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IRRIGATION SYSTEM IMPROVEMENT BY SIMULATION AND OPTIMIZATION: I. THEORY

BY

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ABSTRACT

A theory for simulation and optimization of an irrigation system to evaluate improvement alternatives was presented. The mathematical simulation model of an irrigation system was developed combining existing models of conveyance, application and water use subsystems. The performance of the subsystem simulation models was verified using available field data from Pakistan. A methodology for the optimal design of a level basin irrigation system was described. Irrigation system improvement alternatives such as canal lining, earthen improvement of the canals, and traditional and precision land leveling of the application system were evaluated.

مستخلص

لقد قدمت نظرية التشابه والمثالية لنظام الرى لتقييم البدائل المحسنه . كما تم تطوير نموذج التشابه الحسابى لنظام الرى يجمع بين النماذج الحالية والنظم الفرعية الخاصه بوسائل نقل المياه واستعمالها واستخدامها . وتم التحقق من صحه العمل الذى تؤديه نماذج التشابه للنظم الفرعيه وذلك باستخدام البيانات الحقلية الموجودة من باكستان . ورسم منهج للتصميم الأمثل لنظام رى حوضى ذى منسوب كما تم تقييم بدائل محسنه لنظام الرى مثل تبطين الترع وتحسين أتربتها والتسوية التقليدية والمحكمه للأراضى فى نظام استعمال المياه .

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INTRODUCTION

Irrigation is becoming increasingly important worldwide because of its potential to fill the need for increased food production. An average of only 30 percent of the water diverted from reservoirs is used by crops (Garbrecht, 1979). Thus, improving existing irrigation systems to attain higher yields and increased area irrigated is a high priority need.

This paper presents the theory and procedures for evaluation of irrigation subsystem improvement alternatives. Simulation models are presented for the water delivery, water application and water use subsystems. The concepts and procedures for evaluation of alternative improvements based on system simulation and optimal design are presented. A subsequent paper (Reddy and Clyma, 1981c) presents an application of the theory in an evaluation of improvement alternatives for a system in Pakistan.

LITERATURE REVIEW

An irrigation system consists of four different subsystems: the conveyance subsystem (canals, pipes), the application subsystem (border, basin, furrow, sprinkle, trickle, subsurface), the water use subsystem (root zone storage, evapotranspiration and crop growth) and the water removal subsystem (surface and subsurface drainage). A considerable amount of research has been conducted on each subsystem of the irrigation system and examples abound in the literature. For instance, Hill and Keller (1980) applied a simulation approach for the optimal (maximum) design of irrigation application system. Flow was simulated in furrows, and the crop yield was related to the seasonal depth of water applied in different sections along the length of run, without considering the differential sensitivity of the crops. Similarly, Rydzewski and Nairizi (1979) followed a simulation approach considering the differential sensitivity of the crop growth stages but spatial distribution of the applied water in the field was not considered. These studies considered only the application (and water use) system. On the contrary, Johnson et al. (1979) analyzed the effect of different conveyance system improvement alternatives in increasing the water supplies at the farm. The marginal values of saving the water under different irrigation efficiencies were evaluated without considering the constraints of the farmer in efficiently applying the water on traditional and precision leveled fields. Usually consideration was not given to the interrelationships between the different components.

There are a few research works such as Anderson and Maass (1969), and Darley et al. (1972), where a complete irrigation system was considered, but with unrealistic assumptions. Anderson and Maass assumed that if a crop misses successively two irrigations, then the yield from the crop is zero regardless of the stage of crop growth. Darley et al. used a similar simulation model considering Jensen's (1968) crop production function. Only the on-demand method of delivery was considered. However, neither of these models considered the optimal design of the application system.

Since the benefits are realized from crop production on the farm, the benefits from a proposed improvement of a component of the irrigation system must be evaluated in terms of increased crop production. The cost of the conveyance subsystem improvement must be weighed in terms of increased production from increased area and/or yield per unit area due to an increased water supply. The water saved in the conveyance subsystem improvement may not be used effectively in application to the field. Thus, interactions of the subsystems are important. Similarly, the increase in yield from uniformly distributed water due to land leveling must be weighed against the cost of land leveling. In order to evaluate the economics of improvement alternatives, the components of the irrigation system must be integrated into a single management model.

A mathematical simulation model incorporating the available models of the three distinct components of the irrigation system--the conveyance, application, and water use subsystems--was developed. The water removal subsystem was not considered in this analysis. These models were verified with available data (Reddy, 1980). In addition, an approach for the optimal design of surface (border and furrow) irrigation systems was developed and incorporated into the irrigation system improvement process. Development and application of the optimization model to a specific case is presented by Reddy and Clyma (1981c) in a forthcoming paper.

SIMULATION AND OPTIMIZATION CONCEPTS

The interaction of the subsystems of an irrigation system are substantial. Thus, the water delivery, water application and water use subsystems were considered. The internal structure of each subsystem, particularly the application subsystem, is important if a realistic simulation of the time and space changes of the system are to be adequately represented. The interactions of the time and space distribution of water on a field with rates of evapotranspiration and with crop yield are important. These interactions are important not only to estimate how effectively and efficiently water is used but also to determine the output of the system as crop yield and subsequently the net benefits. Similarly, the estimation of the interactions of increased water supply at the farm in increasing the net benefits due to conveyance system improvement needs evaluation. The above concepts are important in developing the simulation model to represent the internal structure of the irrigation system.

The simulation and optimization procedures used in this paper involve the following sequential steps:

1) Definition of a system simulation model that adequately represents the detailed structure of the irrigation system including the water delivery, water application and water use subsystems.
2) Use of the simulation model in (1) to define the relationships between:
    a) System performance and system design variables.
    b) Crop yield and system performance.
3) Use of the mathematical relationships from 2(a) and 2(b) combined with optimization theory to develop an optimal system design.
4) Use of the simulation model in (1) calibrated for the actual operating system and the optimally designed system to evaluate alternative levels of system improvement based on economic benefits and costs of each alternative improvement.

An important feature of the irrigation system is the seasonal distribution of water that results in shortages during critical growth stages. In other instances, the field distribution of water is variable resulting in significant spatial yield variations on a field. These examples represent important aspects of a system that must be represented in the internal structure of the irrigation system simulation model. Other factors are important under given conditions and must be represented in the simulation model if results are to be appropriate.

The relationships defined in step 2 may be those as defined for this study or they may involve other factors important in a given instance. For example, a careful analysis of deep percolation costs and benefits may consider the time and spatial distribution of infiltrated water in more detail than in this study. The important concept is that an adequate simulation model can be used to develop system performance and system variable relationships which are subsequently used for evaluation of optimal alternatives.

In evaluation of optimal alternatives, step 3, optimization theory in the past has used system relationships that assume unrealistic internal structures for the system. Typical of these assumptions are constant performance levels for the irrigation system in time and space and crop yield as a function of seasonal water applied. Optimal system design also should consider how the various system variables interrelate at differing levels to result in the optimal values for each variable based on realistic system constraints. For example, length of the field, time of application and inflow rate are all related and an optimal combination should be selected. The optimization theory used here has expanded the number of variables and constraints considered but further improvement of the optimal design can be achieved.

The flow rate available at the farm is used in optimally allocating the water to different fields. The amount of water available at a given field is a function of the improvement alternative. Therefore, the cost of an improvement for providing the water at the farm, and the irrigated area and yields must be estimated to evaluate the benefits of improving the conveyance system. The flow rate available at the farm is supplied as a constraint to the optimal design of the application system.

Optimal design, if implemented, is the obvious selection for the level of system operation. In fact, farmers do not operate systems according to design. The purpose of the 4th step is to evaluate the benefits and costs of different levels of system operation. This allows a determination of the benefits of system improvement even when the improvements do not result in optimal operation. Simulation is used to represent realistic operating conditions for the system. By evaluating the value of differing levels of improvement, strategies and their cost can be evaluated against the benefits. The latter emphasis on simulation permits realistic representation of the system while evaluating the benefits of different levels of improvement.

The above four steps use theory from irrigation hydraulics, crop production modeling, optimization theory, and knowledge about system operation and improvement alternatives to develop an appropriate strategy. The theories available are numerous and useful. The knowledge of system operation and improvement alternatives are limited or frequently nonexistent (Clyma and Ley, 1980). Evaluation and improvement of irrigation system needs more effective, useful theory.

DEVELOPMENT AND VERIFICATION OF THE SUBMODELS

Based on the concepts presented, an irrigation system model consisting of the three submodels—conveyance, application and water use—was developed and verified. The development and verification of the models are presented below.

Water Conveyance Subsystem

The conveyance system carries water from the water source (canal outlet or well) to the field. The amount of water delivered at the field is a function of the length of the canal, and the type of lining material. Any model that predicts the flow rate at any given distance based on inflow rate into the canal, the loss rate in the canal, and the length of the canal, is appropriate for this analysis.

There are analytical, finite difference, and finite element models to estimate seepage from channels depending upon the hydraulic conductivity of the medium. These equations are complex. In addition, they cannot be directly used to estimate conveyance losses because they do not consider losses that occur in the field under actual operating conditions. Hence, actual field data are the most reliable. If actual field data are available, empirical equations can be developed that relate outflow from the canal to the inflow into the canal, canal length, and the loss rate in that section of the canal, considering other operational and random losses along the length. Palacios and Day (1977) developed an empirical relationship based on data collected on an irrigation system in Mexico considering the operational and fixed losses. These equations are of immense importance in evaluating different management strategies. Similarly, Trout (1979) has developed another equation using data from Pakistan. It is given as

$$L\% = \{1 - 1/Q_M\ [Q_I^{(1-P)} - (Q_{LFB}/Q_I^P)\ (1-P)\ D_{FB}]^{1/(1-P)}$$

$$+ [.0047L_W - (0.05L_D/Q_M - 0.005L_D]\ 1/T_i\ \} \times 100 \quad (1)$$

where

$$Q_I = [Q_M^{(1-P)} - (Q_{LSK}/Q_M^P)\ (1-P)\ D_{SK}]^{(\frac{1}{1-P})} \quad (2)$$

in which $L\%$ = percent loss; Q_M = watercourse inflow rate; Q_I = flow rate from government canal outlet to the farmer's branch; D_{SK} = length of government canal; D_{FB} = length of farmer's branch; L_D = length of channel drained; L_W = length of channel wetted; P = loss rate exponent; T_i = irrigation turn time; Q_{LFB} = loss rate in the initial section of the farmer's branch; and Q_{LSK} = loss rate in the initial section of the government canal. The model is useful in determining means to improve the conveyance efficiencies of existing systems, or in indicating the watercourse designer alternatives which will lead to reduced losses.

Equations (1) and (2) were derived from actual field data under the operating conditions of the channels. The above equations calculate both the steady state and transient loss rates. In the present analysis only the steady state losses are considered. The input to this model are: the inflow rate into the channel, lengths of government and farm channels, initial section loss rates in the government and farm channels, and the loss rate exponent for that particular location. The output from this model is the flow rate at any given distance.

The conveyance system model was verified using data reported by Johnson et al. (1979). Measured data and predicted results are presented in Table 1. These results show that the model adequately predicts the loss rates of the canals in the project area. Hence, the model will be calibrated for a specific condition.

Table 1. Comparison of Actual and Predicted Loss Rates of the Conveyance System.

Tubewell Number and Improvement Condition	Inflow Rate liters per second	Percent Loss Rate Measured	Percent Loss Rate Predicted
TW 56 before improvement	113.28	6.56	6.62
TW 56 after improvement	152.93	4.03	4.78
TW 51 before improvement	133.10	3.76	3.66
TW 51 after improvement	141.60	2.53	2.98

Water Application Subsystem

The performance of the application system depends upon several variables, such as the inflow rate into the field, length of run, time of inflow, roughness, slope and infiltration characteristics of the field. The model simulates the spatial and temporal distribution of water on the field. Using this model, relationships are developed between system performance parameters and the design variables. The application system model also provides the depths of water infiltrated in different sections of the field at each irrigation.

An extensive amount of research has been done in the area of predicting the spatial distribution of applied water. In the present analysis only level basins were considered, but this methodology can be used for any application system. A surface irrigation hydraulics model, which calculates the advance and recession phases of irrigation, was used to compute the spatial distribution of applied water. The zero-inertia model of surface irrigation is given as follows:

$$\frac{\partial q}{\partial x} + \frac{\partial y}{\partial t} + \frac{\partial z}{\partial t} = 0 \qquad \text{continuity} \qquad (3)$$

$$\frac{\partial y}{\partial x} = S_o - S_f \qquad \text{momentum} \qquad (4)$$

in which q = flow rate in the border; y = depth of flow; $\frac{\partial z}{\partial t}$ = infiltration rate; S_o = slope of the border; and S_f = energy slope. These equations were linearized and solved by Strelkoff and Katopodes (1977) using the Preissman double-sweep technique. At the end of advance phase, the water is ponded in the basin. The depletion and recession phases commense after the time of cutoff. Simultaneous recession throughout the length of the basin was assumed for the present purpose. This aspect was combined with the zero-inertia advance model to compute flow in level basins.

At the end of irrigation, the depth of water infiltrated for different sections of the field was calculated by

$$Z_i = k\tau_i^a \qquad (5)$$

in which Z_i = cumulative infiltration at point i; a and k = constants; and τ_i = infiltration opportunity time at point i. Given the net depth of irrigation, the irrigation quality parameters can be defined as

$$\bar{Z} = \sum_{i=1}^{N} Z_i(x)/N \tag{6}$$

$$V_p = \sum_{i=1}^{N-1} (\bar{Z}_i(x) - D_u)dx_i, \text{ if } \bar{Z}_i(x) \geq D_u \tag{7}$$

$$V_D = \sum_{i=1}^{N-1} [D_u - \bar{Z}_i(x)]dx_i, \text{ if } \bar{Z}_i(x) \leq D_u \tag{8}$$

$$E_r = \frac{[(N-1)\ D_u\ L - V_D]}{(N-1)D_u\ L} \times 100 \tag{9}$$

$$E_a = K\ L\ D_u E_r/(q\ T_a) \tag{10}$$

$$UCC = [1 - \sum_{i=1}^{N} \bar{Z}-Z_i\ /(N\bar{Z})] \tag{11}$$

in which $\bar{Z}$ = average amount infiltrated into the root zone; N = number of stations in the field; $\bar{Z}_i$ = average depth infiltrated in section i; V_p = volume of water deep percolated; V_D = volume of deficit in the field; D_u = requirement depth in the root zone; E_a = irrigation application efficiency; E_r = water requirement efficiency; K = proportionality constant; T_a = time of application; L = length of the field; and UCC = Christiansen's coefficient of uniformity. For a given situation, the slope, infiltration characteristics, roughness, and farm boundaries are fixed. Therefore, the design variables are the flow rate, time of application, and the length of run.

Water Use Subsystem

The water use system model consisted of two submodels: the evapotranspiration model and the crop growth model. The evapotranspiration model provided the soil-water depletion before each irrigation in addition to the ratios of actual to potential evapotranspiration for each growth stage of the crop. The crop growth model related yield to these ratios. The crop growth was simulated in different sections of the field to consider the effect of nonuniformity of applied water on yield. The depths of water applied at each irrigation were obtained from the hydraulic model. A relationship was developed between the irrigation system performance parameters and crop yield.

Evapotranspiration

There are many equations to calculate the evapotranspiration requirements of a given crop (Jensen, 1973). Any of these equations could be used depending primarily upon location, accuracy needed, and climatic data available. The modified Jensen-Haise equation was used to calculate the potential evapotranspiration, ET_{pr}, of a reference crop. The potential evapotranspiration of a given crop is given by

$$ET_p = K_{co} \, ET_{pr} \tag{12}$$

where ET_p = potential evapotranspiration of a given crop; and K_{co} = crop coefficient of the given crop. The ET_p values are calculated under no soil moisture stress conditions. In actual field conditions, the crop experiences some degree of stress. Hence, the actual evapotranspiration usually is less than potential depending upon the soil water content. The soil moisture stress must be taken into account. The soil stress factor, K_s, was defined (Jensen, 1973) as

$$K_s = \frac{\ell n(100(\theta_s/\bar{\theta})+1)}{\ell n(101)} \tag{13}$$

where $\bar{\theta}$ = soil water content at field capacity; and θ_s = actual soil water content. In the model, the evapotranspiration values were calculated for each day. The values were averaged over the particular growth stage. The soil-water content on any particular day was calculated using the following relationship:

$$\theta_i = \theta_{i-1} + R_i + I_i - ET_{ai} \tag{14}$$

in which θ_i = soil water content at the end of ith day; θ_{i-1} = soil water content at the end of (i-1)th day; R_i = rainfall on ith day; I_i = depth of irrigation on ith day; and ET_{ai} = actual evapotranspiration on ith day. If there was no rainfall or irrigation on any day, the values of R_i and I_i were set equal to zero. Immediately after rainfall, the soil surface will be wet. The evapotranspiration rate will be more than the potential. Therefore, a coefficient, K_r, must be added to the stress factor. K_r was defined as:

$$K_r = \begin{cases} 0.8 & \text{first day after rainfall} \\ 0.5 & \text{second day after rainfall} \\ 0.3 & \text{third day after rainfall} \\ 0.0 & \text{for all other days} \end{cases} \tag{15}$$

Therefore, the total stress coefficient, K_c, was given as:

$$K_c = K_{co}K_s + K_r(.90 - K_{co}K_s),\ K_r = 0 \ \text{ if } \ K_{co}K_s \geq 0.90 \tag{16}$$

The actual evapotranspiration of a given crop was calculated by

$$ET_a = K_c\ ET_p \tag{17}$$

where ET_a = actual evapotranspiration of the crop.

Crop Production Function

A relationship between yield and evapotranspiration is needed to plan irrigations on the farm. Several relationships are currently available. The polynomial and exponential type of production functions do not consider the differential sensitivity of different growth stages. Rydzewski and Nairizi (1979) used a multiplicative production function of the type reported by Jensen (1968) for evaluating yield-water deficit relationships of an irrigation system. A multiplicative production function of the following form was developed for the present purpose:

$$Y_R = \prod_{i=1}^{N_G} (ET_a/ET_p)_i^{\lambda_i} \tag{18}$$

where Y_R = relative yield of given crop; λ_i = crop sensitivity factor; and N_G = number of growth periods considered in the analysis. The following values were obtained for the crop sensitivity factors, using the data presented in Table 2 (Reddy, 1980):

Table 2. Effect of Varying Schedule and Frequency of Irrigation on the Yield of Wheat-Sonora-64 (Reddy, 1980).

S. No.	Treatment	days after sowing)						Total Number of Irrigations	Grain yield (q/ha)	Relative yield %
		25 days (crown root)	45 days (tillering)	65 days (jointing)	85 days (flowering)	105 days (milk ripe)	120 days (dough)			
1	A	-	-	-	-	-	-	0	9.29	100
2	B	+	-	-	-	-	-	1	30.41	327
3	C	-	-	+	-	-	-	1	20.61	222
4	D	-	-	-	-	+	-	1	10.54	113
5	E	+	-	+	-	-	-	2	34.18	368
6	F	-	-	+	-	+	-	2	26.05	280
7	G	+	-	-	-	+	-	2	31.59	340
8	H	+	-	+	-	+	-	3	35.41	381
9	I	+	+	+	-	+	-	4	41.77	450
10	J	+	-	+	+	+	-	4	42.75	460
11	K	+	-	+	-	+	+	4	37.57	404
12	L	+	+	+	+	+	-	5	47.75	514
13	M	+	+	+	-	+	+	5	43.27	466
14	N	+	-	+	+	+	+	5	43.45	468
15	P	+	+	+	+	+	+	6	51.09	550
Rainfall (mm)		-	-	-	-	0.8	12.0			

'+' indicates irrigation application
'-' indicates no irrigation
S. Em. = ± 2.09 q/ha
C.D. at 5% = 6.05 q/ha
C.D. at 1% = 8.17 q/ha

$$\lambda_1 = 0.00 \qquad \lambda_5 = 0.35$$
$$\lambda_2 = 6.19 \qquad \lambda_6 = 0.00 \qquad (19)$$
$$\lambda_3 = 1.34 \qquad \lambda_7 = 0.00$$
$$\lambda_4 = 0.00$$

OPTIMAL DESIGN OF APPLICATION SYSTEM

Optimal design of irrigation application systems involves either minimization of costs or maximization of profits. Maximization of profits is the most realistic way of optimizing the irrigation system design. A crop production function is needed to maximize the profits under irrigation. In the design of the system, a relationship must be obtained between yield and the design variables. As mentioned earlier, Hill and Keller (1980) followed a simulation approach to maximize crop production from irrigation system design, without considering the differential sensitivity of the different growth stages. An approach similar to that of Hill and Keller, but considering the differential sensitivity of the growth stages and using generalized geometric programming technique was followed. This was obtained by a two-step process: a relationship was developed between water requirement efficiency and the design variables, and another relationship between yield and water requirement efficiency (Reddy and Clyma, 1981b).

Water Requirement Efficiency Versus Design Variables

The hydraulic model developed earlier was used to simulate the behavior of the application subsystem for different combinations of the system design variables: the inflow rate into the border, time of irrigation, and length of run. Using Equations 7, 8 and 10, and by regression analysis, the following form of relationship was obtained between system performance parameter and the design variables (Reddy and Clyma, 1981b):

$$E_R = K_1 \, Q_u^{a_1} \, T_i^{b_1} \, L^{c_1} \qquad (20)$$

in which K_1 = proportionality constant; and a_1, b_1 and c_1 are exponential constants. The values of K_1 to c_1 are site specific because their values are dependent upon other variables, such as slope, roughness, and infiltration rates.

Yield Versus Water Requirement Efficiency

Crop yield was related to performance parameters of the irrigation system. Yield is dependent upon the amount of water provided in the rootzone at each irrigation. The depths of irrigation provided in each section at each irrigation were obtained from the hydraulic model. Using these seasonally constant depths, crop yield was simulated in different sections of the field. After defining the optimal depths of irrigation, the water requirement efficiency was calculated using the irrigation depths in different sections of the field. The depths of irrigation were related to water requirement efficiency and to yield. Therefore, yield was related, indirectly, to the water requirement efficiency. The relationship was as follows:

$$Y_R = \beta_0 + \beta_1 E_R + \beta_2 E_R^2 \tag{21}$$

where β_0, β_1, and β_2 = regression constants. The water requirement efficiency was related to the system design variables as shown earlier. Thus, the yield was related to the system design variables. In the development of Eq. 21, it was assumed that there is a unique relationship between the water requirement efficiency and the coefficient of uniformity. But, in fact, the same water requirement efficiency can have different coefficients of uniformity, and vice versa. This is not a major problem, however, because the effect of different coefficients of uniformity subsides at higher water requirement efficiencies that are commonly encountered in the field.

In the present analysis, the effect of the nonuniformity was computed by simulating the crop growth in different sections of the field. The average yield of all the sections was taken as the yield for the field. The yield was simulated for different levels of water requirement efficiency by changing the combinations of the design variables.

Problem Formulation and Solution

Maximization of net profit was the objective of the optimal design. The gross returns from the crop production and the cost of production were considered. The costs of production included the cost of labor, water, construction of headland facilities, and fixed costs of production. The difference between the gross returns and the costs, the net benefits, were maximized. The constraints were incorporated into the design process and was solved using the generalized geometric programming technique (Reddy and Clyma, 1981a, 1981b). This technique is useful in design problems, and examples abound in the general area of engineering design. Extensive use of this technique has not been made in irrigation. The technique gives the optimal values of the design variables, along with the optimum profit under the given set of conditions.

IMPROVEMENT ALTERNATIVES

Once the model has been developed based on the previous theory, several alternatives for improvement and levels of improvement can be simulated and evaluated for their feasibility. For a better comparison of the improvement alternatives, the essential structure of the operating system was maintained. Also, system operation and constraints, and actual system performance must be defined and measured for the traditional and improved conditions. The improvement alternatives considered were as follows:

- ∇ The benefits from earthen improvement, and lining of the conveyance system were compared with the benefits for the traditional conveyance system.
- ∇ The benefits from optimal design of the application system with precision land leveling were compared with the benefits from the traditional application system.
- ∇ The benefits from the combined improvement of the conveyance and application systems were compared with the benefits from improving either the application system or the conveyance system. The benefits from the combined improvement were compared with the traditional system also.

There are other improvement alternatives and strategies that can be evaluated for their economic feasibility.

SUMMARY

The theory and concepts for simulation and optimization as applied to irrigation systems improvement was presented. The mathematical models for the water conveyance, water application and water use subsystems were presented. All the three models were verified using available data. A procedure to optimize the design of surface irrigation systems was also reviewed. Finally, some system improvement strategies such as conveyance and application system improvements separately and in combination, irrigation frequency, and optimal system design were discussed.

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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 x 10^4	247.105	238.048	100.000
1 sq. mile	259 x 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	E.G. 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 10/78.	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
PTR#10	Soil Fertility Survey in Kafr El-Sheikh, El Mansuriya and El-Minya Sites.	M. Zanati, P. N. Soltanpour, A.T.A. Mostafa, & A. Keleg.
PTR#11	Kafr El-Sheikh Farm Management Survey Crop Enterprise Budgets and Profitability Analysis.	M. Haider & F. Abdel Al
PTR#12	Use of Feasibility Studies and Evaluation of Irrigation Projects: Procedures for Analysing Alternative Water Distribution System in Egypt.	R. J. McConnen, F. Abdel Al, M. Skold, G. Ayad & E. Sorial

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PTR#15	Village Bank Loans to Egyptian Farmers.	G. Ayad, M. Skold, & M. Quenemoen.
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PTR#16B	Irrigation System Improvement By Simulation and Optimization: 1. Application.	J. Mohan Reddy & W. Clyma
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PTR#21	El-Hammami Pipeline Design.	Fort Collins Staff Team
PTR#22	The Hydraulic Design of Mesqa 10, An Egyptian Irrigation Canal.	W.O. Ree, M. El-Kady, J. Wolfe, & W. Fahim
PTR#23	Farm Record Summary and Analysis for Study Cases at Abyuha, Mansuriya and Abu Raya Sites, 79/80.	F. Abdel Al, & M. Skold
PTR#24	Agricultural Pests and Their Control: General Concepts.	E. Attalla
PTR#25	Problem Identification Report for El-Minya	R. Brooks

NO.	TITLE	AUTHOR
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PTR#32	Accessibility of EWUP Pilot Sites.	A. El-Kayal, S. Saleh, A. Bayoumi & R. L. Tinsley
PTR#33	Soil Survey Report for Abyuha Area Minya Governorate.	A. A. Selim, M. A. El-Nahal, & M. H. Assal
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MAN.#2	Programs for the HP Computer Model 9825 for EWUP Operations.	By: M. Helal, D. Sunada, J. Loftis, M. Quenemoen, W. Ree, R. McConnen, R. King, A. Nazr and R. Stalford.
MAN.#5	Precison Land Leveling Data Analysis Program for HP9825 Desktop Calculator	T. W. Ley
MAN.#8	Thirty Steps to Precison Land Leveling	A. Bayoumi, S. Boctor & N. Dimick
MAN.#9	Alphabetical List of Some Crops and Plants with Their English, Egyptian, Botanical & Arabic Names and Vocabulary of Agricultural and other Terms Commonly Used.	G. Ayad
MAN.#10	EWUP Farm Record System	Farouk Abdel Al, David R. Martella, and Gamal Ayad

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