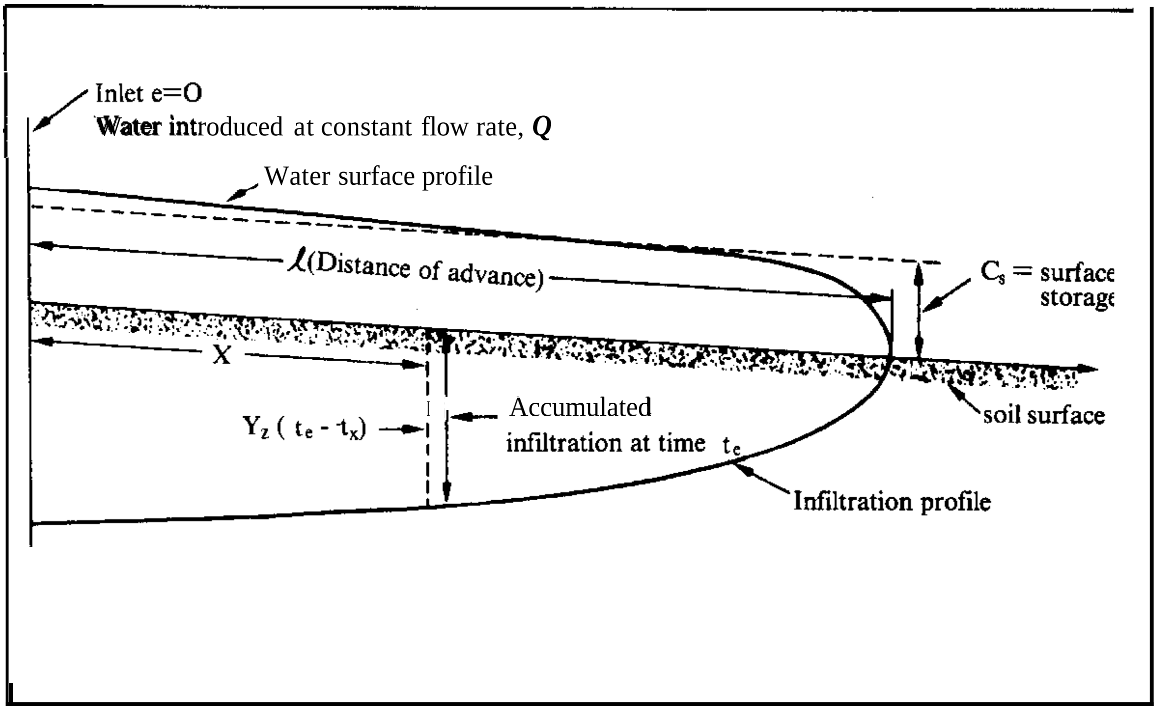

Figure 1. Water profiles the advance phase of basin irrigation.

In equation (I) C_s represents the average depth of water at the soil surface and is a function of time. Ley (1978) and Wilke and Smerdon (1965) indicated that C_s can be assumed independent of time when the surface stream wetting front has advanced a significant distance. This significant distance depends on the field's hydraulic characteristics, i.e. slope, flow rate, roughness and infiltration. In most cases C_s can be considered constant after the wetting front has advanced over 100 m. Rice paddies are seldom that long. Moreover, experience indicated that basin lengths shorter than 100 m are needed in order to achieve application uniformity and water economy and avoid waterlogging. Therefore, C_s cannot be assumed constant. In order to avoid the problem of C_s time dependence in the analysis, C_s is treated as piecewise constant, i.e. constant between two successive points in time but changing over time. This approach was proven satisfactory. The surface storage **is** computed **as**

$$C_s = 0.9\ .n^{3/8} Q_u^{9/16}\left[(t_{m,l})_n^{3\ 16} + (t_{m,l})_{n-1}^{3/16}\right], \tag{4}$$

where

n = **the Manning roughness coefficient;**
$(t_{m,l})_n$ = **the** time **of current calculation (*min*);**
$(t_{m,l})_{n-1}$ = the time **of last calculation (*min*).**

The integral in equation (I) becomes

$$\int_0^{t_l} fz(t_l - t_x)\,dx = \int_0^{t_l} fz(t_l - t_x) I'(t_x) dt_x \tag{5}$$

where

$$I'(t) = \frac{dI}{dt} \tag{6}$$

Combining equations (I) and (5), we obtain:

$$\underbrace{Q_u \cdot t_l}_{TWV} = \underbrace{C_s \cdot I}_{SSV} + \underbrace{\int_0^{t_l} fz(t_l - t_x) I'(t_x) I'(t_x) dt_x}_{I} \tag{7}$$

and TWV, SSV and I represent the total water volume admitted to the basin, the surface storage volume and the total volume of infiltrated water.

Philip and Farrel (1964) determined that equation (7) is valid if I is a monotonically increasing function of t_l, a condition which places a restriction on the form of fz. Sufficient conditions are:

$$fz \geq 0,\ \frac{dfz}{dt} \geq 0,\ \text{and}\ \frac{d^2 fz}{dt^2} \geq 0. \tag{8}$$

These conditions are generally met and equation (I) is valid.

Applying the Laplace transform to both sides of equation (7), we have:

$$L\{Q_u \cdot t_l\} = L\{C_s \cdot I\} + L\left\{\int_0^{t_l} fz(t_l - t_x) I'(t_x) dt_x\right\} \rightarrow$$

$$\frac{Q_u}{s^2} = Cs \cdot L\{I\} + L\left\{\int_0^{t_l} fz(t_l - t_x) I'(t_x) dt\right.^{1} \tag{9}$$

Using the convolution theorem

$$L\left\{\int_0^{t_l} fz(t_l - t_x) I'(t_x) dt_x\right\} = L\{fz\}\ .L\{I'\}\ . \tag{10}$$

From the properties of Laplace transforms

$$L\{I'\} = sL\{I\} - I(0) = sL\{I\} \tag{11}$$

because $I(0) = 0$.

Combining equations (9), (10) and (11) and solving for $L\{I\}$, we obtain:

$$L\{I\} = \frac{Q_u}{s^2 Cs + s^3 L\{fz\}} \tag{12}$$

From a large number of field tests the infiltration of rice soils was determined to be of the form

$$fz = a \cdot t_m^b\ \mathrm{t}\ c = a\left(\frac{t}{60}\right)^b + c;\ 0 \leq b \leq 1;\ t > 0 \tag{13}$$

where

a. b. c, = constants, and t_m = elapsed time (***min***).

Taking the Laplace transform of equation **(13)**,

$$L\{fz\} = \frac{a\Gamma(b+1)}{(60)^b s^{b+1}} + \frac{c}{s} \tag{14}$$

where Γ denotes the gamma function. Substitution in equation **(12)** and rearrangement yields:

$$L\{I\} = \frac{Q_u}{\omega s^{2-b} + (C_s + c)s^2} \tag{15}$$

where

$$\omega = \frac{a\Gamma(b+1)}{(60)^b}$$

The expression for I can then be determined by taking the inverse Laplace transform of equation (15), i.e.

$$\overline{\omega s^{-\sigma} + (C_s + c)s^2}$$

The inverse Laplace transform in equation (16) cannot be readily be found. For $c = 0$, ***Philip*** and *Farell* [1964] obtained the following analytical solution for l:

$$l(t_l) = \frac{Q_u \cdot t_l}{(C_s + c)} \sum_{m=0}^{\infty} \frac{\left[\frac{-a\Gamma(1+b)t_l^b}{(C_s + c)}\right]^m}{\Gamma(2 + mb)} \qquad (17)$$

This solution is valid for small t's. Moreover, calculations are complicated for large values of $at^b/(C_s + c)$ because the magnitude of the individual terms becomes very large. The series alternates in sign and accumulates as differences of very large numbers, which may result in round-off errors.

Equation (16) was inverted numerically by using the *Stehfest* [1970] method. The scheme was based on the following equations:

$$s_i = \frac{ln2}{t_l} i\ , \qquad (18)$$

$$l(t_l) = \frac{ln2}{t_l} \sum_{i=1}^{N} V_i \cdot L\{[l(s_i)]\}\ ,\ \text{and} \qquad (19)$$

$$V_i = (-1)^{\frac{N}{2}+i} \sum_{k=\frac{i+1}{2}}^{\min(i,N/2)} \frac{k^{N/2}(2k)!}{(\frac{N}{2} - k)!k!(k-1)!(i-k)!(2k-i)!} \qquad (20)$$

For double precision variables the optimum value for N is $N = 18$. The $L\{[l(s_i)]\}$ in equation (19) is obtained from equation (15).

The calculations yield pairs of $(t_l,l)_1, (t_l,l)_2, \ldots, (t_l,l)_n$ and proceed until the field length L is reached. The time of advance t_a, i.e. the time corresponding to the field length L cannot be determined directly and an interpolation procedure has to be used. Once the advancing water front reaches L, the advance ceases due to the physical restriction of ridges or bunds and the surface storage C_s increases rapidly. Under these circumstances equation (1) is no longer valid and the infiltration volume is given by the equation

$$I = \int_0^L fz(t - t_l)dl, \qquad t \geq t_L\ . \qquad (21)$$

No analytical expression is available for $t_l = t_l(l)$. Therefore, I has to be evaluated numerically using the data points $(t_l,l)_2, (t_l,l)_2, \ldots, (t_l,l)_{nL}$, where nL the data point number corresponding to the end of the field.

The determination of the 'cut-off time' t, (sometimes called the 'application time?, the 'basinwide opportunity time' t_{opb} (defined **as** the time required for water to infiltrate in the basin), the application efficiency E_a (defined as the fraction of the water applied to a field which remains within **a** management defined soil zone) depends on the design parameter used **as** the measure of water application. Three cases can be identified:

***Case** I: **Given** Gross **Application Depth** d_{gr}*

The cut-off time t_{co} is calculated **as**

$$t_{co} = \frac{L \cdot d_{gr}}{Q_u} \qquad (22)$$

The basinwide opportunity time t_{opb} is then determined from the equation

$$I_T = Q_u \cdot t_{co} = \int_0^L fz(t_{opb} - t_l)dl, \qquad (23)$$

where I_T the total infiltration volume. Since there is no analytical expression for t_l, t_{opb} cannot be analytically determined and an interpolation procedure must be used.

The average application depth d_{avg} is calculated from

$$d_{avg} = \frac{I_T}{L} \qquad (24)$$

With reference to Figure **2** the application efficiency E_a is then

$$E_a = \frac{V_1}{V_1 + V_2} \text{ or } E_a = \frac{d_{avg}}{d_{gr}}\ , \qquad (25)$$

where V_1 is the volume of water above d_{avg} and V_2 the volume of water which infiltrates below d_{avg}.

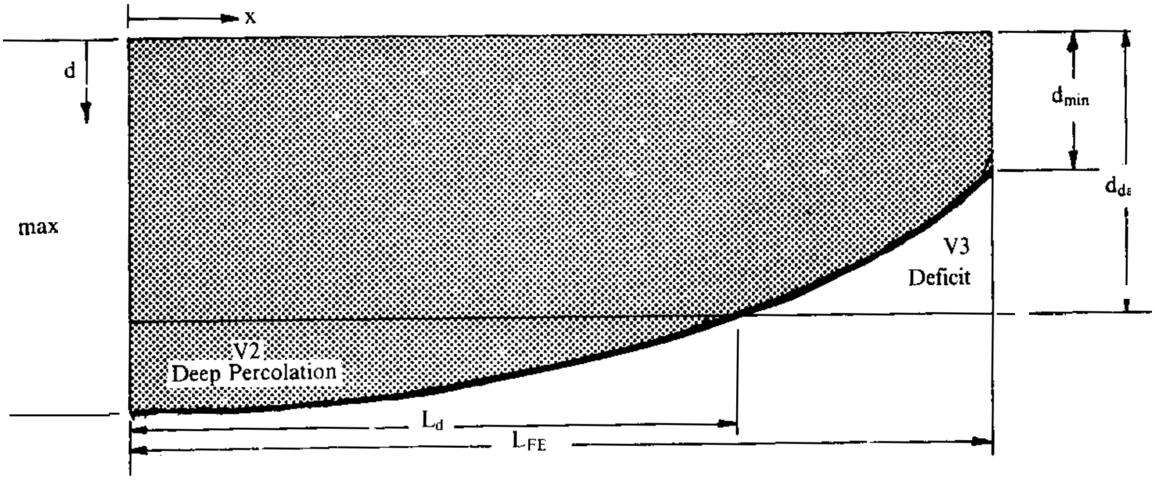

Figure 2. Infiltrated depth profile.

Case 2: Given Desired Application Depth d_{da}

The basinwide opportunity time t_{opb} is determined from

$$d_{da} \,.\, L = \int_0^L fz(t_{opb} - t_l)dl \,. \tag{26}$$

An interpolation procedure must be used since t_{opb} cannot be computed analytically.

With reference to Figure 2,

$$E_a = \frac{V_1}{V_l + V_2} = \frac{d_{da}}{d_{gr}} , \tag{27}$$

where V_1 and V_2 the water volumes above and below d_{da}. From (27)

$$d_{gr} = \frac{d_{da}}{E_a} , \tag{28}$$

and

$$t_{co} = \frac{L \cdot d_{gr}}{Q_u} \tag{29}$$

Case 3: Given Minimum Desired Application Depth $(d_{da})_{min}$

This corresponds to a desired application depth at $l = L$. The opportunity time at L is

$$(t_{op})_l = \left[\frac{(d_{da})_{min} - c}{a}\right]^{\frac{1}{b}} ,$$

and the basin wide opportunity time is then

$$t_{opb} = 1 + (t_{op})_{min} \,. \tag{30}$$

The total infiltration is then given by

$$I_T = \int_0^L fz(t_{opb} - t_l)dl , \tag{31}$$

and

$$d_{avg} = \frac{I_T}{L} , \tag{32}$$

$$t_{co} = \frac{I_T}{Q_u} , \tag{33}$$

$$E_a = \frac{V_1}{V_l + V_2} = \frac{(d_{da})_{min}}{d_{avg}} \tag{34}$$

A computer program was written in FORTRAN **77** to carry out the necessary calculations for the study. For maximum accuracy double precision variables were used.

The infiltration volumes (equations of the type of equation [21]) were calculated using acuhic spline interpolation of the data points $(t_i, l)_i$, $i = 0, 1, \ldots, nL$ and integrating the resulting quadratic equations over the distance $[0, L]$. These calculations begin when $i = 4$ and proceed until the value of I **has** been bracketed. **A** linear interpolation was then **used** to determine the unknown t_{opb}.

Considerations and Constraints

The design of an efficient basin irrigation system for upland crop irrigation in ricelands must meet the following requirements:

1. Minimization of deep percolation for water and energy conservation.
2. Alleviation of waterlogging. which is a frequent and serious constraint lo upland production. The problem is addressed by ensuring that infiltrated water does not reach the traffic pan. It was found that the depth of ricefield traffic pans ranged from 0.15-0.20 m from the soil surface and the water-fillable porosity was roughly $\phi_{wf} = 33\%$. Assumingthat the minimumdepth to the traffic pan $(D_{tp})_{min} = 0.15\,m$, the maximum permissible water application depth (for waterlogging alleviation) is

$$d_{max} = \phi_{wf} \cdot (D_{tp})_{min} = 0.05\ m\ (= 50mm) \qquad (35)$$

   Water application of less than 0.03 m were determined to be operationally inefficient, requiring an excessive number of irrigation and small basin dimensions which **is** not practical. This determines the minimum permissible application depth $d_{min} = 0.03$ m. Application dcptbs have to fall between these two extremes, i.e.

$$d_{min} \leq d_{du} \leq d_{max} \rightarrow 0.03\ \mathrm{m} \leq d_{da} \leq 0.05\ \mathrm{m}. \qquad (36)$$

   The condition **in** equation (36) dictate **a** high number of low volume irrigation to supply the same quantity of water required by the crop, thus, defining a high frequency basin irrigation method.

3. High application efficiency, E_a. For the size, dimensions and, hydraulic characteristics of the bunded rice-field basins or sub-basins, the minimum acceptable application efficiency $(E_a)_{min} = 85\%$. For design purposes $(E_a)_{dsn} \geq 90\%$.
4. High uniformity. Objectives 3 and **4** aim to minimize water and energy losses and their associated costs, and to maximize crop yields. Design for these two objectives has to account for the following variabilities:
   a. Infiltration characteristics variability, both spatial and in time, as quantified by the variability in parameters ***a, b,*** and c of the infiltration equation.
   b. Space and time variability of the hydraulic characteristics of the soil surface, **as** quantified by the Manning roughness coefficient ***n.***
   c. Variability of the flow rate of the water supply.

The irrigation system for upland crops in ricelands was designed to determine sub-basin dimensions capable of accommodating considerable changes in the values of any combination of the uncertainties described above without a significant decrease in application efficiency.

Design Procedure

The design procedure is based on **a** "worst case" scenario **as** follow:

1. Parameters ***a, b*** and c of the infiltration equation and their corresponding range of values are determined through **a** number of tests. The double ring infiltrometer is the most appropriate apparatus because of its simplicity and the similarity of its principle to the conditions pertaining to basin irrigation.

   Of the three parameters, c **has** the most pronounced effect on E_a because of its magnitude and variability, while *a* and ***b*** do not exhibit large variations. In a number of infiltration tests conducted under a different experiment, the value of c ranged from 0.002-0.023 m; at the study site, values ranged from 0.005-0.018 m. The value of c depends on soil texture, moisture content, **as** well **as** land preparation practices and the corresponding time elapsed since the end of the activity. The largest value of c corresponds to the lowest E_a and is used for the design. The value of c is usually at its highest, immediately after the end of land preparation, i.e., at the first irrigation. If infiltration tests cannot be conducted and there is no information, a design **c** value of 0.015 - 0.017 meter is adequate for the conditions of most **rice** fields.

2. The Manning roughness coefficient n is determined. Table I shows the values of n for some soil surface conditions and crops. It **wasfoundthatnwasnotimportantfora** well harrowed field. Therefore, n = 0.05 is sufficiently accurate for corn throughout the growing season.

Table 1. Common Manning Roughness Coefficient n Used in Basin Irrigation Design.

Smooth, bare soil surface non-cultivated	0.04
Small grain, drill rows parallel to direction of water flow	0.10
Broadcast small grains	0.15
Dense sod crops, small grains with drill rows across the water flow direction	0.25

3. The minimum available well flow rate is determined and used as the design rate. However, well flow rate may change considerably during the growth season because of possible interferences from other wells, evapotranspiration and drainage, which lower the water table. Historical data may be used for the determination of Q_{min}. If these are not available, the design flow rate is taken **as**

$$Q_{dsn} = Q_{min} \simeq \frac{Q_{max}}{\,}$$

where Q_{max} the well flow rate at the beginning of the dry season and easily determined through a simple well test.

4. The minimum permissible application depth d, is taken as the design application depth, i.e.

$$d_{dsn} = d_{min} = 0.03\ \mathrm{m} \qquad (38)$$

5. The design application efficiency $(E_a)_{dsn}$ is set at

$$(E_a)_{dsn} = 90\%. \qquad (39)$$

If ample water supply is available and the soil is a silty clay loam or lighter, $(E_a)_{dsn}$ may be taken as low as **80%.**

The values of these design parameters were determined under the “worst case”. Any changes in value indicate an improvement and results in higher E_a. While this is a conservative approach, it was deemed necessary to overcome the extreme sensitivity of rice soils to waterlogging.

Using the above parameters and the computer solution of the Lewis and **Milne** equation, the values of t_{co}, t_a, and E_a were determined for a wide combination of the basin dimensions, W and L. The resulting families of curves are plotted in figure 3 (with $Q_u = Q/W$ as the independent variable) and in figure **4** (with L **as** the independent and $Q_u/L = Q/(W \cdot L) =$ Q/A **as** the dependent variable).

Using these curves, the basin dimensions for a desired d_{dsn} can be determined. For practical purposes, the basin width $W \geq 4$ m. The process can be repeated for a number of different desired application depths d_{dsr} and graphs similar **to** figures 3 and **4** can be developed. If the infiltration equation does not change significantly with time, the graphs can be used to determine *l*,, and t_a for subsequent irrigations and to evaluate the performance of the irrigation system. If the infiltration equation changes significantly with time, then the computer program has to be used to perform these tasks.

The following demonstrate how the graphs in figures 3 and **4** were used in the design procedure:

Example 1: Basin Irrigation Design

The infiltration equation for a rice field is $fz = 0.003 \cdot t_m^{0.5} + 0.006$ (*t*, in *min*, *fz* in ***m***) and the available water flow rate is $Q = 5.0 \times 10^{-3}\ m^3/\mathrm{sec}^{-3}$. Assuming that the remaining design parameters are the same as in the section “DESIGN PROCEDURE”, determine

a. the sub-basin length L if the desired $W = 10$ m,
b. the sub-basin width W if the desired $L = 20$ m,
c. L and W if the desired sub-basin area is A = 160 m^2

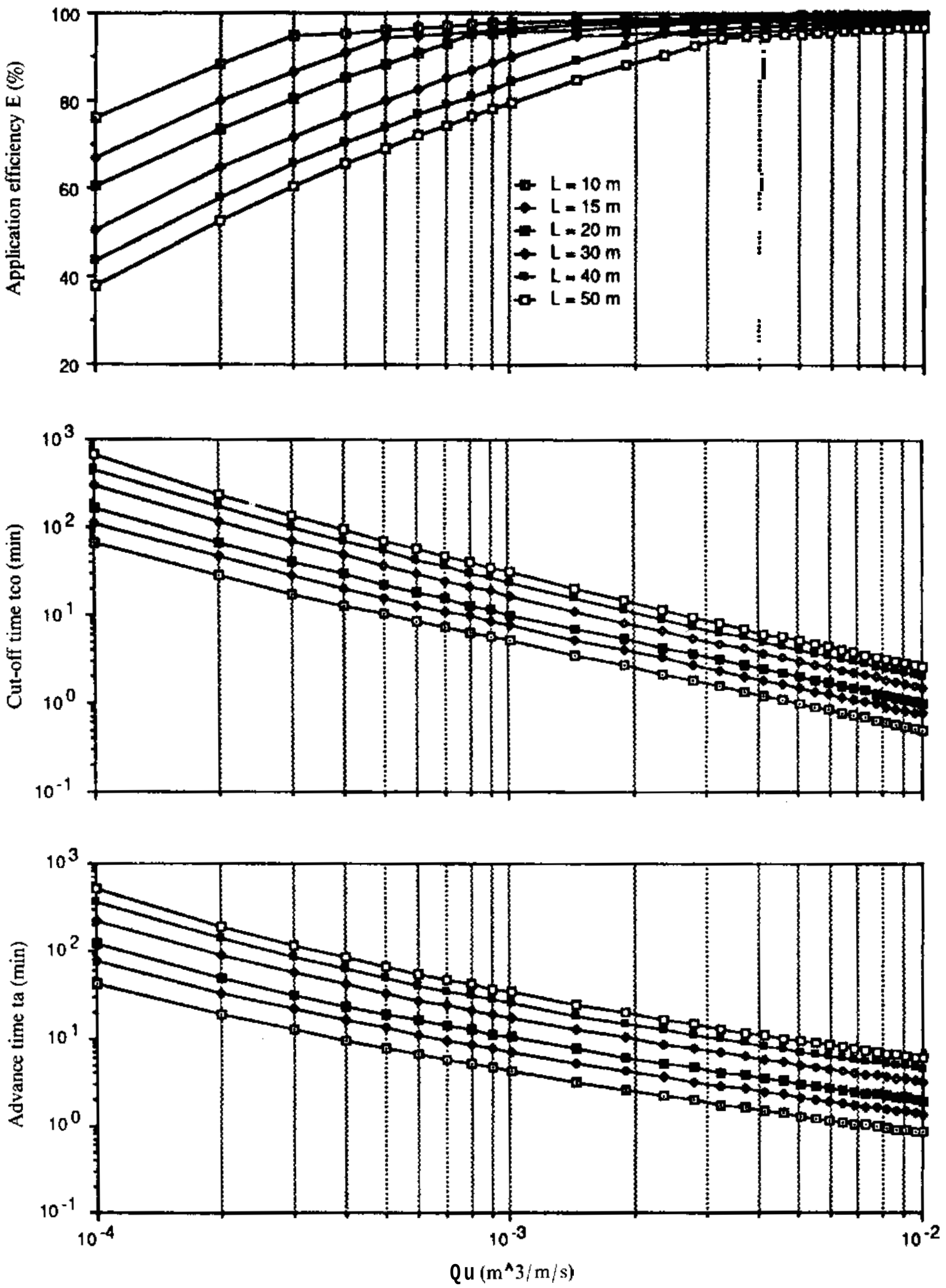

Figure 3. **Application efficiency** E_a, **cut-off time** t_{co} **and time** of **advance** t_a curves for **a desired** application $d_{da} = 0.003\,m$ **when** the **infiltration equation** is $f_z = 0.003 \cdot t_m^{0.5} + 0.006$.

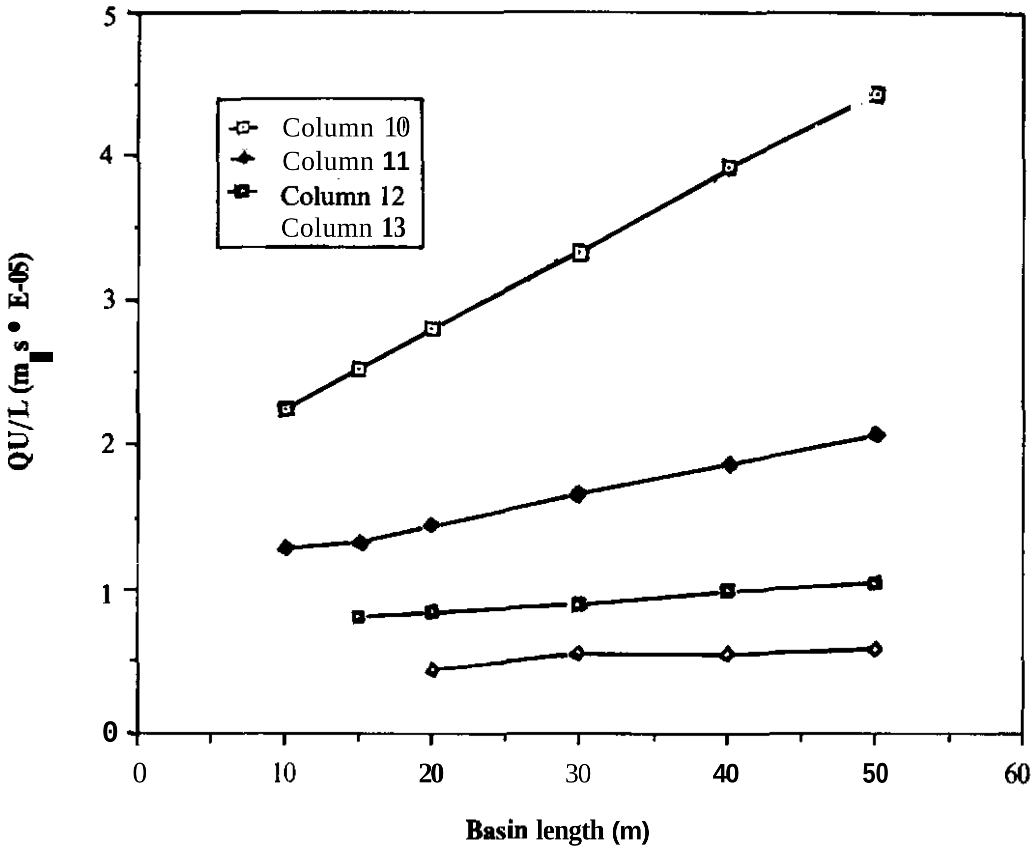

Figure 4. Q_u/L vs. basin length L curves for a desired application $d_{da} = 0.003\ m$ when the infiltration equation is $fz = 0.003 \cdot t_m^{0.5} + 0.006$.

Using the computer solution **of** the Lewis and Milne equation and the procedure already described, the graphs in figure 3 was obtained.

Case a: For $Q_u = Q/W = 5.0 \times 10^{-3}/10 = 5 \times 10^{-4}$ m^{2}sec^{-1} and $(E_a)_{dsn} = 90\%$, and from Figure 3(a) we obtain

$$L = 24 \text{ m.}$$

Case b: For $L = 20$ m, $(E_a)_{dsn} = 90\%$ and **from** Figure 3(a) we have

$$Q_u = 5.7 \times 10^{-4} \text{ m}^2\text{sec}^{-1} = Q/W \rightarrow W = 8.77 \text{ m.}$$

Alternatively, **for** $L = 20$ m, $(E_a)_{dsn} = 90\%$ and from Figure **4** we have

$$Q_u/L = 2.83 \times 10^{-5} = \frac{Q}{W \cdot L} \rightarrow W = 8.83 \text{ m}$$

Case c: For $A = 150\,\text{m}^2$ we have $Q_u/L = Q/A = 3.125 \times 10^{-5}$. From Figure **4** and for $(E_a)_{dsn} = 90\%$,

$$L = 25 \text{ m and } W = A/L = 6.4 \text{ m}$$

Example 2: Basin Irrigation Operation

The sub-basin dimensions **of** a field are $L = 20$ m and $W = 10$ m. The rest of the parameters remain **as** in Problem 1. If the desired application depth $d_{da} = 30$ mm, determine E_a, t_{co}, and t_a.

The stream size $Q_u = Q/W = 5 \times 10^{-3}/10 = 5 \times 10^{-4}$ m^2 sec^{-1}. For $L = 20$ m, we obtain:

from figure 3(a): $E_a = 88\%$
from figure 3(b): $t_{co} = 23$ min, **and**
from figure 3(c): $t_a = 20$ min

Example 3: Evaluation *of* Basin *Irrigation Efficiency*

For the sub-basin **of** Example 2, the observed advance time $(t_a)_{obs}$ was 14 min instead **of** the estimated t_a = 20 min. Determine the application efficiency of the system.

From Figure 3(c) and for $(t_a)_{obs} = 14$ min, $Q_u = 5 \times 10^{-4}$ m^2 sec^{-1}, an "apparent length" was obtained L_a = 15 m, which was the length of a basin with the same Q_u and advance time $t_a = (t_a)_{obs}$ **as** the basin in question. For the same Q_u and $L = L_a = 15$ m, Figure 3(a) yields $E_a = 94\%$, which **was** the actual application efficiency of the system.

Field Testing The Method

The method was tested for corn irrigation in three different rice fields (Figures 4a, 4b and 4c) in Guimba, Nueva Ecija during the 1987/88 dry season. The first (FI) and second (F2) fields were previously planted to corn and had sandy loam and clay soil, respectively. The third (F3) field had clay loam soil and was previously to rice.

Land preparation consisted of plowing and two harrowing operations. Infiltration measurements were taken after land preparation and the infiltration parameter values obtained were used in the design. The irrigation system layouts were developed using the procedure and the computer program earlier described.

Hybrid corn (PIONEER N115R) wasplanted in rows at 0.80 m apart, and at 0.20 m between hills. NPK fertilizer was applied at a rate of 110:60:40 kg/ha. Since corn was a relatively new dry season crop in the area, plants were remarkably free of diseases and insects commonly associated with corn. The extremely low infestation level was also attributed to the basin irrigation method which offered the advantage of water ponding in the basins for periods longer than 20 min (the limit of viability of most soil-borne insects). Weed infestation was a problem in F1 which was not planted to rice during the previous wet season. Weed infestation was moderate to low in F2 and F3. Weeds were controlled using herbicide application and by manual weeding. Once full cover had been achieved, weeds were not aproblem. In F2 and F3, which had heavier soils, there was a need to break the soil crust that formed after irrigation.

All three fields were supplied with water from shallow (10 m deep) and privately owned wells. F3 was well irrigated during the entire growing period. The pumps **at** FI and F2 developed mechanical problems later in the season and water had ***to*** be supplied from a deep, high-output communal well serving the area.

A number of infiltration measurements were taken in the fields prior to irrigation. It was determined that the infiltration parameters of equation (21) demonstrate the largest changes during the first month after land preparation. After this period changes in individual parameters were observed but they were moderate and the cumulative infiltration volume vs. time did not change.

The principle behind the high frequency basin irrigation method was based on the replacement of the moisture depleted from the top 0.15-0.20 m of the soil. Irrigation scheduling was based on evapotranspiration water losses. The FAO version of the Class A Evaporation Pan method [Doorenbos and Pruit, 1974] was used to determine soil moisture losses. Irrigation water was applied when the actual cumulative evapotranspiration since the previous irrigation had reached 30-50 mm. **A** computer program was used to determine both theoretical and actual values off,,,, t_a and E_a for all irrigations. The irrigation schedules for FI, F2 and F3, **as** well as other related information are presented in Tables 2, 3 and 4.

Results and Conclusions

A measure of the efficiency of the design of the basin irrigation system is based on the observed advance time $(t_a)_{obs}$ as opposed to the theoretically calculated t_a. The expected variability in the irrigation design parameters neccesitates that the calculated values of $(t_a)_{dsn}$ and $(E_a)_{dsn}$ for the original design and the t_a and E_a for subsequent irrigations be treated not ***as*** optimum values but as threshold values. Therefore, the efficiency of the system was not measured by the proximity of the observed values to the calculated ones, but by their very divergence. The largest the difference,

$$\Delta = (t_a)_{dsn} - (t_a)_{obs} \quad \text{or} \quad \Delta = t_a - (t_a)_{obs}\,, \qquad \Delta \geq 0$$

the shorter it takes for water to reach the end of the field (thus allowing more time for a more uniform infiltration) and the higher the application efficiency.

Observed vs. calculated advance times for sub-basins in the three fields are presented in

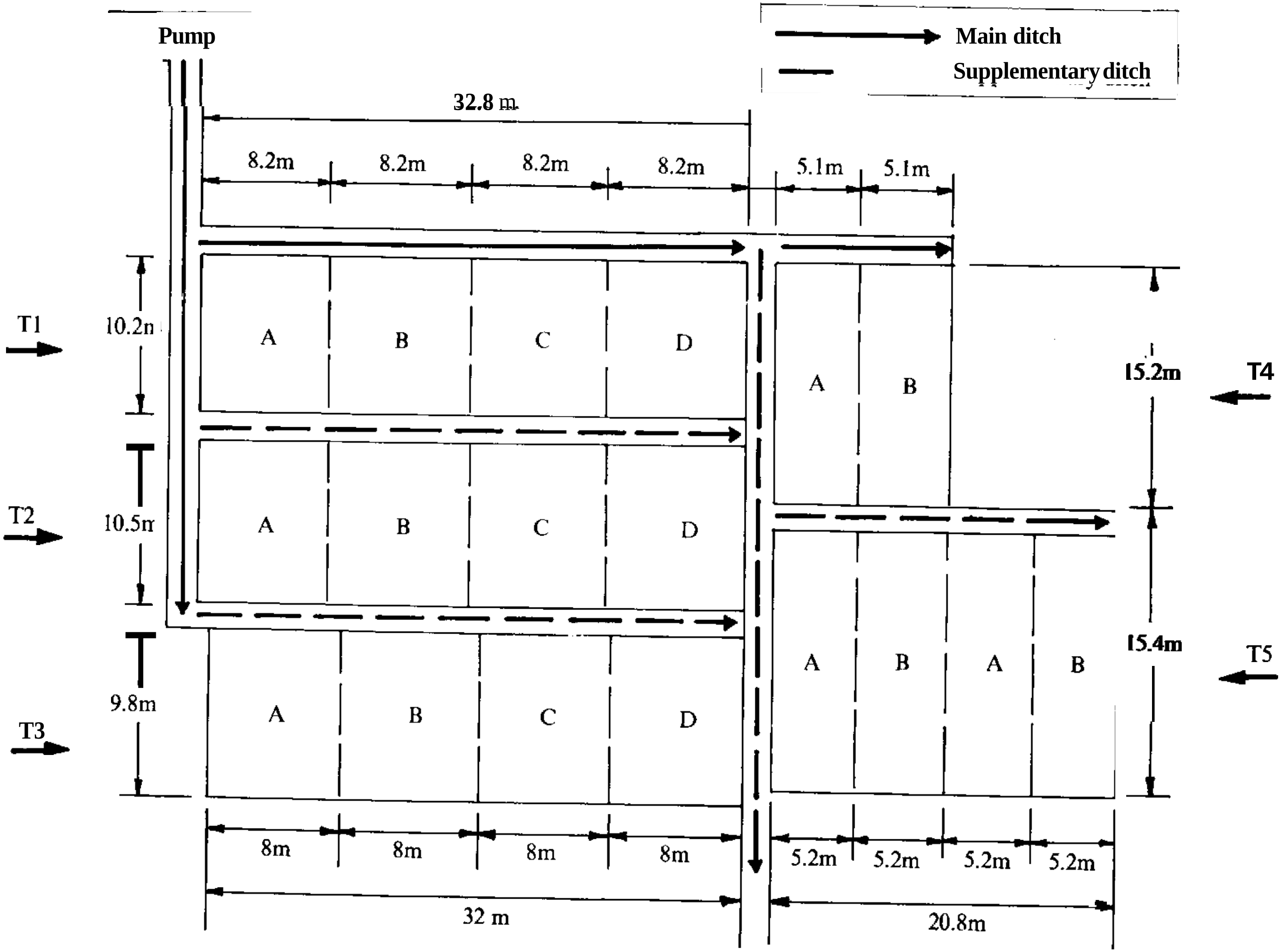

Figure 4a. Field layout of Fl site (Ignacio Acapuyan), Bantug, Guimba, Nueva Ecija

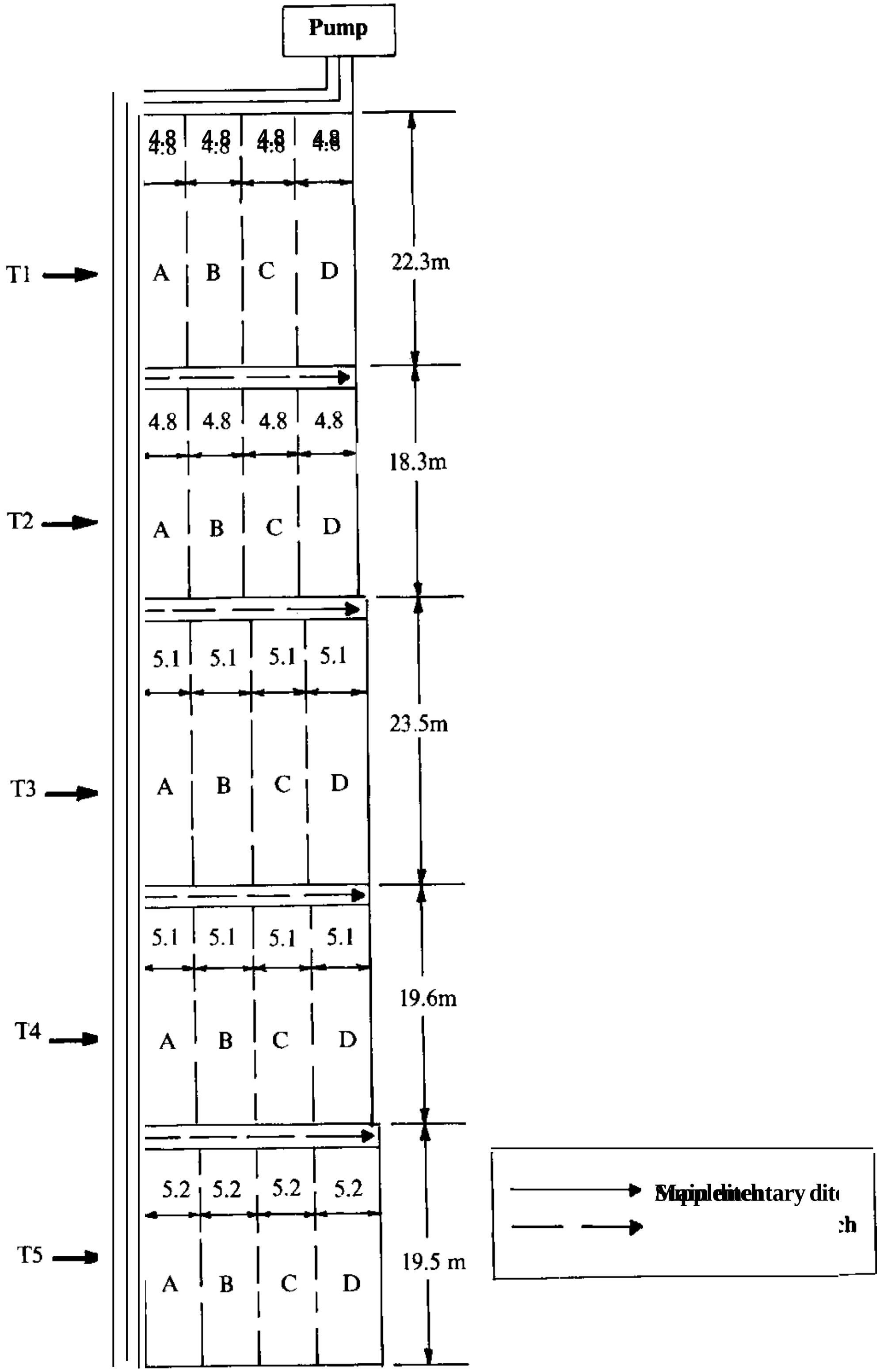

Figure 46. Field layout of F2 site (Alfonso Gragasin), Bantug, Guimba, Nueva Ecija.

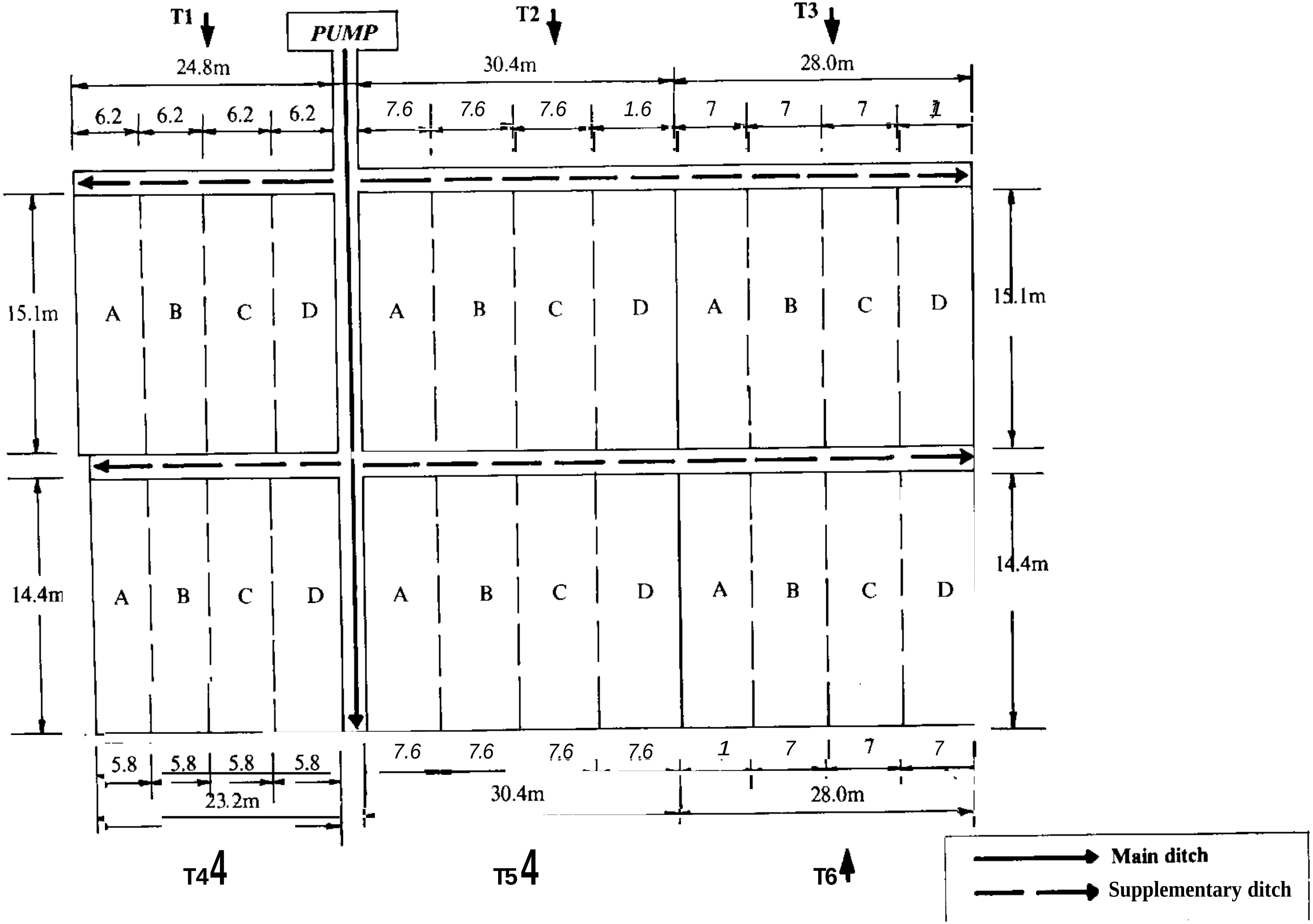

Figure 4c. Field layout of F3 site (Edwin Gragasin), Bantug, Guimba, Nueva Ecija.

Table 2. Irrigation schedule and related information for field F_1, Bantug, Guimba, Nueva Ecija.

Date of planting: Nov. 18, 1988 Number of sub-basins = 18

Irrigation No.	Date d/m/y	Flow Rate (m^3 sec^{-1})	Infiltration Equation-mm $fz=at_m^b+c$	Desired Application Depth (m)	Gross Application Depth (m)	Application Efficiency (%)
Preplant*	14/11/87	*	*	0.040	0.049	81.6
1	23/11/87	13×10^{-3}	$2.93t_m^{0.47} + 12.4$	0.040	0.044	90.8
2	11/12/87	4×10^{-3}	$2.61t_m^{0.50} + 9.13$	0.040	0.043	93.0
3	29/12/87	4×10^{-3}	$2.61t_m^{0.50} + 9.13$	0.050	0.054	92.6
4	06/01/88	4×10^{-3}	$5.78t_m^{0.30} + 5.91$	0.030	0.033	90.9
5	15/01/88	4×10^{-3}	$2.93t_m^{0.48} + 8.76$ $9.10t_m^{0.23} + 2.48$	0.040	0.043	93.0
6	22/01/88	4×10^{-3}	$2.93t_m^{0.47} + 8.76$ $9.10t_m^{0.23} + 2.48$	0.030	0.032	93.8
7	29/01/88	5×10^{-3}	$2.93t_m^{0.48} + 8.76$ $9.10t_m^{0.23} + 2.48$	0.030	0.032	93.7
Total				0.300	0.330	90.9

'Before the construction of the irrigation system.

Table 3. Irrigation schedule and related information for field F_2, Bantug, Guimba, Nueva Ecija.

Date of planting: Dec. 22, 1988 Number of sub-basins = 20

Irrigation No.	Date d/m/y	Flow Rate (m^3 sec^{-1})	Infiltration Equation-mm $fz=at_m^b+c$	Desired Application Depth (m)	Gross Application Depth (m)	Application Efficiency (%)
Preplant*	17/12/87	*	*	0.040	0.046	86.9
I	29/12/87	5×10^{-3}	$22.9t_m^{0.11} + 12.5$	0.050	0.055	90.9
2	08/01/88	5×10^{-3}	$22.9t_m^{0.11} + 12.5$	0.050	0.054	92.6
3	15/01/88	4×10^{-3}	$22.3t_m^{0.46} + 17.96$	0.050	0.053	94.3
4	22/01/88	$5\text{-}6 \times 10^{-3}$	$0.184t_m + 16.94$	0.040	0.043	93.0
5	29/01/88	$3\text{-}5 \times 10^{-3}$	$0.153t_m + 12.53$	0.040	0.043	93.0
6	08/02/88	5×10^{-3}	$0.03t_m + 15.79$	0.030	0.032	93.8
	No further irrigations because of high water table					
Total				0.300	0.325	92.4

'Before the construction of the irrigation system.

figures 5 to 7. $(t_a)_{obs}$ values smaller than their calculated ta's appear as data points below the 1:1 line while the opposite occurred for the E_a's. For total number of sub-basin irrigations, the irrigation systems performed more efficiently than their intended design in 91% of the cases. This was observed in all fields. This indicated that the "worst case" scenario in which the design had been based

Table 4. Irrigation schedule and related information for field F_3, Bantug, Guimba, Nueva Ecija.

Date of planting: Dec. 23, 1988 Number of sub-basins = 24

Irrigation No.	Date d/m/y	Flow Rate ($m^3 sec^{-1}$)	Infiltration Equation-mm $fz = at_m^b + c$	Desired Application Depth (m)	Gross Application Depth (m)	Application Efficiency (%)
Preplant*	17/12/87	*	*	0.040	0.045	88.9
1	29/12/87	6×10^{-3}	$0.79t_m^{0.64} + 13.85$	0.050	0.054	92.6
2	08/01/88	6×10^{-3}	$1.39t_m^{0.49} + 13.27$	0.030	0.032	93.8
3	15/01/88	6×10^{-3}	$0.69t_m + 17.06$	0.030	0.032	93.6
4	22/01/88	5×10^{-3}	$0.054t_m + 17.09$	0.040	0.043	93.0
5	29/01/88	5×10^{-3}	$0.075t_m + 15.91$	0.040	0.042	95.2
6	08/02/88	4×10^{-3}	$0.048t_m + 13.54$	0.030	0.032	93.8
7	16/02/88	6×10^{-3}	$0.184t_m + 13.00$	0.030	0.031	96.8
8	23/02/88	5×10^{-3}	$0.184t_m + 13.00$	0.030	0.032	93.8
9	03/03/88	5×10^{-3}	$0.184t_m + 13.00$	0.030	0.031	96.8
Total				0.350	0.374	93.2

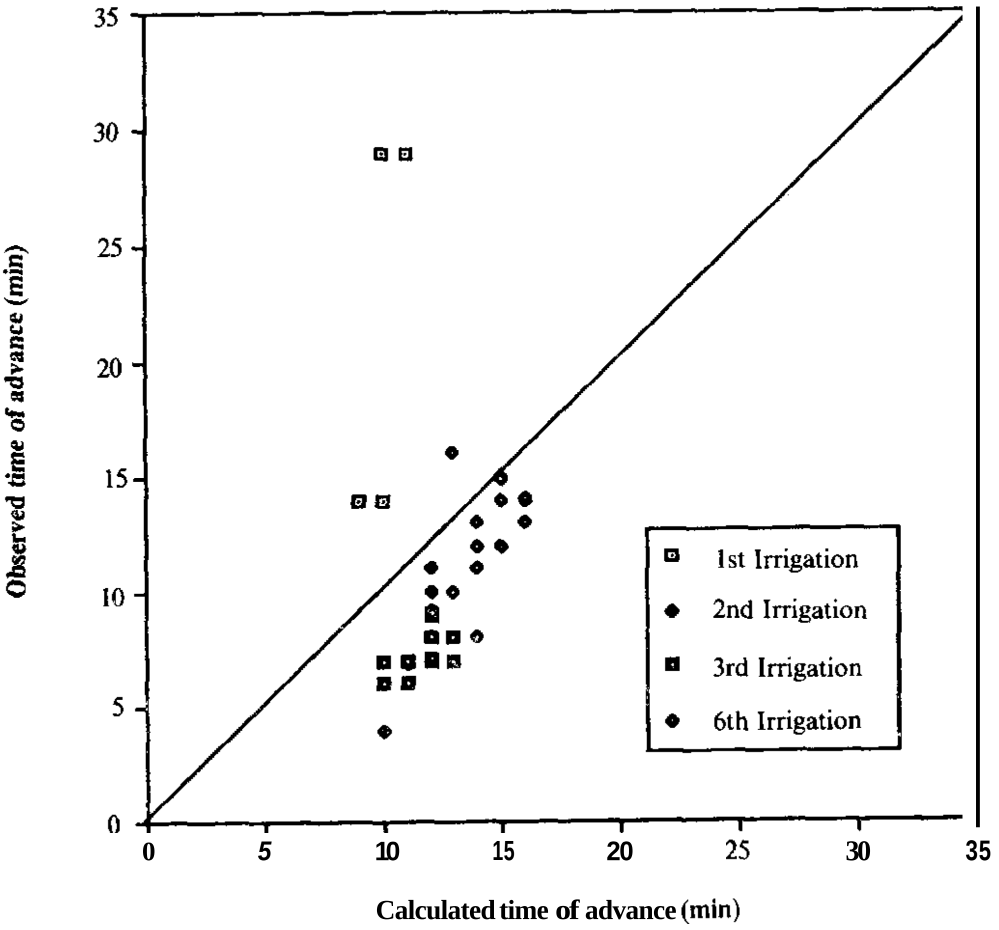

Figure 5. Observed vs. calculated time of advance t_a for field F1.

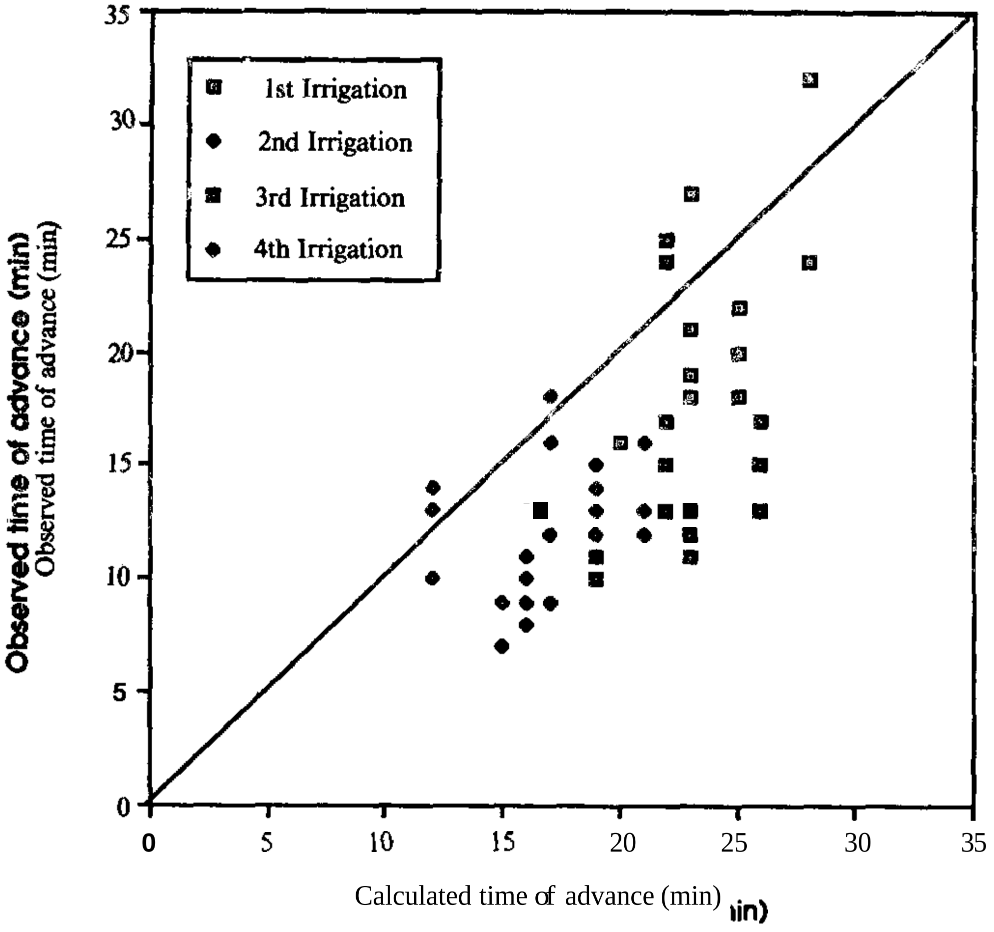

Figure 6. Observed vs calculated time of advance t_a for field F2.

performed better than expected and was probably quite conservative. Due to the physical problems of the rice soils, however, this conservative approach was necessary. There is a need to conduct agronomic research to determine the extent of relaxing design specifications without sacrificing the performance of the irrigation system and crop yield.

Total water applications and the corresponding yields, as well as other related information are presented in Table 5. Overall water application efficiencies for the entire season were very high in all three fields and resulted in high application uniformities. For **0.330,** 0.325 and **0.379 m** of irrigation water, yields of 8.98, **6.14** and **9.17** t/ha where obtained, while corn yields in farmer fields in the area average 2.0-2.5 t/ha. The applied water was very close to the actual plant evapotranspiration water requirements for the growing period and significantly lower than the 0.600-0.800 m of water usually needed for corn production. Using the basin irrigation method, water was applied frequently in small quantities, replenishing an amount of depleted soil moisture roughly equal to the plant evapotranspiration and never stressing the plants. The farm irrigation system design made possible high yields for small quantities of water while conserving water and energy and limiting the associated costs. The lower yield in F2 was attributed to the heavy soil texture (56% clay) and that rice was grown in adjacent fields. These factors resulted in waterlogging, a very high water table (0.20-0.30 m from the surface) and a shallow root system.

This study addresses the field-level irrigation system design and was based on the assumption of complete water control which is the case in shallow privately owned wells. This may not be the case for larger communal or regional irrigation systems.

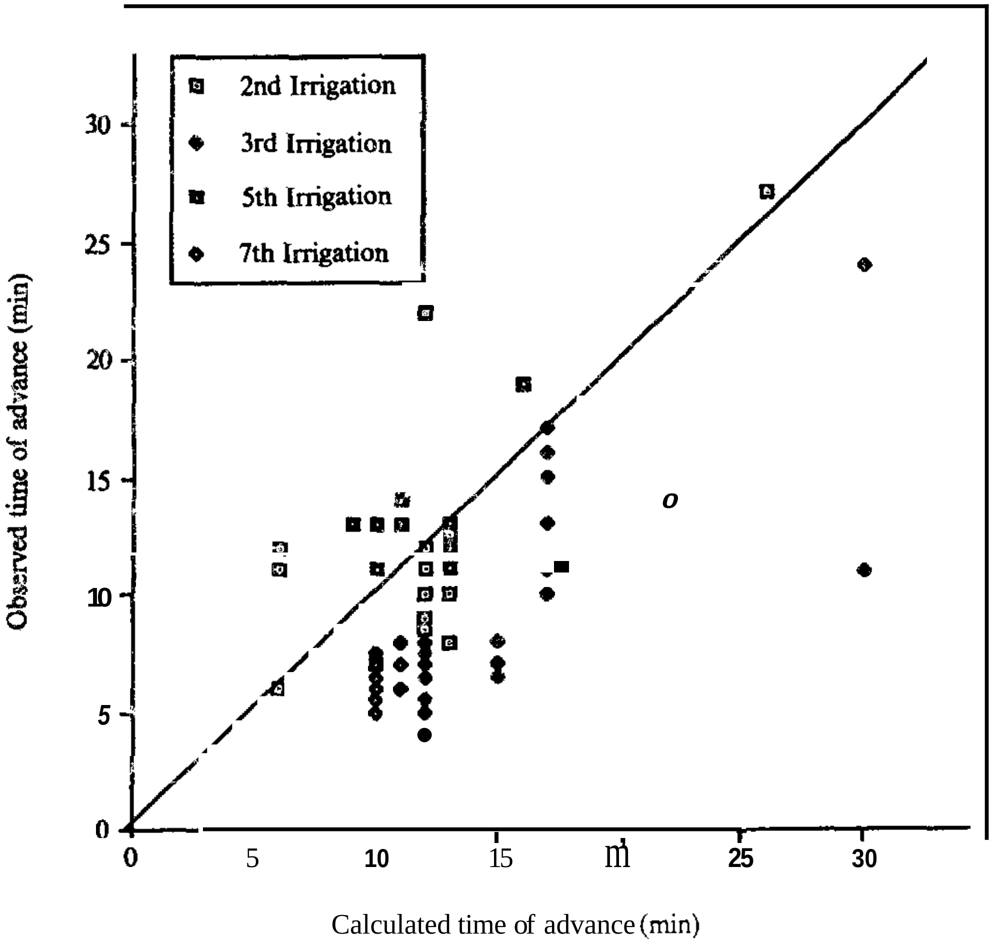

Figure 7. Observed vs. calculated time of advance t_a for **field** F3.

Table 5. Evapotranspiration (ETP), desired and gross applications, overall efficiency and yield in three fields F_1, F_2, F_3.

Field	Total Actual ETP (m)	Desired Total Application (m)	Gross Total Application (m)	Overall Application Efficiency (%)	Yield (t/ha)
F_1	0.284	0.300	0.330	91.1	8.08
F_2	0.309	0.310	0.336	92.4	6.14
F_3	0.327	0.350	0.374	93.1	9.17

Although the same principles of hydraulics apply, the lack of control of water delivery may cause serious irrigation scheduling and operation problems. There is then a need to develop an entirely new large irrigation system management practices in relation with farm level techniques for successful application of basin irrigation method.