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Reducing Farm Delivery Losses in Pakistan

Wayne Clyma, W. Doral Kemper, M. Mohammad Ashraf
MEMBER ASAE MEMBER ASAE

ABSTRACT

A study of on-farm irrigation delivery systems in the Punjab Province of Pakistan shows the factors causing 50 percent delivery losses. Improvement alternatives were evaluated and farmer cleaning and maintenance and reconstruction of earthen channels had benefit:cost ratios from 2.9 to 17.6. Total system improvement rather than partial provided the greatest benefits.

INTRODUCTION

Irrigation is an essential component of Pakistan's agriculture with more than 13 million ha irrigated. Delivery of water from the government owned and operated canal to the farmers' fields is accomplished by delivery channels maintained and managed by the community of farmers served by an outlet. This study reviews the on-farm irrigation water delivery and then details the benefits and costs of a number of alternative improvements for reducing delivery losses. A strategy for future improvements is suggested.

WATER DELIVERY IN PAKISTAN

The irrigation system in Pakistan was developed by the British in the late 1800's. The history and status of this development has been described by Corey and Clyma (1975). A system of barrages divert water from rivers into canals which deliver water to outlet structures. The flow to the farms to be irrigated is controlled by the outlet structure at a rate that is proportional to the area to be irrigated, the crops grown and climatic factors. The canal water supply rate is approximately 1 m³/s for each 5 000 ha (1 cfs/350 ac). Nearly 10,000 public (government owned and operated) and more than 120,000 private wells supplement the canal water supply. Canal water is delivered to farms and fields on a rotation basis usually at 7-day intervals. Each farmer receives all the flow from the channel during his turn. Trading of water turns outside the rotation is illegal under most circumstances.

Because of unleveled fields and relatively small holdings, an extensive system of channels is required to serve the area with 1 km of channel frequently serving 5 ha (1 mi/20 acre). These channels are constructed and maintained by the community of farmers each outlet serves, largely without involvement of government officials. Extensive studies of the irrigation system in Pakistan during the 1960's assumed on-farm delivery losses at 10 percent, but recent studies have suggested that these losses are several magnitudes greater at near 50 percent (Clyma and Corey, 1975; Clyma, Ali and Ashraf, 1975a; and Early, Lowdermilk and Freeman, 1978).

The physical factors which influence water delivery are as follows:

1 Flow rate
2 Cross section
3 Hydraulic radius
4 Roughness
5 Slope
6 Seepage rate

A seventh factor, management, is affected by the allocation rules and operational norms for water delivery. The farmer, who manages the system, is the effector of these factors.

Water delivery is described by the previously listed physical variables and management. Management is influenced by legal, social, economic and institutional factors which are constraints on the individual and community of farmers. In the next section, these variables will be discussed. First, the procedure used to collect data on the operation of the on-farm delivery system will be described.

Procedure

Data from previous reports (Clyma, Ali and Ashraf, 1975a; Kemper, Clyma and Ashraf, 1975; plus unpublished mimeographed materials) defining farm water delivery practices will be summarized and interpreted for the Punjab Province. Data were collected from delivery channels with two kinds of measurements as follows:

1 Inflow-outflow measurements of losses with Parshall or cutthroat flumes.

2 Ponding studies by measuring the rate of water surface decline.

Variables used to describe delivery channel performance were channel delivery efficiency and loss rate. Channel delivery efficiency (E_d) for a length of channel is defined as follows:

$$E_d = \frac{\text{Inflow rate (m}^3\text{/s)}}{\text{Outflow rate (m}^3\text{/s)}} \times 100 \quad \text{[1]}$$

Loss rate is measured as m³/s per km of channel (cfs/1000 ft) and is defined for a length of channel as follows:

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The authors are: WAYNE CLYMA, Associate Professor, and W. DORAL KEMPER, Professor, Agricultural and Chemical Engineering Dept., Colorado State University, Fort Collins; and M. MOHAMMAD ASHRAF, Chief Engineer, Surveys and Research Division, Master Planning Organization, Water and Power Development Authority, Lahore, Pakistan.

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$$\text{Loss rate} = \frac{\text{Inflow rate} - \text{Outflow rate } (m^3/s)}{\text{Length of channel (number of km)}} \quad \ldots\ldots\ldots \quad [2]$$

Ponding measurements were converted to a loss rate as defined by equation [2] by computing the rate of volume change of water in storage in the section. Loss rate and delivery efficiency measurements represent steady-state delivery efficiencies unless otherwise specified.

The detailed procedures followed during flume measurements were described by Mohsin, Clyma and Early (1975) but consisted of measurement of inflow and outflow for channel lengths, most frequently with a cut throat flume (Skogerboe et al., 1973). Kemper et al. (1975) compared the results of ponding measurements and inflow-outflow measurements and concluded that results were similar with careful regulation of the water levels during the ponding measurements. Evaluation of the physical variables and their influence on water delivery will now be discussed.

Flow Rate

Groundwater from public wells usually is supplied on a weekly rotation at approximately a constant rate as is canal water. With crop consumptive use low initially, increasing to a peak and then decreasing, some flexibility in the delivered supply is needed. In general, farmers trade turns to obtain some flexibility. The primary result is that farmers must dispose of this relatively constant supply of water on their fields. Usually there are no official means for regulation of the flow at the canal outlet and no official provision to bypass the water to the river or a drain.

Water delivery at the field needs to be supplied at an appropriate constant flow rate on a dependable basis. The variability of flow available at the field is illustrated by the data given in Table 1. These data are for one farm located at about 1.5 km (5,000 ft) from the outlet and for a period of 1 yr. The farmer borrowed water 11 additional times. Sixty-five percent of these turns were less than 0.011 m^3/s (0.4 cfs).

The flow at the canal outlet ranged from near 0.028 m^3/s (1 cfs) to 0.14 m^3/s (5 cfs) but most of the time was 0.057 or 0.14 m^3/s (2 or 5 cfs). Average flow at the field ranged from near 0.0057 to 0.105 m^3/s (0.2 to 3.7 cfs). When a farmer, as discussed by Clyma and Ali (1977), manages these ranges in flow without explicitly considering the flow rate, ineffective use of water will result. Low delivery efficiencies that average near 50 percent caused by high loss rates result in variable flow rates at the field. Ineffective use of the delivered water is also the result.

Cross Sections

Existing channel cross sections in Pakistan range from narrow and deep to wide and shallow. Buffalo wallows, animal crossings, and junctions for branch channels are usually wide and shallow. Ratios of b/d (width of flow-depth of flow) may range from 3 to 10 at the wide sections. In other instances, erosion or repeated, excessive cleaning of sediment results in deep, narrow channels with b/d ranging from 0.25 to 0.5.

TABLE 1. VARIABILITY IN FLOW RATE AT THE FARM FIELD

Average flow rate during turn, m^3/s	Turns no.	Interval pct. of total	Accum. pct.
≤ 0.0057	5	12	12
$0.0057 \leq 0.028$	18	43	55
$0.028 \leq 0.057$	15	36	91
$0.057 \leq 0.085$	3	7	98
> 0.085	1	2	100

Adequate and regular maintenance is lacking on most channel systems. As a result, grass, weeds and sediment decrease the cross section, increase the channel roughness and raise the water level in the channel. Lack of adequate freeboard results in overtopping as the water level rises. Increasing the depth of flow by 5 cm (2 in.) may double the loss rate. Trees further decrease the cross section and result in meandering channels. Tree roots increase the seepage rate, particularly when holes develop along dead roots.

Hydraulic Radius

Hydraulic radius has two primary effects on delivery of water. The section should approach the most efficient to minimize construction and maintenance costs. The wetted perimeter should approach a minimum to reduce loss rate per unit length of channel for a given loss rate per unit area. Land resources are scarce from the farmer's point of view and a minimum hydraulic radius minimizes the area used by the channel. Uncontrolled, random maintenance procedures tend to change a given efficient section to a less appropriate section.

Slope

Channel slopes in Pakistan are small. Natural gradients of 0.001 are frequent topographic reliefs. The average for the Indus Basin is near 0.00014 but local relief results in natural gradients that produce channel erosion unless controlled.

Canals in Pakistan carry sediment loads of approximately 200 ppm (Mahmood, 1971). The canal design requires that each outlet take from the canal an amount of sediment proportionate to the water removed from the total flow (Mahmood, 1971). In principle each field receives its share. Particular channels because of local topography may have low gradients resulting in deposition of sediment. Farmers also expand the area irrigated by an outlet to fields which are higher than the designed command area elevation. The latter results in a low water surface slope. As a result, both conditions cause sediment deposition in the channel. The result is that on many outlets sediment removal is a major labor problem. But most important, the sediment raises the water level downstreamn of the outlet and submerges the outlet. This reduces the flow rate for all farmers irrigated from the outlet. Measured reductions in flow rate of 20 to 60 percent were usual on these problem outlets.

Seepage Rate

Soils in Pakistan are predominantly silt loams with some small areas grading to sandy loams or silty clay loams. For very large areas, more than 90 percent of the soils are silty loams. Surface infiltration rates for these silt loams approach 2.5 mm/h (0.1 in./h) as a terminal rate. Measured, average infiltration rates for channel lengths from 10 to several thousand meters usually exceed 25 and even 100 mm/h (1.0 to 4.0 in./h). Such excessive loss rates were not known as other assumptions and data had assigned an average delivery efficiency of 90 percent for on-farm channels (Clyma and Corey, 1975). Specific circumstances caused this discrepancy between assumed and measured losses.

Delivery channels from the outlet to a field follow land boundaries and have remained in the same location up to a hundred years. Maintenance operations on the channel places silt and vegetation on top of the banks. Growing vegetation and its roots occupy the banks of the channel. Traffic, natural settlement, and repeated cleanings cause organic matter to accumulate within the banks. As Kemper et al. (1975b) have aptly described channel banks:

> The plants are not generally harvested and their seeds, stems and roots furnish a rich supply of food for a teeming population of ants, beetles, worms and other insects and grubs which honeycomb the banks as they harvest their food and build their homes and nesting places. Rodents which live on these insects and their larva are attracted to their prey and further riddle the banks in their search for food.

The banks in many areas are the only place high enough to escape inundation during field irrigations and make the best natural home for insects and rodents. These conditions combine to make channel banks the most permeable soils in Pakistan. They also contribute to the high rate of water loss from delivery channels.

Management

The farmer receives all the flow for a turn time, which is largely determined by his farm area, once each week. During periods of low crop demand or high rainfall, the water supply may remain constant. Excess water is used as insurance against an undependable future supply on fields that "most need" irrigation. Clyma, Ali and Ashraf (1975b) observed a number of irrigations on fields that were already at field capacity. During the summer, rice and sugarcane are commonly irrigated with surplus water. During the winter, berseem, sugarcane or wheat receive the water.

Lowdermilk, Clyma and Early (1975) found that all farmers without supplemental water (from wells) listed inadequate water supply as their most important problem. Unauthorized use of water is also a major source of conflict. Patterns of conflict also make cooperative efforts difficult to organize. These same conflict patterns make joint efforts even more difficult to enforce. With very limited resources a farmer is reluctant to invest resources which benefit other farmers who make no investment.

Delivery efficiencies for various water supply conditions were measured and an overall delivery efficiency of 60 percent was estimated by Clyma, Ali and Ashraf (1975a). The measured losses were for steady-state delivery efficiencies. Kemper et al. (1975a) suggested that efficiencies that included operational losses could be 50 percent lower. Early, Lowdermilk and Freeman (1978) in another study obtained a median delivery efficiency of 53 percent. Loss rates ranged from 0.0069 to 0.032 m³/s per 1,000 m (0.075 to 0.5 cfs per 1,000 ft) (Kemper, Clyma and Ashraf, 1975). In measurements of actual water supply versus designed water supply, outlets had reduced flow ranging from 20 to 60 percent because of improper maintenance and design of the channels. Measurements of Manning's n for channels from must after maintenance to several months later resulted in values initially near 0.02 that increased up to 0.05.

Results from measurements of losses suggested improvement of channels should have high priority with farmers and government as water supply alternatives were considered. An evaluation of alternative improvements is presented in the following section.

WATERCOURSE IMPROVEMENT ALTERNATIVES

A review of the factors affecting the flow of water in on-farm channels suggests proper maintenance or redesign and reconstruction of the channels would provide appreciable increases in the flow rate and water supply volume. Further, more adequate control structures at the junctions were needed because of unusually high loss rates and because present methods used by farmers would tend to degrade existing and improved channels.

Two approaches, including subsets under reconstruction, to reduction of channel losses were considered as follows:

1 Improved maintenance
2 Channel reconstruction and maintenance: (a) Lining of the channel; (b) Earthen improvements; (c) Combinations of lining and earthen improvements.

In both instances use of appropriate control structures at channel junctions and farm outlets would be included.

Preliminary analyses of these alternatives were given by Eckert, Dimick and Clyma (1975) and Kemper, Clyma and Ashraf (1975). Additional data on both the measured costs and benefits are available from Johnson, Kemper and Lowdermilk (1978). An analysis of the benefits and costs of these alternatives provides the basis for suggesting several improvement programs.

Evaluation Data

Outlet command conditions vary widely as to water supply, total area, geometry, and channel conditions. Eckert, Dimick and Clyma (1975) specified five average conditions of water supply, outlet command area and channel length. This analysis will be restricted to their Case V with the conditions summarized in Table 2. The key principle in this analysis will be to use data and assumptions that reflect conditions as they exist now in Pakistan. When projections are made, they will be explicitly stated.

Measurements of main plus branch channel length for several command area improvements suggest that average length for main plus branch channels was 24 m/ha (30 ft/acre) and for the main channel 8 m/ha (10 ft/acre). These lengths were used in this analysis.

TABLE 2. DESCRIPTION OF THE OUTLET CONDITIONS ASSUMED FOR THIS ANALYSIS

Case V*	Tubewell plus canal	Canal only	Tubewell only
Days of operation	135	215	11
Duty, ha/m³ s⁻¹	2142	5002	3744
Supply rate, m³/s	0.104	0.044	0.059
Water supplied, 10⁶ m³	1.22	0.83	0.06
Culturally commanded area; ha		222.6	
Water supply at canal outlet, 10⁶ m³		2.11	
Water supply at field, 10⁶ m³		1.06	
Average losses, 10⁶ m³		1.06	

*As described by Eckert, Dimick and Clyma (1975).

TABLE 3. COST, LIFE AND MAINTENANCE DATA FOR ANALYSIS OF CHANNEL IMPROVEMENT ALTERNATIVES

Type of improvement	Annual maintenance	Life* (yr)	Cost* Rs/m†
Brick-masonry lining	1.5‡	20	130
Soil-cement block lining	1.5‡	15	80
Side lining	10 ‡	20	50
Farmer reconstructed	4,500 Rs/yr	8	7
Cleaning and maintenance	—	1	—

*From Johnson, Kemper and Lowdermilk (1978).

†Ten Rupees (10.00 Rs) equals approximately one U.S. dollar ($1.00).

‡Percentage of the initial capital cost.

The basic data necessary for evaluation of the alternative methods of improvement are as follows:

1 The cost of each alternative improvement.

2 The cost of maintenance and the life of the improvement.

3 The savings in water through improvement of the delivery efficiency.

4 Any other benefits from improvement.

5 The value of the water saved.

Benefits of the improvement of watercourses occur from increased dependability of the supply, reduction of crop loss caused by seepage from adjacent channels and reduction in waterlogging. The value of the water saved occurs as increased yields on concurrently farmed areas, increased income from growing higher valued crops and cultivating increased area. From 25 to 45 percent of the area on each command area is fallow in part because of a shortage of water. Benefits in this analysis will be ascribed primarily to increased yield due to increased water for existing crops and increased area.

The maintenance, life and cost of construction for each improvement are given in Table 3. The annualized cost, annual maintenance and total annual cost (Rs/m)* all on a hectare basis are given in Table 4. The interest rate was 15 percent.

The alternatives for improvement for which data were available are as follows:

Brick-Masonry Lining—Rectangular cross-section and 11.5, 23 or 33 cm (4-1/2, 9 or 13 in.) wall thickness. This is a standard method of construction in Pakistan.

Soil-Cement Block Lining—Same method of construction as above but bricks (blocks) are constructed of a mixture of soil and cement and air dried (see Kemper and Akram, 1976).

Side Lining—Panels of an appropriate dimension are precast and installed in the sides of the channel banks with no bottom provided (Johnson, Kemper and Lowdermilk, 1978).

Farmer Reconstructed—Earthen improvement of existing channels by reconstruction to the proper grade, alignment and cross-section with concrete control and outlet structures (see Bowers et al., 1976).

Cleaning and Maintenance—Regular, thorough cleaning and maintenance by the farmers with routine maintenance provided by a hired person.

Method of Comparison

Increased flow at the end of a length of improved channel is the primary, measurable benefit of channel improvement. However, the value of this water must reflect the conditions of use by the farmer. Eckert, Dimick and Clyma (1975) explicitly evaluated whether the water saved was applied to leveled or unleveled fields. Johnson (1978) in developing a value for water assumed a system efficiency (delivery x application efficiency) of 50 percent even though the reports cited gave 50 percent as the delivery efficiency only. Eckert, Dimick and Clyma (1975) valued the water saved from leveling at yield levels that projected yield increases from improved extension. Johnson (1978) stated the yields were for farmers under present conditions in the Sargodha District but cited the yields for wheat that were the projected yields from Eckert, Dimick and Clyma (1975).

Johnson, Kemper and Lowdermilk (1978) compared the costs of saving a volume of water by various improvement alternatives. The delivery efficiencies and savings from the unimproved conditions are shown in Table 5. The analysis gives no basis for concluding the value of benefits from the investment because the saved water is assumed to be 100 percent beneficially used.

An analysis where land leveling is combined with watercourse improvement into a total system will be used to document the value of a comprehensive improvement program. With present application efficiencies on traditional fields, as much as two-thirds of the water saved by improving channels would be lost in application to fields.

Improvements in System Efficiency

The on-farm system in Pakistan consists of the following components and subcomponents.

1 Delivery system: (a) Main and branch channels, (b) Field channels

2 Field application system

3 Water use system

TABLE 4. TOTAL ANNUAL COST (Rs/ha) FOR CASE V WATERCOURSE CONDITIONS FOR IMPROVEMENT OF MAIN PLUS BRANCH CHANNELS

Type of improvement	Annualized cost, * Rs/ha	Annual maintenance, Rs/ha	Total annual cost, Rs/ha
Brick-masonry lining	474	44	518
Soil-cement lining	316	27	343
Side lining (experimental)	178	17	195
Farmer reconstructed	32	12	44
Cleaning and maintenance			18

*Interest rate was 15 percent.

TABLE 5. DELIVERY EFFICIENCY AND PERCENTAGE SAVINGS OF LOSSES FOR VARIOUS IMPROVEMENTS FOR THE MAIN PLUS BRANCH CHANNELS

(Adapted from Johnson, Kemper and Lowdermilk, 1978)

Channel condition	Delivery efficiency, %	Savings from unimproved, %
Brick-masonry lining	94	88
Soil-cement lining	87	74
Side lining	80	60
Farmer reconstructed	75	50
Maintenance	63	26
Unimproved	50	0

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*Ten Rupees (10Rs) equals approximately one U.S. dollar ($1.00).

TABLE 6. FIELD SUPPLY AND ROOT ZONE STORAGE FOR CASE V WATERCOURSE WITH UNIMPROVED DELIVERY CHANNELS AND TRADITIONAL FIELDS COMPARED TO VARIOUS COMBINATIONS OF FARMER RECONSTRUCTED CHANNELS AND LEVELED FIELDS

Improvement condition no.	Condition description	Delivery efficiency,%	Field supply, 10^3 m^3	Application efficiency, %	Root zone storage, 10^3 m^3
1	Unimproved main, branch and field channels with traditional fields	40	845	30	253
2	Improved main and branches, but unimproved field channels with traditional fields	42.5	898	30	269
3	Improved main, branch and field channels with traditional fields	76.5	1616	30	485
4	Improved main, branch and field channels with leveled fields	76.5	1616	60	970

*Outlet supply was 2,111,000 m^3 from Table 2.

Under present conditions, improvement of the main channel and branch channels leaves a segment of the delivery system unimproved. Losses in the short but unimproved segment can be significant. The losses are high because improvement of the main and branch channel supplies a flow at the field channel that may be double or more the previous flow. Early, Lowdermilk and Freeman (1978), Johnson, Kemper and Lowdermilk (1978) and unpublished data from Clyma† confirm the high losses in the field channels.

To be able to value the water stored in the root zone, a delivery efficiency to the field must be determined. In addition, an application efficiency must be assumed. Four conditions of water delivery are considered to be of interest for comparison. Since more detailed data for the farmer reconstructed channels are available, the conditions for this improvement are described in detail in Table 6.

Both Early, Lowdermilk and Freeman (1978) and Clyma, Ali and Ashraf (1975a) have observed that in Salinity Control and Reclamation Projects (SCARP) watercourse losses are the highest. An average delivery efficiency of 40 percent for the unimproved watercourse (Table 5) is more reasonable than the average of 50 percent reported by Lowdermilk, Early and Freeman (1978) for all water supply conditions.

Application efficiency defines the ratio of the water stored in the root zone to that delivered to the field. Application efficiencies vary widely with time and location in an area. Clyma, Ali and Ashraf (1975a) studied several SCARP watercourses for a year and a median of the measured efficiencies was between 20 and 30 percent. Unpublished data from Clyma‡ do not contradict the above conclusion. This study will assume an application efficiency of 30 percent as suggested by Clyma and Ali (1977).

A delivery efficiency of 85 percent was assumed for the improved main and branch channels. A delivery efficiency of 50 percent for the unimproved field channels was assumed as supported by Early, Lowdermilk and Freeman (1978) and unpublished data from Clyma‡. Improving the field channels was assumed to improve the field channel efficiency to 90 percent. With the short distances, this is high but achievable value. The last assumption was improvement of the application efficiency to 60 percent when precision leveled fields are provided. The doubling of application efficiency through precision land leveling is based on the rationale that present unleveled fields cause farmers to apply water until all areas of the field are covered including high spots. This causes excess application of water that can be reduced when precision leveling reduces the range in elevations in a field. Both Ali, Clyma an Ashraf (1975) and Johnson, Khan and Hussain (1978) reported that the time of irrigation was reduced to half the previous time. These studies suggested than an application efficiency of 60 percent for precision leveled fields is possible with potential for further improvement by improving farmer water management practices.

Delivery efficiencies for the other improvements, for unimproved and improved field channels were assumed as follows:

Type of improvement	Delivery efficiency (%) Unimproved field channels	Improved field channels
Brick masonry lining	47	85
Soil-cement block lining	47	85
Side lining	45	81
Farmer reconstructed	42.5	76.5
Cleaning and maintenance	—	63
Unimproved	40	—

Application efficiencies are the same as for the farmer reconstructed alternative conditions in Table 6.

A summary of the water supply delivered to the field and stored in the root zone for the various combinations

TABLE 7. WATER SUPPLY AT THE FIELD AND IN THE ROOT ZONE (10^3 m^3/yr) FOR ALL IMPROVEMENT ALTERNATIVES FOR THE FOUR CONDITIONS AS DESCRIBED IN TABLE 6 (CANAL OUTLET SUPPLY WAS 2,111,000 m^3)

		Water supply (10^3 m^3) for type of improvement				
Condition* no.	Water supply location	Brick-masonry lining	Soil-cement lining	Side lining	Farmer reconstructed	Cleaning and maintenance
1	Field	845	845	845	845	845
	Root zone	253	253	253	253	253
2	Field	991	991	950	898	—
	Root zone	297	297	285	269	—
3	Field	1794	1794	1711	1616	1330
	Root zone	539	539	513	485	399
4	Field	1794	1794	1711	1616	1330
	Root zone	1076	1076	1026	970	798

*See Table 6 for a description of each condition.

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†Clyma, W. et al., 1978. Seasonal Irrigation Evaluations. Unpublished manuscript.

‡Clyma, W., Ibid.

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TABLE 8. AVERAGE VALUE OF WATER SAVED AND STORED IN ROOT ZONE THROUGH WATERCOURSE IMPROVEMENT

(Adapted from Johnson, Kemper and Lowdermilk, 1978)

Water saved, $10^3 m^3$/yr	Average value, Rs/$10^3 m^3$
269	107
285	107
297	106
399	103
485	101
513	100
539	99
798	91
969	81
1026	79
1076	76

of improvements is shown in Table 7. The water saved by the improvement that becomes available for use in the root zone has now been determined. This analysis valued the water stored in the root zone as the primary benefit of the improvement. A more comprehensive analysis that would value each improvement alone and in combination with other improvements would be most appropriate.

Value of Water

Johnson, Kemper and Lowdermilk (1978) provided a value of water saved from watercourse improvement versus percentage of water losses saved. Since the percentage saved was for an "average" watercourse, then the savings percentage can be equated to volume of additional water supply on an annual basis. Since the data are for an average value of water coming from a linear programming analysis, they represent the marginal value of an additional volume of water. These marginal values were used to compute an average value of water for the alternative conditions of improvement and the volumes of water saved in Table 7. The results are shown in Table 8.

The marginal value of an additional increment of water approaches zero as the amount of additional water that a farmer can use increases to a maximum. The average value of the additional water saved was computed as a weighted, arithmetic average of the straight line segments of the value of water curve from Johnson, Kemper and Lowdermilk (1978). As observed earlier, the value of the water given here is probably inflated because of the use of projected rather than current farm yields. The value of the water may be less because Johnson, Kemper and Lowdermilk (1978) assumed an unrealistically high overall system efficiency. These effects are compensating although the effect of each may be considerably different in magnitude.

Benefit: Cost Analysis

An analysis of the benefits and the benefit:cost ratios for each alternative improvement and improvement condition are given in Table 9. The cost of the improvement is taken from Table 4. The benefit is determined from the volume of water saved as presented in Table 7 and the average value of the water in Table 8.

TABLE 9. BENEFITS AND BENEFIT: COST RATIOS FOR ALTERNATIVE IMPROVEMENTS AND IMPROVEMENT CONDITIONS

Type of improvement and improvement condition*	Annual cost†,	Annual benefits,	Benefit: cost
	Rs/ha	Rs/ha	
Brick-masonry lining	518		
#2		141	0.27
#3		240	0.46
#4		368	0.71
Soil-cement lining	343		
#2		141	0.41
#3		240	0.70
#4		368	1.07
Side lining	195		
#2		136	0.70
#3		230	1.18
#4		363	1.86
Farmer reconstructed	44		
#2		128	2.90
#3		220	4.92
#4		353	7.94
Cleaning and maintenance	19		
#3		185	10.0
#4		326	17.57

*Improvement conditions are those described in Table 6.
†See Table 4 for an analysis of costs.

Under the conditions of this analysis brick-masonry construction, alone or combined with land leveling, is not economical. The soil-cement block lining combined with improved field ditches and land leveling is economically feasible. Side lining is economically feasible if farmers improve field ditches. Land leveling just provides additional benefits to channel improvement when combined with side lining. Both the farmer reconstructed, and cleaning and maintenance programs are beneficial without field ditches being improved or without land leveling.

In this analysis, the conclusions about which alternative is economical is very sensitive to both costs of the improvement and the value of the water saved. The value of the water saved is not vested in just yield increases. There are a number of other values and costs that could not be considered in this analysis because of both a lack of data and in some instances because of a lack of methodology for establishing the value or cost. The important point to remember is that the procedure for analysis may be appropriate at future times, but the conclusions about the economic benefits of a particular improvement must be updated as economic conditions change. Also, the specific conditions of a particular watercourse will frequently be significantly different from those assumed in this analysis. The conclusions about which alternative is economical can be equally different.

A complete analysis of the benefits and costs of each separate alternative and the overall benefits and costs of the combined improvements must be conducted to provide data for final conclusions. Farmer improvements of field ditches approach zero in cost because studies have shown that the marginal value of farmer labor approaches zero for significant periods. Therefore, not including any costs for improvement of field ditches is not unrealistic. The point that needs emphasis is that one of the major needs in the watercourse improvement program in Pakistan is an extension emphasis on farmer improvement of field ditches. This should be one of the highest priorities for extension agents.

Land leveling provides a number of benefits in addition to the improvement of application efficiency. Land leveling combined with watercourse improvement provides a number of complementary benefits and an analysis of their combined costs and benefits would be most appropriate. Shafique, Clyma and Bowers (1978) have evaluated some of these benefits. Land leveling must be provided to justify the soil-cement block lining and provides substantial increases in benefits to the other channel improvement alternatives (Table 9). Since land leveling does have definite costs, improvement condition No. 4 is not strictly appropriate. However, the analysis is included here to illustrate the value of the combined programs.

Cleaning and maintenance of channels is a highly beneficial improvement. This improvement provides sufficient benefits to have first priority among extension efforts all over Pakistan. A brochure which provides simple instructions for farmers to follow and a national publicity program would be beneficial in promoting the adoption of this significant improvement.

Another specific program not addressed explicitly here is an extension program that would increase farm yields significantly. Increased yields provide added benefits to all improvements and was the explicit reason that the analysis by Eckert, Dimick and Clyma (1975) provided high benefit:cost ratios. Projected yield increases were one of the major benefits. With yields so low and the potential increases in yields so high, several magnitudes for most crops (Haider et al., 1976; Ali et al., 1976; Quershi et al., 1977), the improvement of farm yields through improved extension must remain a high priority.

Additional Benefits

Only the value of the water saved was included in the above benefit-cost analysis. Watercourse improvements that reduce losses result in benefits other than additional water saved. Use of the concrete control structures reduces labor. A well-maintained channel also reduces labor during irrigation. One person usually patrols the channel to stop major leaks during his particular turn while another person irrigates. Limited experience since improvement also suggest that the total time to do periodic, thorough cleaning and major maintenance is also reduced.

Kemper, Clyma, and Ashraf (1975) have estimated that channel improvement increased yields on land immediately adjacent to the watercourse channel where leakage has damaged crop production. They estimated these benefits at 250 Rs/ha.

Water that goes to groundwater contributes to a major problem of waterlogging. Millions of dollars are expended each year to reduce the effects of waterlogging and salinity. Canal water seepage into groundwater results in lower water quality. This may render the water unfit for further use in several major saline groundwater zones. Energy, both electrical and petroleum derived, is required to lift the water to an appropriate elevation for future use. Electrical power is in short supply even to the extent of rationing during certain periods. Balance of payment deficits also exist because, in part, of petroleum imports.

The last benefit probably has considerable effect but is extremely difficult to evaluate. An improved channel increases the dependability of the water supply. During periods of peak demand, tubewell plus canal water generally flows in the channel and losses are greatest. Unpublished data and seasonal deliveries of water indicate that the ratio of high flow to low flow of an improved main and branch channel but unimproved field channel can range between 5 to 10. With less improvement, the ratio was 18. Unimproved channels are assumed to be even more variable. This variable flow makes management of water extremely difficult for the farmer. The costs of an undependable supply are expected to be great. The benefits of a dependable supply are an unstated assumption in the previous analysis.

Summary and Recommendations

A study on on-farm delivery in the Punjab Province of Pakistan suggests a number of factors which contribute to inefficient water delivery. Flow rate at the canal outlet is approximately constant. Total seasonal flow is adequate for only half the cultivated land while periods of surplus and shortages occur during a cropping season. Water supply at the field is extremely variable and ranged from one to two orders of magnitude. Cross sections of channels vary from wide and shallow to narrow and deep with many of the sections having inadequate capacity. Hydraulic radius appears to result from random factors and does not approach the most effective section to minimize seepage nor cross section. Channel slopes may result in siltation or erosion. Sediment deposition is a frequent problem. The result is submergence of canal outlets and consequent reduction in the flow rate and water supply available to the outlet command area. Seepage rates from channels are excessive ranging from 10 to 40 times the surrounding soil. Lack of maintenance combined with the above factors have caused these high loss rates. Difficult social conditions, lack of knowledge and unavailability of technical assistance prevent most farmers from improving the management of their delivery systems.

Delivery improvement alternatives were evaluated based on current costs and values as available or estimated. Alternatives considered were brick-masonry lining, soil-cement block lining, side lining, farmer reconstructed earthen improvement, and cleaning and maintenance. Improvements to the (a) main and branch channels, (b) main, branch and field channels and (c) main, branch and field channels with leveled fields were considered to evaluate the alternatives of partial versus total system improvement. An estimated value of the water saved was derived from a study by Johnson (1978) and costs of the improvements from Johnson, Kemper and Lowdermilk (1978). Only brick-masonry lining is not economical under present stated conditions. Soil-cement lining requires total system improvement for a benefit:cost greater than 1.0. Side lining requires improvement of the field ditches. Both farmer reconstructed, and cleaning and maintenance are economical at all improvement combinations with benefit:costs ranging from 2.9 to 17.6. Providing total system improvements results in the highest benefit:cost ratio.

Farmer reconstructed channels, and cleaning and maintenance of existing channels are highly recommended watercourse improvement programs for Pakistan. Total delivery channel improvement from the canal outlet to each field should be a part of either program. Presently field ditches have been neglected in many instances, and water saved by other improvements is lost between the branch channel and the farmer's field. Even greater benefits will be derived from improved extension that increases yields—and this potential is very great. Land leveling provides benefits in excess of costs to the farmer when leveling his field but also adds substantial benefits to the channel improvement. Total system im-

provement by reducing delivery losses, precision land leveling and improved extension provides the best basis for water management improvement in Pakistan.

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