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OPTIMAL DESIGN OF BORDER IRRIGATION SYSTEMS

By:

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ABSTRACT

Using a surface irrigation hydraulics simulation model, relationships were developed between water requirement efficiency and the system design variables. A crop production function was utilized to relate crop yield to the water requirement efficiency. Gross returns from the crop, and the costs of water, labor, ditch construction and crop production were considered in the optimization problem. Several system constraints were incorporated into the design process. The generalized geometric programming technique was applied to the optimal design of border and basin irrigation systems. the design variables were: the length of run, inflow rate into the border, time of inflow, number of lengths of run, width of the border, and the number of border widths in the field.

ARABIC ABSTRACT

نبذة

تم تطوير العلاقة بين كفاءة الأحتياج المائى والعوامل المتغيرة فى تصميم نظام الرى السطحى وذلك بأستخدام النموذج الهيدروليكى المناظر وذلك بربط الأنتاج المحصولى بكفاءة الأحتياج المائى وعند تقدير أكبر عائد محصولى وضع فى الحسبان تكلفة المياة والعمالة وإنشاء القنوات وبرزت كل المعوقات فى العمليات التصميمية وقد أستخدم نظام البرمجة الهندسية وذلك للوصول لأكفأ نظام لرى الأحواض والمسطحات وكانت العوامل المتغيرة فى التصميم هى طول المسار ومعدل كمية المياة الداخلة للحوض والزمن المستغرق فى ذلك وأيضا عدد المسارات الطولية فى الحوض وعدد الأحواض فى الحقل .

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OPTIMAL DESIGN OF BORDER IRRIGATION SYSTEMS

J. Mohan Reddy and Wayne Clyma

INTRODUCTION

Border irrigation systems, both graded and level, are widely practiced methods of surface irrigation. Effective designs of border systems have frequently been based on arbitrary constraints and performance criteria. The farmer, as the owner of the farm, is interested in the highest net benefits from crop production. Depending upon the amount of water available, the cost of production and the value of the produce, the farmer may or may not irrigate all the farm. He is not sure how much area he should irrigate to obtain maximum benefits. Hence, a procedure to analyze a given situation and optimally design the irrigation system would facilitate effective on-farm water management. This paper presents a procedure for optimal design of border irrigation systems based on maximization of profit while incorporating system operation constraints and the variables of the operating system.

LITERATURE REVIEW

Hall (4) presented a simple procedure to optimize the design of border irrigation systems. But only maximization of the application efficiency was considered. Vierhout (12) applied differential calculus to the optimal design of border and furrow irrigation systems. Once again the criteria was to maximize application efficiency. Wu and Liang (13) presented a procedure to optimize only the length of run of a

furrow irrigation system. There are many other variables such as inflow rate, time of irrigation, and net depth of application which should be simultaneously included in the optimization to arrive at an optimal design for the system.

Marjai (7) developed a procedure to determine the optimum inflow rate into a border with the other variables remaining constant. The objective was to maximize uniformity along the length of the border. Karmeli (6) presented a procedure to optimize the irrigation quality parameters such as tailwater ratio, deep percolation ratio, and water requirement efficiency for furrow irrigation. Though it is not difficult to extend the same procedure to border irrigation, the procedure becomes highly tedious and lengthy as the number of combinations of the variables increases. Besides, this procedure does not allow for system constraints. Similarly, Peri, Hart and Norum (1979) developed the concept of optimal irrigation depth, considering the economic loss due to deficit and excess irrigation along with the distribution uniformity of the applied water. This procedure does not specify the optimal size of the irrigation unit, and the operational variables such as the flow rate and the time of inflow to achieve the desired performance. Recently, Reddy and Clyma (9) presented a procedure to optimize furrow irrigation system design based on minimum costs and considering the design variables, performance parameters, and incorporating the system constraints. A similar approach for borders is presented here considering maximization of profit after deriving the relationship between the design variables and the quality parameters.

SYSTEM RELATIONSHIPS BY SIMULATION

In irrigated agriculture maximum profit is obtained when the losses are minimum and the water requirement efficiency is at an optimum. Water requirement efficiency is defined as a percent of the amount of water made available for plant use to the water requirement at the time of irrigation (5). Both can be obtained simultaneously with proper design and appropriate management of the system. If losses are high, excess costs are incurred in providing irrigation water. Net benefits from crop production are reduced if the water requirement met by each irrigation is less than optimum. Hence, there is a trade-off between maximizing water requirement efficiency and minimizing losses. Therefore, the irrigation system should be designed for optimum net benefits.

A relationship between yield and design variables must be established to optimize the system design. This was achieved by a two-step process. First, a relationship was obtained between water requirement efficiency and the design variables using a hydraulic model. Second, a relationship between yield and water requirement efficiency was obtained using a crop production model and the hydraulic model. Later, these two relationships were combined with a mathematical programming technique to optimize the design of freely draining graded border and level basin irrigation systems.

Performance and Design Variables

Hydraulic simulation of the applied water is an important component of this optimization model. Conceptually the hydraulic model represents accurately the operational conditions of the irrigation system. Actually the hydraulic model provides the volumes (depth) of water that enters the root zone, goes to deep percolation, and runs off the field. The

hydraulic model simulates these volumes for given conditions of intake, slope, and design depth (irrigation requirement) and different combinations of the design variables such as length of run, unit inflow rate, and time of irrigation.

All the system variables can be constrained to specified limits for given field conditions. The constraints were as follows:

$$Q_u \leq Q_{u,max} \tag{1a}$$

$$Q_u \geq Q_{u,min} \tag{1b}$$

$$T_i \leq T_{max} \tag{1c}$$

$$n_\ell L = L_F \tag{1d}$$

where Q_u = unit inflow rate into the border, L/s; T_i = time of inflow into the border, min; L = length of irrigation run, m; $Q_{u,max}$ = maximum non-erosive stream size, L/s; $Q_{u,min}$ = minimum flow rate required, L/s; T_{max} = maximum time available per irrigation, min; L_F = length of the field, m; and n_ℓ = number of lengths of run. After defining these limits, the values of the variables were discretized to a finite number and simulated by using the appropriate hydraulic model. The models used in this study were those of Strelkoff and Katopodes (11), and Clemmens and Strelkoff (1). Finer discretizations increase the cost of simulation. The length variable was discretized into a limited number because there are a limited number of acceptable alternatives, i.e., the length of run may be halved or reduced to one-third. For each combination of the variables, the water requirement efficiency, the volume of runoff, and the deep percolation volume were calculated. Here, only freely draining graded borders, and level basins are considered.

Graded Borders

Graded borders are well suited to soils of moderate intake characteristics and slopes. Efficient irrigation is possible by balancing the advance and recession of water. In graded borders, the water frequently is freely draining at the downstream end of the field. Hence, runoff water becomes an important component of the irrigation system design. If desired, the detrimental effects of deep percolation also may be incorporated into the problem.

After simulating for a set of given conditions and various combinations of the design variables--length of run, unit inflow rate, and time of irrigation--the values of the quality parameters such as water requirement efficiency, and deep percolation and tailwater ratios were obtained. By a statistical analysis of the data, the following types of relationships were defined with a high degree of correlation, between the quality parameters and the design variables. They are:

$$E_r = K_1 Q_u^{a_1} T_i^{b_1} L^{c_1} D_u^{d_1} \tag{2}$$

$$R_t = K_2 Q_u^{a_2} T_i^{b_2} L^{c_2} D_u^{d_2} \tag{3}$$

and

$$R_p = K_3 Q_u^{a_3} T_i^{b_3} L^{c_3} D_u^{d_3} \tag{4}$$

where E_r = water requirement efficiency in percent; R_t = tailwater ratio or the volume of runoff divided by the total volume applied; R_p = deep percolation ratio or the volume of deep percolation divided by the total volume applied; D_u = water requirement at the time of irrigation; and K_1 to d_3 are constants which are site dependent. For given

conditions and constraints, these equations provide the relationships between system performance and design variables for graded borders.

Level Borders

A level border or basin is defined as an irrigation unit of zero slope with the downstream end diked. The tailwater ratio is zero because there is no runoff. Here, an approach similar to the one in the previous section is followed. Hence, the relationship is given as:

$$E_r = K_4 \, Q_u^{a_4} \, T_i^{b_4} \, L^{c_4} \, D_u^{d_4} \tag{5}$$

in which d_4 = a constant.

In level border irrigation the water requirement efficiency relationship is sufficient to describe the quality parameters. There is no runoff. Hence, deep percolation is the only loss in the field. Thus, the deep percolation ratio can be derived easily from the water requirement efficiency. The derivation is as follows:

$$V_p = K_5 Q_u T_i - K_6 L D_u \, (E_r/100) \tag{6}$$

where V_p = volume of deep percolation; and K_5 and K_6 = units conversion factors. The deep percolation ratio is given as:

$$R_p = V_p/(Q_u T_i) \tag{7a}$$

$$= \frac{K_5 Q_u T_i - K_6 L D_u (E_r/100)}{K_5 Q_u T_i} \tag{7b}$$

$$= 1 - \frac{K_6 L D_u E_r}{100 K_5 Q_u T_i} \tag{7c}$$

$$= 1 - \frac{K_6 K_4 Q_u^{a_4} T_i^{b_4} L^{c_4} D_u^{d_4} L D_u}{100 K_5 Q_u T_i} \tag{7d}$$

or

$$R_p = 1 - (K_6 K_4 Q_u^{a_4-1} T_i^{b_4-1} L^{c_4+1} D_u^{d_4+1})/100K_5 \quad (8)$$

Equations (5) and (8) provide the relationships between system performance and design variables for given conditions and constraints. Now, a relationship between system performance and yield is developed.

Yield and Performance

Evaluation of the optimum level of crop production for a given irrigation system requires a crop production model which defines yield as a function of system performance at each irrigation during the season. The system performance at each irrigation in each section of the field is obtained from the hydraulic model. The model used in simulating the yield is presented elsewhere (10). The depth of water applied was assumed constant for each irrigation during the season. Any other sequence of depth of irrigations may be specified including empirical or experimental approaches to defining the depth and/or the sequence. Once the optimal depth of irrigation and the crop production model are given, the relative yield of the crop as a function of different levels of water requirement efficiency, a constant at each irrigation during the season, was simulated. Different combinations of yield and water requirement efficiency were obtained by varying the design variables: inflow rate, length of run, and time of irrigation. Other variables such as slope, intake family, or design depth may be considered. A yield versus water requirement efficiency function can be developed from the above simulation data. For a given set of field conditions, the relationship of relative yield to water requirement as obtained from the simulation is shown in Fig. 1. The relationship was quadratic as follows:

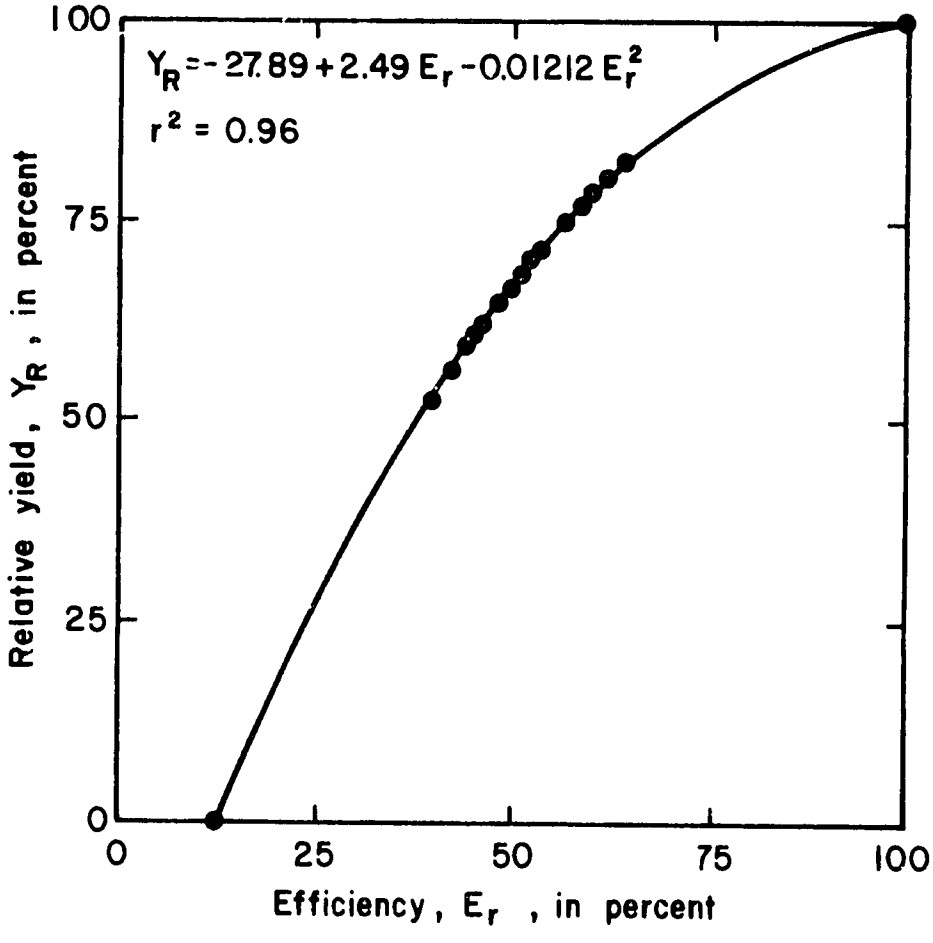

Figure 1. Relationship between water requirement efficiency and relative yield of wheat crop.

$$Y_R = -0.279 + 0.0249\ E_r - 0.0001212\ E_r^2 \tag{9}$$

in which Y_R = percent relative yield, and is defined as:

$$Y_R = Y_a/Y_{max} \tag{10}$$

where Y_a = actual yield, kg/ha; and Y_{max} = potential yield under optimum conditions, kg/ha. A high coefficient of correlation (r^2=0.96) was obtained between relative yield and the water requirement efficiency.

PROBLEM FORMULATION

Problem formulation is an important component of any optimization. The problem is defined in terms of an objective function (either minimization or maximization) and related constraints. For this problem, the objective was to maximize the profit from crop production, i.e., searching for a particular value of water requirement efficiency and the corresponding values of the design variables that give the optimum net benefit. The profits were due to crop production in a particular field. The costs associated with irrigation system design are: labor, water and energy, ditch construction, and any negative effects of runoff and deep percolation. If no direct costs of runoff or deep percolation can be quantified, then their costs are included in the increased amounts of water required. After the cost coefficients and the mathematical relationships of the quality parameters are obtained, the problem can be formulated as shown below:

$$\max G_o = \underbrace{P_c\ Y_R\ K_7\ Ln_\ell\ W\ n_w}_{\text{value of the produce}} - \underbrace{C_1\ \alpha_1\ Q_u\ T_i\ W\ n_i\ n_1\ n_\ell}_{\text{cost of water}} - \underbrace{C_2\ \alpha_2\ \alpha\ T_i\ n_i\ n_w\ n_\ell}_{\text{cost of labor}}$$

$$- \underbrace{C_3\ n_\ell\ W_F}_{\text{cost of ditch construction}} - \underbrace{C_4\ K_7\ L\ n_\ell\ W\ n_w}_{\text{cost of production}} - \underbrace{C_5\ f_1(Q_u,T_i,L,D_u)}_{\text{cost of runoff}} - \underbrace{C_6\ f_2(Q_u,T_i,L,D_u)}_{\text{cost of deep percolation}} \tag{11}$$

where G_o = objective function as a function of L, n_ℓ, W, n_w, Q_u and T_i; P_c = profit coefficient, \$/ha; C_1 = cost of water, \$/L; C_2 = cost of labor, \$/h; C_3 = cost of ditch construction, \$/linear m; C_4 = cost of production, \$/ha; C_5 = cost of runoff water, \$/ha-m; α_1 = units conversion factor, 60.0; α_2 = conversion factor, 1/60.0; K_7 = units conversion factor, .0001; C_6 = cost of deep percolated water, \$/ha-m; α = fraction of the time labor is utilized during the irrigation time; n_i = number of irrigations per season; n_w = number of borders in the width direction; W = width of the border, m; W_F = width of the field, m; f_1 = volume of runoff, a function of (Q_u, T_i, L, D_u); and f_2 = volume of deep percolation, a function of (Q_u, T_i, L, D_u).

After substituting the yield-water requirement efficiency relationship (Eq. 9) into Eq. 11, and neglecting the cost of runoff and deep percolated volumes the objective function becomes:

$$\max G_o = \underbrace{P_c K_7 [-0.279 + 0.0249 E_r - 0.0001212 E_r^2] L n_\ell W n_w}_{\text{value of the produce}}$$

$$\underbrace{- C_1 Q_u T_i W n_i n_\ell n_w \alpha_1}_{\text{cost of water}} \underbrace{- C_2 \alpha T_i n_i n_\ell n_w \alpha_2}_{\text{cost of labor}} \underbrace{- C_3 n_\ell W_F}_{\text{cost of ditch construction}} \underbrace{- C_4 K_7 L n_\ell W n_w}_{\text{cost of production}} \quad (12)$$

By substituting the relationship between the design variables and the water requirement efficiency (Eq. 2) into Eq. 12, the objective function is given as:

$$\max G_o = P_c K_7 [-0.279 + 0.0249 K_1 Q_u^{a_1} T_i^{b_1} L^{c_1} D_u^{d_1} - 0.0001212 (K_1 Q_u^{a_1} T_i^{b_1} L^{c_1} D_u^{d_1})^2]$$

$$\underbrace{L n_\ell W n_w}_{\text{Value of the produce}}$$

$$\underbrace{\alpha_1 - C_1 Q_u T_i n_i W n_w n_\ell}_{\text{cost of water}} \underbrace{- C_2 \alpha T_i n_i n_w n_\ell \alpha_2}_{\text{cost of labor}} \underbrace{- C_3 n_\ell n_w W}_{\text{cost of ditch construction}} \quad (13)$$

$$\underbrace{- C_4 K_7 n_\ell n_w L W}_{\text{cost of production}}$$

and the constraints, G_K, are given as:

$$K_1 Q_u^{a_1} T_i^{b_1} L^{c_1} \leq 100 \quad \rightarrow G_1 = K_1 \, Q_u^{a_1} \, T_i^{b_1} \, L^{c_1}/100 \leq 1 \tag{14a}$$

$$Q_u \leq Q_{u,max} \quad \rightarrow G_2 = Q_u/Q_{u,max} \leq 1 \tag{14b}$$

$$Q_u \geq Q_{u,min} \quad \rightarrow G_3 = Q_{u,min}/Q_u \leq 1 \tag{14c}$$

$$L \geq L_{min} \quad \rightarrow G_4 = L_{min}/L \leq 1 \tag{14d}$$

$$L \leq L_{max} \quad \rightarrow G_5 = L/L_{max} \leq 1 \tag{14e}$$

$$Q_u \, W = Q_F \quad \rightarrow G_6 = Q_F/(Q_u \, W) \leq 1 \tag{14f}$$

$$n_\ell \, n_w \, T_i \leq T_{max} \quad \rightarrow G_7 = n_\ell \, n_w \, T_i/T_{max} \leq 1 \tag{14g}$$

$$n_\ell \, L = L_F \quad \rightarrow G_8 = n_\ell L/L_F \leq 1 \tag{14h}$$

$$n_w \, W \leq W_F \quad \rightarrow G_9 = n_w W/W_F \leq 1 \tag{14i}$$

$$W \geq W_{min} \quad \rightarrow G_{10} = W_{min}/W \leq 1 \tag{14j}$$

$$W \leq W_{max} \quad \rightarrow G_{11} = W/W_{max} \leq 1 \tag{14k}$$

where W_{min} = minimum width of the border, m; W_{max} = maximum width of the border, m; L_{min} = minimum length of the run, m; L_{max} = maximum length of the run, m; and Q_F = total flow rate available at the farm, L/s.

In the above problem, the equality constraints were formulated as less than or equal to constraints, in conformity with the requirement for the geometric programming technique which is explained in the next section. The constraint is so formulated that it is satisfied as an equality. In the solution of the problem, it is not assumed that the whole field is irrigated. Therefore, the constraint on the width of the

field (Eq. 14i) is not specified as an equality. If it is profitable to the farmer, the solution will satisfy the constraint (Eq. 14i) as an equality and the farmer irrigates the whole field. Though, the less than or equal to constraint could have been specified on Eq. 14h (instead of Eq. 14i), for the present purposes it is specified on the width constraint, assuming that the farmer irrigates the full length of the field, thereby adjusting the number of borders in the width direction if it is not profitable to irrigate the whole field.

OPTIMIZATION TECHNIQUE

Generalized geometric programming, which is applicable to engineering design problems of this type, is most appropriate for the above problem. The same technique was presented by Reddy and Clyma (9) for furrow irrigation systems. Generalized geometric programming (GGP) is formulated with an objective function of the form:

$$G_o(\bar{X})_{min} = P_o(\bar{X}) - Q_o(\bar{X}) \tag{15}$$

with K constraints of the form:

$$G_k(\bar{X}) = P_k(\bar{X}) - Q_k(\bar{X}) \leq 1.0, \; k = 1,2,3, \; \ldots \; K \tag{16}$$

in which $\bar{X}$ = the vector of variables to be considered $(x_1, x_2, x_3, \ldots x_M)$; M = the number of variables; and P_k and Q_k = posynomial functions of the form:

$$P_k(\bar{X}) = \sum_{i=1}^{I} U_{ik}(\bar{X}); \; k = 0, \; 1,2,3, \; \ldots \; K \tag{17}$$

$$Q_k(\bar{X}) = \sum_{j=1}^{J} V_{jk}(\bar{X}); \; k = 0, \; 1,2,3, \; \ldots \; K \tag{18}$$

where U_{ik} and V_{jk} = terms with positive and negative coefficients, respectively, in the objective function and the constraints; I = number of terms in the objective function or the constraints with positive coefficients ($P_k(\bar{X})$); and J = number of terms in the objective function or the constraints with negative coefficients ($Q_k(\bar{X})$). The terms U_{ik} and V_{jk} are defined as follows:

$$U_{ik} = C_{ik} \prod_{m=1}^{M} x_m^{\varepsilon_{ikm}} \; ; \; \begin{array}{l} k = 0,1,2, \ldots K \\ i = 1,2,3, \ldots I \end{array} \tag{19}$$

$$V_{jk} = C_{jk} \prod_{m=1}^{M} x_m^{\varepsilon_{jkm}} \; ; \; \begin{array}{l} k = 0,1,2, \ldots K \\ j = 1,2,3, \ldots J \end{array} \tag{20}$$

where C_{ik} and C_{jk} = coefficients; ε_{ikm} and ε_{jkm} = exponents of the variables in the objective function and the constraints; and x_m = system variable.

Equations (15) and (16) are called signomials. A signomial is defined as the difference of two posynomials. In the formulation of GGP, the terms with the negative coefficients ($Q_k(\bar{X})$) are moved to the right of the inequality, resulting in $P_k(\bar{X}) \leq 1 + Q_k(\bar{X})$. Dividing the inequality by the right-hand side term results in a rational function of posynomials. The posynomial in the denominator is reduced to a monomial (single term) by a process of condensation as defined by Dembo (2). A posynomial divided by a monomial is still a posynomial. This posynomial is then condensed to a monomial again by condensation. After the monomials are obtained, the constraints and the objective function are linearized by taking the natural logarithm of the monomial function. This set of equations is solved by linear programming. Convergence of the

solution to the original problem is obtained by additional constraints called 'cuts' to the original problem. By solving the linear program a finite number of times, an optimum solution is obtained to the original nonlinear problem. Being a nonlinear programming problem, the global solution cannot be guaranteed. Different local optima are obtained by starting at different initial feasible solutions. The maximum of all the optima is considered the global solution to the problem. A signomial geometric programming code has been developed to solve the problem.

The values of the variables obtained from the above technique are continuous (non-integer). In the design of an irrigation system some of the variables such as the number of lengths of run, number of sets, number of borders in the width direction should have integer values. Therefore, a different technique was attached to the above procedure to obtain an optimal solution in terms of integers for the above variables. The branch-and-bound (3) technique was chosen to express the related variables in an integer form.

OPTIMAL SYSTEM DESIGN

The generalized geometric programming technique presented above was applied to the optimal design of border irrigation systems: graded borders and level basins. The two cases are discussed separately as an example with specific conditions.

Example 1 - Graded Border

The data for this problem is presented in Table 1. Using this data the hydraulic model was simulated for different combinations of the design variables as presented in Table 2. A relationship of the following form was obtained between water requirement efficiency and the design variables:

Table 1. Cost coefficients, system constants and system constraints for a freely draining border.

Parameters	Value
Cost Coefficients	
Value of produce, $\$/m^3$	56.8
Cost of production, \$/ha	494.0
Maximum production, m^3/ha	17.41
Cost of labor, \$/h	3.00
Cost of water, \$/ha-m	40.0
Cost of ditch construction, \$/lin m	3.25
System Constants	
Length of the field, m	805.0
Width of the field, m	402.0
Slope of the field, m/m	0.001
Roughness of the field, $m^{1/6}$	0.024
Depth of requirement, mm	76.0
Infiltration constants, $z = kt^a$	
k, mm/min^a	18.0
a	0.2716
Number of irrigations per season	5
α	1
System Constraints	
$Q_{u)max}$, L/s	11.20
$Q_{u)min}$, L/s	0.92
Q_F, L/s	158.0
T_{max}, min	3600.0
L_{min}, m	67.0
L_{max}, m	402.0
W_{min}, m	9.0
W_{max}, m	30.5

Table 2. Relationship between the design variables and the water requirement efficiency for a freely draining border.

Inflow rate, in liters per second (1)	Time of inflow, in minutes (2)	Length of run, in meters (3)	Water requirement depth, in millimeters (4)	Water requirement efficiency, in percent (5)
3.28	40.0	91.50	51	99.50
3.28	60.00	91.50	76	76.33
3.28	80.00	91.50	76	82.74
3.28	100.00	91.50	102	65.00
3.28	150.00	91.50	76	98.22
4.16	30.00	91.50	51	96.40
4.16	60.00	91.50	76	77.29
4.16	80.00	91.50	76	83.58
4.16	100.00	91.50	102	65.50
4.16	150.00	91.50	76	98.93
4.62	70.00	183.00	102	59.40
5.58	60.00	183.00	58	99.50
5.58	80.00	183.00	76	83.55
5.58	100.00	183.00	76	88.87
5.58	150.00	183.00	102	73.10
7.41	40.00	183.00	76	69.88
7.41	60.00	183.00	76	78.31
7.41	80.00	183.00	102	62.70
7.41	100.00	183.00	76	89.90
7.41	150.00	183.00	76	99.97
4.62	80.00	366.00	102	66.70
4.62	100.00	366.00	76	83.68
4.62	120.00	366.00	76	89.37
4.62	150.00	366.00	76	96.05
4.62	180.00	366.00	76	99.88
6.04	70.00	366.00	76	76.51
6.04	90.00	366.00	114	56.10
6.04	120.00	366.00	76	91.85
6.04	150.00	366.00	102	72.60
7.41	100.00	366.00	102	66.00

$$E_r = 2045\ Q_u^{0.07678}\ T_i^{0.28299}\ L^{-0.04829}\ D_u^{-0.9938} \tag{21}$$

A very good correlation ($r^2 = 0.99$) was obtained between the predicted and actual water requirement efficiency. A comparison of actual versus predicted water requirement efficiency is shown in Fig. 2.

After obtaining the relationships between the design variables and the irrigation quality parameters, the problem was formulated in terms of the cost coefficients, system constraints, system constants and the design variables. In the present study, the effect of deep percolation and tail water are not considered. But when appropriate cost coefficients are available, they can be incorporated into the optimal design process. For the given situation P_c was calculated by

$$\begin{aligned} P_c &= Y_{max}(m^3/ha) \times P_u(\$/m^3) \\ &= 17.41\ m^3/ha \times (56.8\$/m^3) = \$989/ha \end{aligned} \tag{22}$$

where P_u = price per unit of produce ($\$/m^3$). After substituting Eq. 22 and the cost coefficients into Eq. 11, and neglecting the coefficients of runoff and deep percolation, the objective function becomes:

$$\max G_o = \underbrace{989\ Y_R\ K_7\ L\ n_\ell\ W\ n_w}_{\text{Value of produce}} - \underbrace{0.0012 Q_u\ T_i\ W\ n_\ell\ n_w}_{\text{cost of water}}$$

$$\underbrace{-0.25\ T_i\ n_\ell\ n_w}_{\text{cost of labor}} - \underbrace{3.95\ W\ n_\ell\ n_w}_{\text{cost of ditch construction}} \underbrace{-0.0494\ L\ n_\ell\ W\ n_w}_{\text{cost of production}} \tag{23}$$

By substituting Eqs. 9 and 21 (at D_u = 76 mm) into Eq. 23 and simplifying, the result becomes:

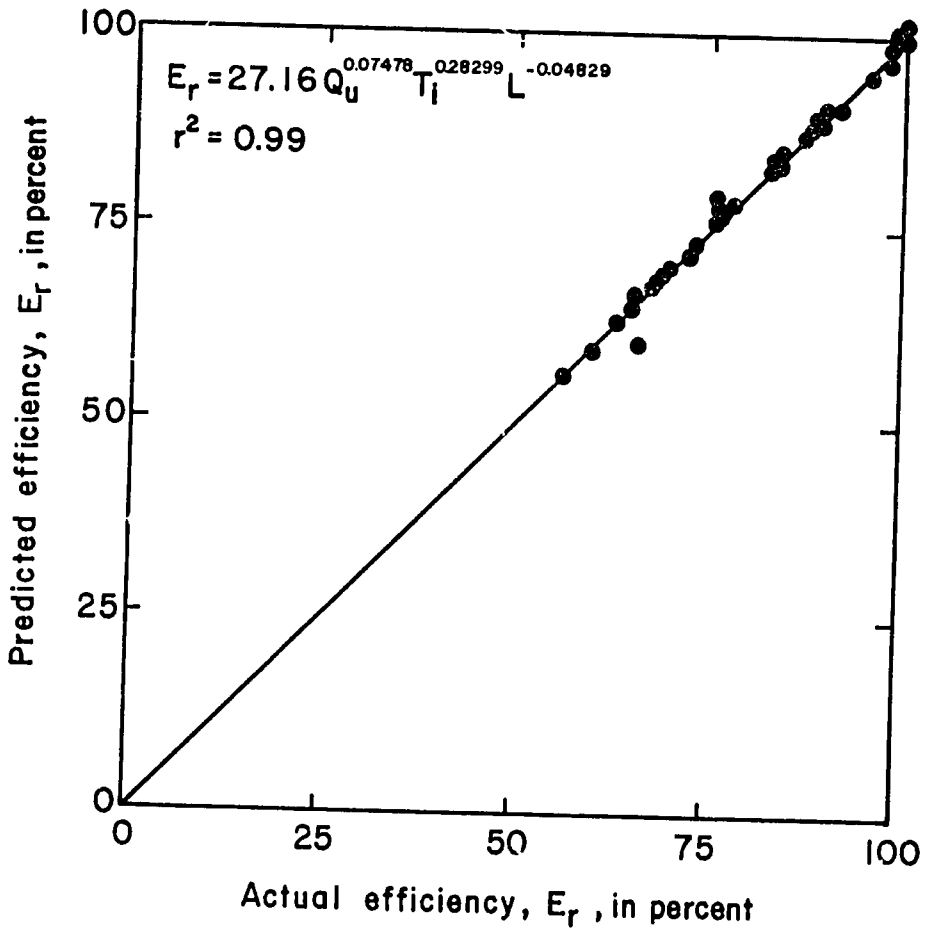

Figure 2. Actual versus predicted water requirement efficiency for a freely draining border.

$$\max G_o = -0.02758\ L\ n_\ell\ W\ n_w + 0.06688\ Q_u^{0.07478}\ T_i^{0.283} L^{0.9517} n_\ell\ W\ n_w$$
$$- 0.0884\ Q_u^{0.1496} T_i^{0.566}\ L^{0.9034} n_\ell\ W\ n_w - 0.0012\ Q_u\ T_i\ W\ n_\ell\ n_w$$
$$- 0.25\ T_i\ n_\ell\ n_w - 3.25\ n_\ell\ W\ n_w - 0.0494\ L\ n_\ell\ W\ n_w \qquad (24)$$

The system constraints are given as follows:

$E_r \leq 100 \rightarrow \qquad G_1 = 0.2716\ Q_u^{0.07478} T_i^{0.28299} L^{-0.04829} \leq 1$ (25a)

$n_\ell\ L = L_F \rightarrow \qquad G_2 = 0.001242\ L\ n_\ell \leq 1$ (25b)

$n_w\ W \leq W_F \rightarrow \qquad G_3 = 0.002487\ W\ n_w \leq 1$ (25c)

$L \leq L_{max} \rightarrow \qquad G_4 = .003727\ L \leq 1$ (25d)

$L \geq L_{min} \rightarrow \qquad G_5 = 67\ L^{-1} \leq 1$ (25e)

$W \leq W_{max} \rightarrow \qquad G_6 = 0.0328\ W \leq 1$ (25f)

$W \geq W_{min} \rightarrow \qquad G_7 = 9.146\ W^{-1} \leq 1$ (25g)

$Q_u W = Q_F \rightarrow \qquad G_8 = 151.42\ Q_u^{-1} W^{-1} \leq 1$ (25h)

$n_\ell\ n_w\ T_i \leq T_{max} \rightarrow \qquad G_9 = .0002778\ n_\ell\ n_w\ T_i \leq 1$ (25i)

$Q_u \leq Q_{u,max} \rightarrow \qquad G_{10} = 0.1350\ Q_u \leq 1$ (25j)

$Q_u \geq Q_{u,min} \qquad G_{11} = 0.92\ Q_u^{-1} \leq 1$ (25k)

The generalized geometric programming technique was applied to the solution of the above problem. The following optimal values of the design variables are obtained:

$Q_u = 4.98$ L/s	$T_i = 122$ min
$L = 269$ m	$W = 31$ m
$n_\ell = 3$	$n_w = 13$

The water requirement efficiency (E_r) obtained was 91 percent. The net profit was \$9,833 for the field which equals \$304/ha. At the optimum,

the cost of design was $186/ha. The application efficiency for the optimum was 51 percent. In fact, when the objective is to maximize net benefits, much emphasis cannot be given to application efficiency. The technique presented here selects the optimal water requirement efficiency and yield without directly considering the application efficiency.

In defining the constraints, care must be exercised in selecting proper limits for the variables. These limits should not be different from the limits used in simulating the hydraulic model; if so, the relationships developed may not be valid. If a wide range of alternatives for the design variables are considered, these same limits should be included in the hydraulic simulation model.

Example 2 - Level Basin

The optimization technique was applied for a level basin. The system cost coefficients, constants, and constraints are given in Table 3. The hydraulic model was used to simulate the relationships between the quality parameters and the design variables. The different combinations of the design variables used in the simulation are presented in Table 4. For the given situation, the following relationships were obtained between the quality parameters and the design variables:

$$E_r = 3103\ Q_u^{0.8232} T_i^{0.9182} L^{-0.8393} D_u^{-0.9201} \tag{26}$$

or

$$E_r = 85\ Q_u^{0.8232} T_i^{0.9182} L^{-0.8393},\ D_u = 50\ \text{mm} \tag{27}$$

and the equation for R_p is given as:

$$R_p = 1\text{-}31\ Q_u^{-0.1768} T_i^{-0.0818} L^{0.1607} D_u^{0.0799} \tag{28}$$

Table 3. Cost coefficients, system constants, and system constraints for a level basin irrigation system.

Parameter	Value
Cost Coefficients	
Value of produce, $/kg	1.00
Cost of production, $/ha	1482.0
Maximum production, kg/ha	2500.0
Cost of ditch construction, $/linear m	6.56
Cost of labor, $/h	3.0
Cost of water, $/ha-m	40.0
System Constants	
Length of the field, m	335
Width of the field, m	302
Slope of the field, m/m	0.0
Roughness of the field, $m^{1/6}$	0.15
Depth of requirement, mm	50
Infiltration constants, $z = kt^a + ct$	
k, mm/h^a	28.52
a	0.1088
c, mm/h	2.25
System Constraints	
$Q_{u,max}$, L/s	11.20
$Q_{u,min}$, L/s	0.92
Q_F, L/s	52.0
T_{max}, min	3600.0
L_{max}, m	168
L_{min}, m	67
W_{max}, m	30.5
W_{min}, m	9

Table 4. Relationship between the design variables and the water requirement efficiency for a level basin irrigation system.

Length of run, in meters (1)	Inflow rate, in liters per second (2)	Time of inflow, in minutes (3)	Water requirement depth, in millimeters (4)	Water requirement efficiency, in percent (5)
67	1.00	50.00	50	88.50
67	1.00	50.00	76	59.00
67	1.87	25.00	58	68.00
67	1.87	25.00	76	52.00
67	1.87	25.00	89	44.50
67	1.87	40.00	76	86.00
67	1.00	50.00	114	39.30
67	1.87	56.00	102	91.00
67	1.87	56.00	114	81.00
100	1.00	120.00	76	88.90
134	3.76	25.00	76	58.00
134	3.74	33.00	76	69.00
134	3.74	45.00	76	97.00
134	4.66	30.00	114	53.00
134	3.76	50.00	76	100.00
168	1.87	120.00	102	74.70
168	3.74	40.00	102	52.00
201	2.79	50.00	76	66.00
201	3.74	65.00	76	92.00
201	4.66	45.00	127	49.00
201	4.66	50.00	102	66.00
268	2.79	100.00	76	80.00
268	3.74	80.00	76	87.00
268	4.66	60.00	76	79.00
268	5.58	50.00	89	68.00

or

$$R_p = 1-0.85\ Q_u^{-.1768} T_i^{-.0818} L^{0.1607},\ D_u = 50\ \text{mm} \tag{29}$$

A good correlation ($r^2 = 0.96$) between the actual and predicted water requirement efficiency was obtained. A comparison of predicted versus actual water requirement efficiency is presented in Fig. 3. The above relationship was used to formulate the problem.

The profit coefficient for the given situation is calculated as:

$$\begin{aligned} P_c &= Y_{max}(\text{kg/ha}) \times P_u(\$/\text{kg}) \\ &= 2500\text{x}1 = \$2500/\text{ha} \end{aligned} \tag{30}$$

After substituting the cost coefficients (from Table 3) and Eq. 27 into Eq. 12 and simplifying, the objective function becomes:

$$\begin{aligned} \max G_o = &-0.06973\ L\ n_\ell\ W\ n_w + 0.529\ Q_u^{0.8232} T_i^{0.9182} L^{0.1607} n_\ell\ W\ n_w \\ &-0.2189\ Q_u^{1.646} T_i^{1.836} L^{0.6786} n_\ell\ W\ n_w - 6.56\ n_\ell\ W\ n_w \\ &-0.1482\ L n_\ell\ W\ n_w - 0.0012\ Q_u\ T_i\ n_\ell\ n_w - 0.25\ T_i\ n_\ell\ n_w \end{aligned} \tag{31}$$

and the system constraints are given as:

$$E_R \leq 100 \rightarrow \qquad G_1 = 0.85\ Q_u^{.8232} T_i^{.9182} L^{-0.8393} \leq 1 \tag{32a}$$

$$n_\ell\ L \leq 335 \rightarrow \qquad G_2 = .00298\ L\ n_\ell \leq 1 \tag{32b}$$

$$n_w\ W \leq 302 \rightarrow \qquad G_3 = .00331\ n_w\ W \leq 1 \tag{32c}$$

$$Q_u\ W \leq Q_F \rightarrow \qquad G_4 = 0.01929\ Q_u W \leq 1 \tag{32d}$$

$$n_\ell\ n_w\ T_i \leq T_{max} \rightarrow \qquad G_5 = .00022\ T_i n_\ell n_w \leq 1 \tag{32e}$$

$$W \leq 45.7 \rightarrow \qquad G_6 = 0.05263\ W \leq 1 \tag{32f}$$

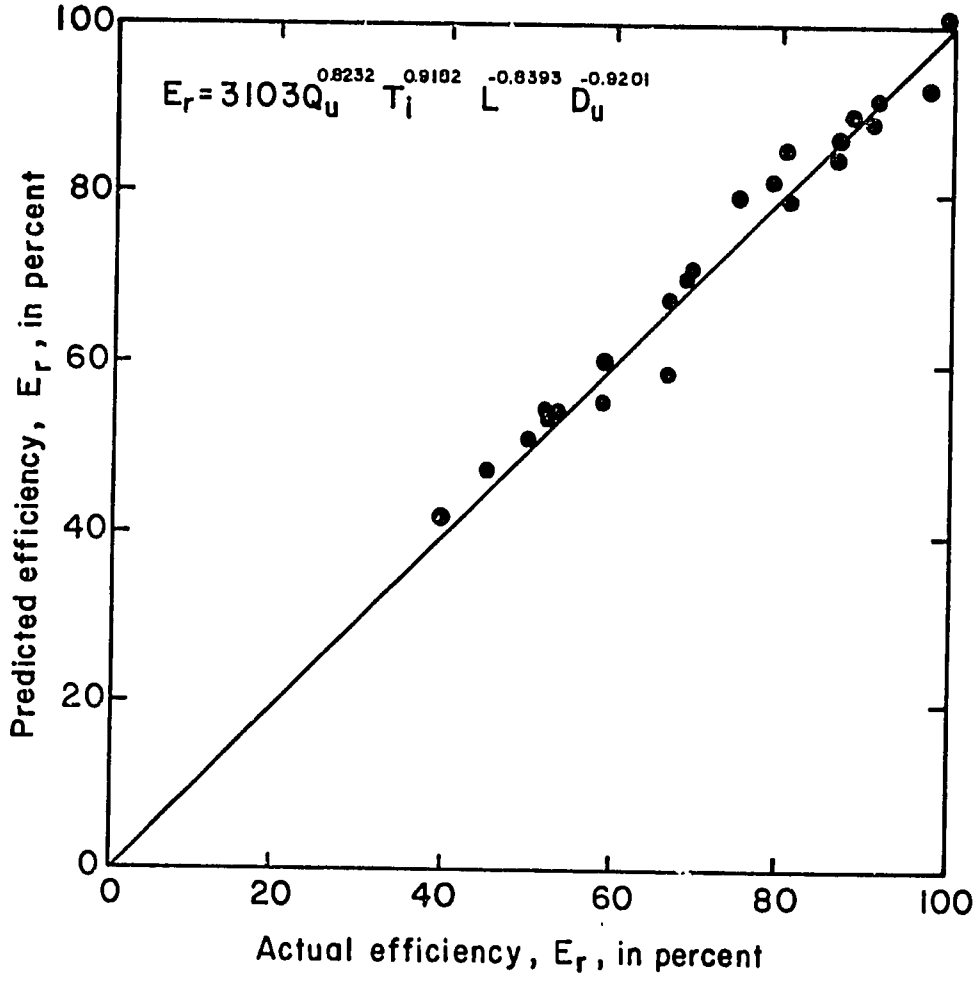

Figure 3. Actual versus predicted water requirment efficiency for a level border.

$W \geq 24.4 \rightarrow$ $\quad G_7 = 9.15\ W^{-1} \leq 1$ (32g)

$Q_u \leq 11.2 \rightarrow$ $\quad G_8 = 0.0894\ Q_u \leq 1$ (32h)

$Q_u \geq 0.918 \rightarrow$ $\quad G_9 = 0.918\ Q_u^{-1} \leq 1$ (32i)

$L \leq 167 \rightarrow$ $\quad G_{10} = 0.005988\ L \leq 1$ (32j)

By applying the generalized geometric programming technique, the following optimal values of the design variables were obtained.

$Q_u = 1.20$ L/s	$T_i = 110$ min
$L = 168$ m	$W = 43.3$ m
$n_\ell = 2$	$n_w = 7$

The water requirement efficiency satisfied at the optimum was 100 percent. The maximum net profit at the optimum was \$5797/per field or \$573/per ha. The application efficiency found at the optimum was 93 percent.

In the analysis, the cost of runoff and deep percolation water was included indirectly in the cost of water provided in excess of the requirement in the root zone. But, the negative effects of these parameters (runoff and deep percolation) were not considered because of lack of appropriate cost coefficients for these parameters. The cost coefficient for runoff includes the cost of removing the excess water from the field, and the negative effects on water quality. Similarly, the cost coefficient for deep percolation must take into account the effects of waterlogging and fertilizer leaching on crop yield. The cost coefficients should be given in terms of dollars/unit volume of water. Once these coefficients are available, they can be incorporated into the optimization process. This would help in evaluating different management

practices in controlling the quality of irrigation return flow while increasing agricultural production.

An implicit assumption in the problem was that the farmer can apply the total available flow rate on one border. No consideration was given to irrigating more than one border at a time. This was not considered in the problem to reduce the number of variables considered, but can be incorporated into the optimization process if desired. It was also assumed that the relationship between the yield and water requirement efficiency was identical under graded and level basin irrigation systems.

SUMMARY AND CONCLUSIONS

A combination approach of simulation and mathematical programming was used to develop an optimal system design. First, the irrigation quality parameters were developed in terms of the application system design variables using a hydraulic simulation model. Second, a relationship was developed between crop yield and the system quality parameters (water requirement efficiency) using a crop production function. Maximization of net benefits was the objective. The value of the produce, and the costs of labor, water, ditch construction, and crop production were considered in the objective function. The negative effects of runoff and deep percolation were not considered. The problem was defined in terms of system variables, cost coefficients and system constraints, and the generalized geometric programming technique was applied to the optimal design of border and level basin irrigation systems. The design variables considered were the inflow rate, time of inflow, length of the run, number of lengths of run, width of the border and number of border widths. The procedure gives an optimal design

under given field conditions. In addition, the procedure shows the possibility of combining simulation and mathematical programming techniques in optimizing system designs. The technique presented provides guidelines for improving existing on-farm irrigation systems for better management of the scarce resources of agricultural production.

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

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

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

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

EGYPTIAN UNITS OF FIELD CROPS

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

EGYPTIAN FARMING AND IRRIGATION TERMS

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

EGYPT WATER USE AND MANAGEMENT PROJECT

PROJECT TECHNICAL REPORTS

NO.	TITLE	AUTHOR
PTR#1	Problem Identification Report for Mansuriya Study Area, 10/77 to 10/76.	Egyptian and American Field Teams.
PTR#2	Preliminary Soil Survey Report for the Beni Magdul and El-Hammami Areas.	A. D. Dotzenko, M. Zanati, A. A. Abdel Wahed, & A. M. Keleg.
PTR#3	Preliminary Evaluation of Mansuriya Canal System, Giza Governorate, Egypt.	American and Egyptian Field Teams.
PTR#4	On-farm Irrigation Practices in Mansuriya District, Egypt.	M. El-Kady, W. Clyma & M. Abu-Zeid
PTR#5	Economic Costs of Water Shortage Along Branch Canals.	A. El Shinnawi M. Skold & M. Nasr
PTR#6	Problem Identification Report For Kafr El-Sheikh Study Area.	Egyptian and American Field Teams.
PTR#7	A Procedure for Evaluating the Cost of Lifting Water for Irrigation in Egypt.	H. Wahby, G. Quenemoen & M. Helal
PTR#8	Farm Record Summary and Analysis for Study Cases at Abu Raya and Mansuriya Sites, 1978/1979.	F. Abdel Al & M. Skold
PTR#9	Irrigation & Production of Rice in Abu Raya, Kafr El-Sheikh Governorate.	Kafr El-Sheikh Team as Compiled by T. W. Ley & R. L. Tinsley
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PTR#34	Soil Survey Report for Abu Raya Area, Kafr El-Sheikh Governorate	A. A. Selim, M. A. El-Nahal, M. A. Assal & F. Hawela.
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