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IRRIGATION SYSTEM IMPROVEMENT BY SIMULATION AND OPTIMIZATION: 2 APPLICATION

BY

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ABSTRACT

Wheat production on a watercourse in Pakistan was analyzed. Models for the water conveyance, application, and water use subsystems were calibrated with data from the study area. The existing irrigation system operated at a 39 percent application efficiency and 53 percent conveyance efficiency. Optimal design of the application system with precision land leveling provided net benefits of 3625 rupees (Rs) compared to Rs 2612 under traditional field conditions. Canal lining was not economical. Earthen improvement of the conveyance system was beneficial to the farmer with a net profit of Rs 3304. Combined improvement of the application and conveyance systems almost doubled the total net benefits over the traditional system, but with an increased level of investment. The increase in benefits was mostly a result of the increased irrigated area that could be irrigated after the improvements. The benefit/cost ratio of each improvement alternative was different. The difference in benefits between improving the conveyance system and the application system was small, but there was a significant difference in net benefits between any single improvement and the combined improvement of the application and conveyance systems.

KEY TERMS: simulation, optimization, irrigation systems, optimal design, mathematical model

مستخلـــــص

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لقد تم تحليل مساحه قدرها ٢٤ر٣ هكتار بزمام المسقى رقم ١٠٦ بباكستان كما تمت معايرة نماذج النظم الفرعية لنقل المياه واستعمالها واستخدامهما وذلك باستخدام البيانات المأخوذه من المساحه الدراسية . ولقد وجد أن نظام الرى الحالى يعمل بنسبه ٣٩ ٠/٠ من كفاءة الاستعمال وبنسبه ٥٣ ٠/٠ من كفاءة النقل . ولقد كان التصميم المثالى لنظام استعمال المياه مع التسوية المحكمه للأراضى أقتصاديا وبصافى أرباح أجمالية مقدارها ٣٦٢٥ روبيه لو قورنت بـ ٢٦١٢ روبيه فى الظروف التقليدية لمناسيب الأراضى . كما أن تبطين الترع لم يكن أقتصاديا . والتحسين الترابى لنظام النقل كان مربحا للفلاح بصافي ربح قدره ٣٣٠٤ روبيه . هذا كما أن الجمع بين تحسين نظام استعمال المياه والنقل غالبا ما ضاعف من اجمالى صافى الأرباح ، ولكن بمستوى استثمارى زائد . وغالبا ما ترجع الزيادة فى الأرباح الى زياده المساحه المنزرعه نتيجة التحسينات . كما أن نسبه الربح والتكاليف للبدائل المختلفه المحسنه كانت هى نفس الشىء .

(م)

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IRRIGATION SYSTEM IMPROVEMENT BY SIMULATION AND OPTIMIZATION: 2. APPLICATION

J. Mohan Reddy and Wayne Clyma[1]

INTRODUCTION

Evaluation of the on-farm irrigation system in Pakistan suggested that the performance of the existing irrigation system was not satisfactory and could be improved. Since the beneficial alternative is desirable, the cost and effectiveness of each alternative improvement must be evaluated. The benefits from improvement of the irrigation system are realized in terms of increased crop production in the command area. Therefore, any improvement of a component of the irrigation system is related to the resulting increase in crop production.

The aim of this paper is to illustrate the usefulness of the methodology presented in Part 1 (Reddy and Clyma, 1981b) in evaluating irrigation system improvement alternatives. Because of insufficient data, some simplified assumptions were made in the analysis. The results of calibration and application of the model to specific conditions in Pakistan are presented. The benefits of improving the application system by optimal design with precision land leveling, and the conveyance system by canal lining or earthen improvement was compared with the existing system. The value of improving both the conveyance system and the application system separately and in combination was evaluated.

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DESCRIPTION OF THE STUDY AREA

The model developed in Part 1 of this paper (Reddy and Clyma, 1981b) was applied to a specific location in Pakistan on a 3.17 ha farm near Bhalwal in the Sargodha district. Data for this study were obtained from studies of the Mona Reclamation Experimental Project at Bhalwal (Haider et al., 1975).

The soils at the site are silty loams. Some soils are saline but the majority of the area is nonsaline. The bulk density of the soils was 1.52 grams/cm^3. The permanent wilting point and the field capacity were 6.9 percent and 18.6 percent, respectively. The infiltration characteristics of the soils at Bhalwal were obtained from Haider et al. (1975) (see Table 1).

The growing season of Spring (Rabi) wheat is from October to April. The values of potential evapotranspiration, irrigation treatments, and the wheat yield data for the spring season of 1974-75 were obtained from Haider et al. (1975). The irrigation practices, the farm sizes and application efficiencies of the fields in the Sargodha district area, as reported by Freeman et al. (1978), are given in Table 2. The fields were approximately level but with low and high spots. The hydraulic roughness of the fields (Mannings n) was assumed to be 0.15, as recommended by USDA (1974) for wheat.

CALIBRATION OF THE MODEL

The irrigation system model was verified in Part 1 (Reddy and Clyma, 1981b) of this paper. The model now is calibrated for a given farm. The data required are the input and output variables of each subsystem considered in the simulation study. The input values were used to generate output from the simulation models. The output from the

Table 1. Infiltration data from Bhalwal area (Haider, Farooqui and DeMooy, 1975).

Time, minutes	Cumulative Infiltration, mm
60	24.6
120	33.0
180	38.6
240	42.7
300	45.2
360	47.5

Table 2. Operating conditions of watercourse 106 command area in Sargodha District, Pakistan (Early, Lowdermilk and Freeman, 1975).

Parameter	Location of the farm on the mogha		
	Head	Middle	Tail
Nakka discharges (lps)	65.4	59.47	59.47
Days since last irrigation	7	24	27
Area of the basin (ha)	0.20	0.20	0.24
Time of irrigation (minutes)	0.24	54	120
Depth of irrigation (mm)	46	84	114
Soil moisture deficiency (mm)	--	84	69
Irrigation delivery efficiency (%)	41	38	51
Watercourse length (meters)	476	777	1073
Application efficiency (%)	--	72	61

simulation of the subsystem models was compared with actual output from the subsystem. If the difference was significant, then the parameters of the system were adjusted until the output from the simulation models agreed closely with the actual (given) output of the system. The calibrated model was then used to evaluate different management alternatives.

Water Conveyance System

In the calibration of the conveyance system model, the data reported by Early et al. (1978) were used (Table 3). The length of the canal considered in the present analysis was 777 m. The predicted values deviated from actual field discharges (Table 3).

The equation for water conveyance, as presented in Part 1 (Reddy and Clyma, 1981b), was developed from data collected on watercourses in Pakistan. Therefore, no further verification was thought to be needed. For the particular watercourse of interest in this study, under the set of canal conditions, most of the data were given, except the loss rate in the initial section of the canal. The average loss rate measured in the initial sections of the canal was 29.7 lps. This did not give a very good prediction of the flow rate at the farm. Therefore, the loss rate in the initial section of the canal was changed to 22.65 lps for the first 305 m, and this improved the performance of the model. This recalibration reduced the prediction error at the head of the canal from 26 to 10 percent and at the middle of the canal from 30 to 13 percent. Given the variability of the actual measurements, the performance of the model was deemed adequate at this point.

Table 3. Performance of the conveyance system model before and after calibration.

Condition	Inflow Rate, lps	Loss Rate, lps	Field Outlet Discharges, lps			
			Head		Middle	
			Actual	Predicted	Actual	Predicted
Before Calibration	97.4	29.7	65.1	58.9	59.5	41.6
After Calibration	97.4	22.7	65.1	66.8	59.5	51.8

Water Application System

The water application system model was calibrated for given field conditions. The values of the application system parameters were as follows:

soil type: silty clay loam
length of the border: 67 m
width of the border: 30.5 m
inflow rate into the field: 1.86 lps/m
infiltration function: $z = 5.33\ t^{.38}$
Manning's roughness factor: 0.15
time of irrigation: 56 minutes
depth of water requirement, D_u: 76 mm

The application system model developed in Part 1 of this paper was used to simulate the flow in level basins. The simulated recession time was 34 hours, which was considered too long to infiltrate only 89 mm of irrigation water. This resulted because the Kostiakov infiltation function does not have a constant term for longer times. Therefore, an adjustment was made in the equation to include a constant for longer times. An infiltration function of the following type was developed:

$$z = Kt^{a} + Ct \tag{1}$$

A basic intake rate of 2.25 mm/hr was assumed for the value of C in Eq. 1. The following equation was obtained by regression with field data:

$$z = 28.5\ (\mathrm{mm/hr}^{a})t^{0.1087} + 2.25\ t \tag{2}$$

From Eq. 2, the recession time was found to be 10 hours, which was considered more reasonable than the previous value of 34 hours. Hence, Eq. 2 was used in the analysis.

The simulated application efficiency predicted by the model was 70 percent, which was more than the average value reported by Clyma and

Ali (1977). This application efficiency was for a level field condition as opposed to an uneven topography under the actual field conditions. For the specific set of data presented here, the performance of the model was judged to be adequate.

Water Use System

The water use system model, as described by Reddy and Clyma (1981b), consisted of two sub-models: the evapotranspiration model and the crop growth model. The evapotranspiration model was calibrated by Clyma and Chaudhry (1975), hence it was not recalibrated here. Calculated potential evapotranspiration values were available (Reuss et al., 1976) for the crop season and were used along with the irrigation treatments (Haider et al., 1975) in calculating the ratios of actual to potential evapotranspiration. The relative crop yield was calculated from the sensitivity coefficients presented in a previous paper (Reddy and Clyma, 1981b). The performance of the model was satisfactory. The simulated crop was irrigated at 1, 2 and 4 bars tension in the top 15 cm of soil. Thus, most of the time, the ratios of actual to potential evapotranspiration were high. Calibration of the sensitivity coefficients for moderate to severe stress conditions was limited because sufficient data were not available. Hence, the model verified previously for a location in India was assumed valid for the study area. When sufficient data become available, a better verification and calibration of the model can be made.

These three subsystem models: conveyance, application and water use, were combined into a single model and were used for the farm to simulate the existing system and the different improvement alternatives.

PERFORMANCE OF THE TRADITIONAL IRRIGATION SYSTEM

The model was first applied to simulate the performance of the system under existing operating conditions. The irrigation depths applied at each turn (Table 4), the potential evapotranspiration values (Reuss et al., 1976) and the crop production model developed earlier were used to predict the relative yield of wheat crop for the spring (Rabi) season of 1975-76.

The existing system was operating at an application efficiency of 39 percent (Table 5) with a relative yield of only 0.64 with an area in wheat of 1.45 ha. Considering the nonuniformity of the field slopes, the application efficiency obtained under the traditional conditions were only 30 percent (Clyma and Ali, 1977). The conveyance efficiency of the existing system was 53 percent (Reddy, 1980). These low levels of performance reveal the potential for improvement of the irrigation system and increased crop yield.

The yield levels under the existing system were low because so little water was available for the crops at each "turn". (The canal system was designed to deliver at the canal outlet a constant flow rate which was available to the individual farmer for a fixed time each week--his "turn"). The actual water supply available at the field outlet was extremely variable (Clyma, 1978) suggesting a ratio of 3 between the maximum and the mean flow rate. The mean field supply was only one-half the canal outlet supply.

The farmer allocates his field supply to different fields and crops at each turn. His criteria for allocation are not well understood but they appear to result in 3 to 10 times as much water being applied in one field as is applied in another for the same crop (Table 4, and

Table 4. Allocation of water (ha-mm/ha) on Farm No. 4 for Rabi 1975-76 at TW 78, Mona Reclamation Experimental Project (Clyma, 1978).

Field #	Crop	Date of Warabundi Turn (day/mo.)																
		16/10	23/10	30/10	6/11	13/11	20/11	27/11	4/12	11/12	18/12	25/12	1/1	8/1	15/1	22/1	29/1	5/2
168/3E	Wheat				50									105				
168/9W	Wheat			59	50									90				
268/(21,22)$_N$	Wheat/Rouni				59							102						
168/18N	Fallow	135																
168/18S	Fallow/Rouni																	
168/13N	Berseem		28															
168/13S$_1$	Berseem		48	39														
168/13S$_1$	Berseem		33															
168/8E	Wheat				50									82				
168/8W$_1$W$_2$	Shaftal			59														
168/14N	Fallow																	
168/14S	Wheat		50											30				
176/1B$_1$	Berseem	111		67		50		85			165							
174/1B$_2$	Berseem	111		31	50			74			165							
174/2A$_1$	Berseem	111		30	50	50		76			165							
174/2A$_2$	Berseem	111		30	50	50		78			165							
173/10W	Berseem		52						28									
168/3W	Wheat				50									56				
168/(21,22)$_S$	Wheat				59							160						
TOTAL		580	211	315	469	150		314	28		660	262		362				
RAINFALL													1.25		30	10	8	6

1/Estimated

Table 4. continued.

Field #	Crop	12/2	19/2	26/2	4/3	11/3	18/3	25/3	1/4	8/4	15/4	22/4	29/4	6/5	13/5	20/5
							Date of Warabundi Turn (day/mo.)									
168/3E	Wheat									33						
168/9N	Wheat															
$168/(21,22)_N$	Wheat/Rouni							39							181	
168/18N	Fallow											70				87
168/18S	Fallow/Rouni											208				
168/13N	Berseem								13			50				
$168/13S_1$	Berseem								13			50				
$168/13S_2$	Berseem								13			50				
168/8E	Wheat															
$168/8W_1W_2$	Shaftal								77	91		50	130		49	
168/14N	Fallow															87
168/14S	Wheat								50							
$174/1B_1$	Berseem							40		93		109	57	23	73	
$174/1B_2$	Berseem							40		93		109	57		73	
$174/2A_1$	Berseem							40		93		109	57		73	
$174/2A_2$	Berseem							40		93		109	57		73	
173/10W	Berseem							40					57			18
168/3W	Wheat									33						
$168/2(21,22)_S$	Wheat							39						135		
TOTAL								278	165	530		914	424	158	525	191
RAINFALL			8	33	13	11	34	3	34	13	14		8	26		10.0

Table 5. Irrigation interval, net depths, irrigation depths and application efficiency under traditional system.

Fields	Interval, Days	D_a[1], mm	D_u[2], mm	E_a, %	Interval, Days	D_a, mm	D_u, mm	E_a, %	Interval, Days	D_a, mm	D_u, mm	E_a, %	Interval, Days	D_a, mm	D_u, mm	E_a, %	Relative Yield
1	21	50.8	16.6	32.6	63	106.7	74.4	69.7	91	33.5	0.0	0.0	--	--	--	--	.667
2	14	60.0	12.1	20.2	7	50.8	7.1	13.9	63	90.0	73.4	80.7	--	--	--	--	.650
3	21	60.2	16.6	27.5	49	103.4	53.9	52.1	91	39.6	12.6	31.8	--	--	--	--	.681
4	21	50.8	16.6	32.6	63	83.3	74.4	89.3	--	--	--	--	--	--	--	--	.667
5	7	50.8	7.1	13.9	77	30.5	82.4	100.0	84	50.8	13.5	26.5	--	--	--	--	.515
6	21	50.8	16.6	32.6	63	56.6	74.4	100.0	91	33.5	0.0	0.0	--	--	--	--	.667
7	21	60.2	16.6	27.5	49	162.3	53.9	33.2	91	39.6	12.6	31.8	42	137.4	12.6	9.2	.681

Average relative yield = .648.
Average application efficiency, E_a = 39 percent.

[1] D_a = depth of application

[2] D_u = depth of requirement in the root zone.

Clyma, 1978). The result is, a highly variable amount of water is supplied to each field.

From an operating point of view, it was assumed that the farmer applies at least 76 mm (the requirement) per irrigation under the traditional field conditions. Based on this assumption, the farmer can irrigate 0.64 ha each turn with a 4-week irrigation interval. The resulting application efficiency (31 percent) was approximately that estimated previously for traditional operating conditions (Clyma and Ali, 1977). With a 4-week interval for each field, but with a turn available to hime each week, the farmer can irrigate 4 x 0.64 ha = 2.56 ha. The simulated relative yield under this condition was 0.93 with an application efficiency of 31 percent. (The actual application efficiencies ranged from 13-64 percent.) With a simulated potential yield of 2594 kg/ha, therefore, the farmer could obtain an actual yield of 2412 kg/ha. Only wheat crop was considered in this comparative study of improvements.

The irrigation turn time just to irrigate the wheat fields under the traditional operation was calculated to be 72 minutes (based on the fraction of the field area irrigated). It was found that, with a dependable water supply and perfect rotation, almost the same area (1.45 ha with traditional supply and farmer management, and 1.32 ha with dependable supply and perfect scheduling) could be irrigated but with a significantly higher relative yield of 0.93 as compared to a relative yield of only 0.64 with the traditional operating conditions. The volume of water supplied to the farm was also increased. The traditional field supply to wheat fields was only 370.82 ha-mm, as compared to a field supply of 536.5 ha-mm under the dependable water supply conditions or an increase of 45 percent in the water supply. In addition, the benefits to the farmer per unit of area increased significantly.

IMPROVEMENTS FOR THE IRRIGATION SYSTEM

Two alternatives were considered in improving the performance of the existing system: improvement of the application system and improvement of the conveyance system. These are discussed separately below.

Improvement of the Application System

Precision land leveling was considered as the improvement for the application system. With precision leveling it was assumed that the farmer was able to apply 38 mm of water efficiently and uniformly at each irrigation. The generalized geometric programming technique was applied to the optimal design of the application system (Reddy and Clyma, 1981a). The farmer now could irrigate 1.28 ha per turn instead of 0.64 ha under the traditional operating conditions. The optimal design gives the optimal rate of inflow, time of irrigation and dimensions of the irrigation unit. An average application efficiency of 60 percent was assumed under precision leveled conditions (Clyma et al., 1977). Therefore, the average irrigation interval was adjusted with the improved application system to result in a 60 percent application efficiency. By simulation it was found that the farmer irrigated at a 4-week interval with a 60 percent application efficiency under precision leveled conditions. (The actual application efficiencies ranged from a low of 19 percent to a high of 100 percent.)

Johnson et al. (1978) reported that wheat farmers in Pakistan achieved yields of 1927 kg/ha with precision land leveling under traditional canal operating conditions. The relative yield under the traditional operating conditions was 0.64. Therefore, the estimated potential yield under precision level conditions was 2974 kg/ha. The yield obtainable with improved design of the application system was computed to be 2766 kg/ha (2974 x 0.93).

The average cost of leveling was reported by Johnson et al. (1978) to be approximately Rs 1750/ha. (Rs = Rupees; 1 U.S. dollar ≅ 10 Rupees.) The average life of a leveled field was assumed to be 10 years. The annual cost of leveling with an interest rate of 15 percent was calculated to be Rs 349/ha. With an annual maintenance cost of Rs 74/ha (Johnson et al., 1978), the annual cost of leveling becomes Rs 423/ha.

The costs and net benefits for the traditional and the precision leveled systems were calculated (Table 6). As a result of the increase in the application efficiency, the area irrigated was assumed to be doubled under precision-levelled conditions. The net benefits were Rs 1989, and Rs 3625 for the traditional and precision leveled systems, respectively, which shows an increase of 82 percent in net benefits.

Improvement of the Conveyance System

Canal lining and earthen reconstruction were considered in the improvement of the conveyance system. The cost and effectiveness of each of these alternatives were evaluated. The life of a lined canal was assumed to be 20 years and that of an earthen improved system to be 8 years (Clyma et al., 1977). The interest rate was 15 percent.

The total length of channels (main, branches and field channels) in the overall irrigated area of 212 ha was 27,423 m (Freeman et al., 1978). At the rate of Rs 6.56/m, the total cost of earthen improvement was Rs 179,896, with an annual cost of Rs 188/ha. Similarly, the annual cost of canal lining was Rs 2446/ha. An annual maintenance cost of

Table 6. Irrigation depths (D_a) and application efficiency (E_a) with 3-week interval under traditional system.

Irrigation Number	CASE I Irrigation Interval, Days	CASE I D_a, mm	CASE I E_a, %	CASE II Irrigation Interval, Days	CASE II D_a, mm	CASE II E_a, %	CASE III Irrigation Interval, Days	CASE III D_a, mm	CASE III E_a, %
1	7	50.8	14.0	14	50.8	25.1	21	50.8	32.6
2	21	50.8	33.7	21	50.8	36.5	21	50.8	37.4
3	21	50.8	41.3	21	50.8	47.0	21	50.8	51.4
4	21	50.8	55.7	21	50.8	59.0	21	50.8	63.5
5	21	50.8	15.6	21	50.8	29.7	21	50.8	42.1
6	21	50.8	54.8	21	50.8	69.7	21	50.8	22.0
7	21	50.8	13.0	21	50.8	30.6	21	50.8	15.1
8	21	50.8	29.2	21	50.8	34.0			

Average application efficiency = 37 percent.
Total amount of water applied = 8 x 50.8 mm + 130 mm = 536.40 mm.

Rs 44/ha and Rs 12/ha (Clyma *et al.*, 1977), respectively, were also added to the cost of canal lining and earthen improvement (Table 7).

Canal lining was more expensive than earthen improvement (Table 8). The total yields under each improvement were considered in an economic comparison. Clearly, earthen improvement was more economical than the other alternative. The net benefits for earthen improvement were Rs 2397 as compared to Rs 1989 for a traditional field supply (Table 8).

Under the improved conveyance system more area was irrigated. An area of 4.12 ha can be irrigated with earthen improvement compared to 2.56 ha under the traditional canal system. This amounts to an increase of 61 percent in the area. Under the traditional simulated system, the yield levels were near potential (a relative yield of 0.93). Hence, most of the increased supply was applied to additional area.

The above discussion reveals that earthen improvement was more economical than canal lining. The dependability of the supply may also have been a major factor in the increased benefits. Under the traditional system some of the land area was always fallowed. So, this additional field supply was used to increase the irrigated area by bringing the fallowed land under irrigation.

Combined Improvement of the Conveyance and Application Systems

An analysis of the conjunctive improvement of the conveyance and application systems was also performed to evaluate combined or separate improvements. The field supply under earthen improvement was 83 lps. With the increased supply of water and the improved application system, the area that could be irrigated increased to 8.17 ha. Areas irrigated for separate improvements were 4.12 ha and 5.12 ha for delivery and application systems, respectively.

Table 7. Characteristics of the conveyance system improvement alternatives.

Type of Improvement	Loss Rate Before Improvement lps/hm	Loss Rate After Improvement lps/hm	Cost of Improvement Rs/metre	Canal Inflow Rates lps	Field Supply Rate, lps
No improvement	7.43	--	--	97.42	51.81
Earthen Improvement	7.43	1.95	6.56	97.42	83.0
Canal lining	7.43	0.46	98.4	97.42	93.86

hm - hectametre = 100 metres.

Table 8. Operating characteristics and net benefits from conveyance system improvement alternatives.

Type of Improvement Characteristic Parameter	Traditional System	Earthen Improvement	Canal Lining
Life of the system (yrs)	--	3	20
Annualized cost (Rs/ha)	--	(183 + 12) = 195	(520 + 44) = 564
Field supply rate (lps)	51.8	83.0	94.0
Area irrigated (ha)	2.56	4.12	4.67
Gross returns (Rs)	2412 x 2.56 = 6175	2412 x 4.12 = 9937	2412 x 4.67 = 11256
Cost of production + lining (Rs)	1635 x 2.56 = 4186	(1635 + 195) x 4.12 = 7540	(1635 + 564) x 4.67 = 10269
Net benefit (Rs)	1989	2397	987

The area of the individual field units can be increased significantly under precision-leveled conditions because leveling removes the requirement for most of the field channels that were present under the traditional field conditions thereby reducing the total length of the canals significantly. Therefore, the cost of canal improvement now becomes Rs 38/ha and Rs 412/ha, respectively, for earthen improvement and canal lining, compared with 188 and 2446 Rs/ha previously.

Canal lining without improving the application system was not beneficial to the farmer: The farmer would receive less benefits by lining the canals than under the traditional operating system (Table 9). Earthen improvement combined with optimal design of precision leveled field was more beneficial under the given situation. It must be mentioned that canal lining also would become beneficial if used in conjunction with precision leveling, as the potential returns per unit area increase.

The net benefits were Rs 408, Rs 1636, and Rs 3384 for the improvement combinations of traditional application and improved conveyance, improved application and traditional conveyance, and improved application and conveyance, respectively (Table 10). The area of cultivation has been more than doubled under the combined improvement alternative over the traditional system. The benefit/cost ratios of these improvement alternatives were different. The difference in benefit/cost ratio between the application system improvement and the conveyance system improvement is significant. There was no difference between the benefit/cost ratio of the combined improvement, and the improved application and traditional conveyance system. The benefits from the combined improvement were much greater than the sum of the benefits obtained from the individual improvements.

Table 9. Comparison of benefits from different conveyance and application system improvements.

Characteristic Parameter	Earthen Improvement		Canal Lining	
	Traditional	Precision	Traditional	Precision
Canal length (m)	27,423	5,559	27,423	5,559
Earthen (m)	27,423	5,559	21,864	0.0
Lining (m)	0.0	0.0	5,559	5,559
Annual cost of improvement (Rs/ha)	183 + 12	38 + 12 + 423	520 + 44	412 + 44 + 423
Total cost of improvement (Rs/ha)	195	473	564	879
Cost of production (Rs/ha)	1,635	1,635	1,635	1,635
Gross return (Rs/ha)	2,412	2,766	2,412	2,766
Area under cultivation (ha)	4.12	8.17	4.67	9.24
Total benefit (Rs)	2,397	5,373	987	2,326

Table 10. Comparison of benefits from 4-different combinations of improvements.

Performance Parameter	Traditional Application and Conveyance	Traditional Application and Improved Conveyance	Improved Application and Traditional Conveyance	Improved Application and Conveyance	Traditional System under Farmer Management Conditions
Field supply rate (lps)	52	83	52	83	variable
Area irrigated, (ha)	2.88	4.64	5.12	8.17	2.52
Yield (Kgs/ha)	2542	2542	2766	2766	1660
Total benefits (Rs)	7321	11795	14162	22598	4184
Cost of production (Rs/ha)	1635	1635	1635	1635	1635
Cost of improving conveyance system (Rs/ha)	--	183 + 12 = 195	--	38.3 + 12 = 50.3	--
Cost of improving application system (Rs/ha)	--	--	423	423	--
Cost of improvement (Rs/ha)	--	195	423	473.3	--
Total cost (Rs)	4709	8491	10537	17225	4120
Total net benefit (Rs)	2612	3304	3625	5373	64
Total added benefits (Rs)	--	4474	6841	15277	--
Total added costs (Rs)	--	3782	5827	12516	--
Percent improvement	--	26	39	106	--
Benefit: cost	--	1.18	1.17	1.22	--
Total added net benefits (Rs)	--	692	1014	2761	--

A comparison was also made between the performance of the farmer managed irrigation system and the performance of the irrigation system with combined improvement alternative. For the improved situation, the area had more than tripled, from an initial area of 2.52 ha to an area of 8.17 ha.

For the farmer-managed conditions, only 2.52 ha were cultivated with wheat and berseem, with a relative wheat yield of 0.64. Under the simulated conditions (dependable supply), 2.56 ha of wheat was cultivated but with a relative yield of 0.93. This reveals the importance of dependable water supply on benefits. The benefits to the farmer increased substantially from a mere subsistence level under farmer managed conditions to a total net benefits of Rs 5373 under the combined improvement alternative (Table 10).

Under the traditional system, there was always some fallowed land. The increased supply could be used for growing crops on the fallowed land, and growing higher value crops, even with a higher price for water. If the water supply were still greater than the crop requirements, then the tubewells could be shut down followed by regulation of flow into the watercourse.

SUMMARY AND CONCLUSIONS

A farm of 3.24 ha in Pakistan was considered in the present analysis. The theory developed in Part 1 of this paper was applied to evaluation of alternative improvements of the irrigation system. The conveyance, application, and water use subsystem models were calibrated with data for the study area. Simulation showed the performance of the existing irrigation system was found to be poor with an application efficiency of only 39 percent and a conveyance efficiency of 53 percent.

Three alternatives were considered for improving the performance of the existing system: improvement of the conveyance system, improvement of the application system, and conjunctive improvement of both. A comparison of the performance of the traditional system under farmer-management conditions and under dependable water supply revealed that the crop yield on the farm can be significantly increased. The benefits of optimal design with precision land leveling were analyzed. The area of cultivation was almost doubled with an application efficiency of 61 percent. Investments in precision land leveling resulted in a benefit/cost ratio of 1.17.

Similarly, earthen reconstruction and canal lining were considered for improvement of the conveyance system. Analysis showed that canal lining was not at all economical to the farmer, even though the conveyance efficiency was 95 percent to the middle of the watercourse (777 m). Earthen improvement was economical. Net benefits of Rs 2397 were obtained under earthen improvement compared to Rs 1989 and 987 for the traditional system and canal lining, respectively. The benefit cost ratio for earthen improvement was 1.12.

A comparison of benefits under earthen improvement and optimal design of the application system with precision land leveling indicated that the total net benefits were 66 percent more for the combined improvements than the sum of the benefits for each improvement completed separately. The analysis revealed that improvement of the application system and combined improvements were more beneficial, with a benefit/cost ratio of 1.26, than improvement of the conveyance system. The increase in benefits came mostly from increased area irrigated.

The performance of the existing system can be improved significantly by a combined improvement of the application and delivery systems. The area under irrigation can be increased 2.8 times by the improvement. Since the benefit/cost ratios of the improvement alternatives (application system, conveyance system, or the combined system) were greater than one, any of the improvement alternatives can be justified, depending upon the financial, social and political constraints under the given set of conditions. Economically, the combined improvement is the most attractive alternative.

ACKNOWLEDGMENTS

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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.)

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