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The irrigation system of the Indus basin in Pakistan is the largest in the world, with 38,000 miles of canals and 100,000 private tubewells delivering water to 78,000 watercourses serving more than three million farms on 31 million acres. The system is not very efficient. For every 100 million acre feet (MAD) of water diverted, only about 30 MAF are effectively stored in root zones on client farms for crop use. Most of these losses occur in the poorly constructed, poorly maintained earthen channels of the watercourses. Thus it is imperative that a water management program be launched to raise the efficiency for the entire system. The three objectives of the program would be to (1) improve the watercourses, so as to deliver much more irrigation water; (2) conduct extensive land-leveling, so as to more effectively distribute the received water; and (3) improve irrigation practices on the farms, so as to permit extension of the irrigated areas. The report presents cost-benefit evaluations of several different water management program alternatives for the Indus basin. Among the many recommendations in the report, the authors emphasize that routine watercourse maintenance should be initiated and institutionalized at the village level as soon as possible through development of local Water User Associations.

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WATER MANAGEMENT ALTERNATIVES FOR PAKISTAN: A TENTATIVE APPRAISAL

by Jerry Eckert,
Niel Dimick and
Wayne Clyma

Colorado State University
Fort Collins, Colorado
June 1975

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A Tentative Appraisal

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Prepared by

Jerry Eckert
Niel Dimick
Wayne Clyma

Water Management Research Project
Engineering Research Center
Colorado State University
Fort Collins, Colorado

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WATER MANAGEMENT ALTERNATIVES FOR PAKISTAN: A Tentative Appraisal

by

Jerry Eckert[1], Niel Dimick[2] and Wayne Clyma[3]

More than one hundred years of irrigation development in the Indus basin have resulted in the world's largest integrated irrigation system. 38,000 miles of canals and distributaries deliver water to more than 78,000 individual watercourses with a total commanded area of 31.7 million acres. Large link canals, unparalleled elsewhere, transfer water from one river system to another. Storage reservoirs, including the world's largest earth fill dam at Tarbella, even out the seasonality of river flows. Annual diversions into this system exceed 100 million acre feet of water. More than 100,000 private tubewells pump an additional 20 million acre feet into the system each year. Three million individual farms with a median size of 5.2 acres benefit from these developments.

Yet for all this investment this system operates at less than 30 percent overall efficiency. From each 100 million acre feet (MAF) of water diverted, at most 30 MAF, and probably less, are effectively stored in root zones on client farms for crop use.

Most of these losses occur in watercourses below the mogha (outlet). The 78,000 watercourses contain some 1.5 million miles of poorly constructed, poorly maintained earthen channels. Recent research on watercourse losses (3) has shown that previous assumptions and research substantially underestimated the extent of delivery losses. Most studies have simply assumed unrealistically high efficiencies for the watercourse system.

Until recently, very few measurements have been made on irrigation application efficiencies which relate the amount of water stored in the root zone to the amount applied to the field. Several hundreds of field observations of farmer's practices over the last two years have, however, shown these efficiencies to be quite low.

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[1]Agricultural Economist, Colorado State University, Fort Collins, Colorado, 80523.

[2]Agricultural Engineering Advisor, USAID/Pakistan.

[3]Agricultural Engineer, Colorado State University Field Party, Islamabad, Pakistan.

Given the magnitude of water losses now known to occur below the mogha, it is imperative that a water management program be launched to raise the efficiency with which water is used. It will become clear in later sections that such a program has a greater potential for increasing the effective water supply and making a contribution to food production and rural incomes than perhaps any other agricultural development program.

An effective water management program must contain three elements:

1. Watercourse improvement
2. Precision land leveling
3. Irrigation and irrigated cropping extension.

All deserve high priority. It should be emphasized, however, that if farmers continue their present irrigation and cropping practices, then the potential benefits from either watercourse improvement or precision land leveling are limited. Therefore, while extension and information transfer programs may be much more difficult to implement and their benefits harder to quantify than other components, it is essential that they receive just as much or more emphasis and full coordination within the overall program. In fact all three components are interdependent, just as much so as nitrogen, phosphorus and water inputs to wheat. A coordinated balanced program is essential if Pakistan is to realize the full potential of increased food production through better water management.

In the balance of this paper we first define several characteristic watercourse situations which are most common in Pakistan. Delivery losses based on recent findings are summarized. A second section develops the value of water used for irrigation as a prelude to evaluating the benefits of several possible program alternatives. Subsequent sections discuss or evaluate alternative solutions to current causes of inefficient water use, including watercourse lining, earthen watercourses, precision land leveling and irrigation extension. Finally there are suggested criteria for selecting project watercourses with high potential payoffs.

The analyses in this paper rest on the best current estimates and data as presented where relevant in the body of the text. Continued research by many institutions in Pakistan will contribute to refining these estimates and a revised version of this paper may be warranted in the future. The present results, however, should provide adequate guidelines for an initial evaluation of the potential of a water management program in Pakistan. The analysis and many of the conclusions will be valid for water management programs in other countries as well.

The Watercourse Environment

Before proceeding to an examination of several watercourse improvement options it is necessary to define the most common types of watercourses in terms of their water delivery and water loss characteristics. The term watercourse is used variably in Pakistan to mean either the total network of delivery ditches fed by one outlet or the area commanded by that outlet. We have restricted our use of the term to the first definition, that being the entire network of delivery channels supplied by one outlet or mogha.[1] The term "watercourse command area" will be used to designate the acreage served by a watercourse.

Pakistan has over 78,000 watercourses with an average culturable command area of 400 acres each. This means the average watercourse serves 40 farmers and that a normal village of 100-120 farms will have approximately three watercourses. Since watercourse command areas are topographically determined and land ownership is not, it can happen that one watercourse serves lands owned by farmers in different villages. Conceivably, either the watercourse or the village could serve as the basic organizational unit for water management program. There appears to be several sociological reasons suggesting the village as the organizational unit. These are discussed in the section suggesting a program structure. For most of this paper, however, the watercourse is used since that is the level at which construction costs and benefits are most readily calculated.

Close examination of several watercourses has shown that there is approximately one mile of delivery channel including main ditch, laterals and farmers ditches for every 20 acres, or 264 feet of channel per acre. We have further developed an approximation that about 7.5 percent (20 feet/acre) is main ditch (sarkari khal) for which a 16 foot right-of-way is reserved. The remainder (244 feet/acre) are laterals and minor channels with no official right-of-way.

It must be pointed out that the 7.5 percent main ditch figure applies to watercourses in which a single main channel serves the entire watercourse. Where topography, unusual watercourse geometry or ownership patterns require multiple main channels, then the percentage of ditch length in the sarkari khal can easily exceed 10 percent. A 400 acre watercourse with a single main ditch under layouts common today will contain 1.5 miles of main channel and 18.5 miles of minor ditches. Further examination based on maps of normal layouts indicates that the main ditch will account for some

[1] Mogha is the permanent structure which forms the outlet from a distributory. While the Irrigation Department does have some responsibilities beyond this point they are, in fact, rarely exercised.

70 percent of the delivery distance which water must travel from the outlet to the average field. Toward the head, the main channel may provide a small portion of the delivery distance, toward the tail it is the dominant portion.

Watercourses vary widely in size and geometry. It could almost be said that each one is unique in itself. Nevertheless, for program purposes some generalizations are necessary. Five watercourse environments are elaborated here in order to permit focusing on prevalent types that might qualify as recipients of a water management program. They are:

1. Average watercourses with the most common discharge rates.
2. Watercourses with a mogha discharge of 2.0 cusecs. (Two cases).
3. Salinity Control and Reclamation Project (SCARP) watercourses (Two cases).

Case I - Normal Watercourses (400 ac)

The most common duty is one cusec per 350 acres of culturable command area. Several canals are designed for higher duties but since this low extreme is also the most prevalent it is used here as our benchmark.

Cases II and III - Heavier Discharge (2.0 cfs) Watercourses

Since delivery loss rates are in part related to initial discharge, two cases are examined in which mogha discharges are 2.0 cubic feet per second (cfs). This size of mogha or a larger one will be constructed whenever the combination of water duty and watercourse commanded area exceeds certain levels. Case II is for the most prevalent duty. Case III is for a duty of 1 cfs/265 acres which is probably the second most common rate. Table 1 summarizes several parameters of water supply for these three typical situations.

Cases IV & V - SCARP Watercourses

The SCARP[1] concept involves placing a tubewell at the head of a watercourse and discharging into the watercourse to augment supplies. The rotational delivery of water and other aspects of watercourse management are not officially changed. Design criteria call for a duty of 1 cfs/100-150 acres when both tubewell and mogha are discharging. In most SCARP areas, mogha discharge alone is at the rate of 1 cfs/350 acres.

Data from the Mona Reclamation Experimental Project (MREP) show that in the absence of administrative restraints -

[1]Salinity Control and Reclamation Project

Table 1. Water Discharge at Mogha for Three Typical Water-course Situations

	Case I	Case II	Case III
Duty (acres/cfs)	350	350	265
Acreage	400	700	530
Mogha supply rate (cfs)	1.15	2.0	2.0
Daily Water Supply (AF)	2.3	4.0	4.0
Annual Water Supply*			
Total: (AF)	800	1400	1400
Per Acre: (AF/ac.)	2.0	2.0	2.64

*Assuming 350 days of water supply per year.

when operated on the basis of assumed farmer demand and crop needs alonge - tubewells were operated an average of 65 percent of the time. In recent years, however, a budget constraint has been applied to expenditures for power, and electrical shortages have occurred with the result that wells have been operating at only 40 percent of capacity. Cases IV and V are developed to represent these two situations respectively.

Table 2 summarizes irrigation water discharges for Cases IV and V. 365 and 350 days are taken as the annual possible operating time for tubewells and canals respectively, since most canals are closed two weeks a year for maintenance. Tubewells normally run during canal closure periods. We have assumed an average command area of 550 acres, a figure drawn from MREP averages.

Water supplied at the head of the watercourse totals 2076 acre feet or 3.77 AF/day in Case IV. With tubewell operation reduced to 40 percent of capacity (Case V) annual discharge declines to 1698 AF or 3.09 AF per acre.

Delivery Losses Within the Watercourse

Two generalized types of delivery losses occur, seepage and spillage. The concept of seepage is well understood. Spillage is defined here to include all instances in which water is lost through or over the top of watercourse banks to the surface of the surrounding land by direct flow.

Adequate data are not yet available to precisely quantify delivery losses under all conditions. In truth, each watercourse will have its own combination of sources of loss which will have to be enumerated individually when a water management program is applied. Some generalization, however, is possible.

A growing body of evidence suggests that on a 400 acre, 1 cfs/350 acre, "normal" watercourse, delivery losses will average 25 percent of mogha discharge. This loss can be approximately subdivided into 10 percent seepage and 15 percent spillage of various types. There is, however, a very different water loss situation in SCARPs. With both tubewell and canal water flowing, losses have been repeatedly measured at an average of 40 percent, approximately 15 percent due to seepage and 25 percent due to spills (6). Where private tubewell water is added to canal flow the loss situation is often nearly the same as in SCARP watercourses.

It should be emphasized that these figures are averages of a variable situation. In all watercourse categories there will be a range of actual loss figures among different individual watercourses. In many cases losses will be higher

Table 2. Water Discharge at Mogha for Two SCARP Situations

	Tube Plus Canal	Canal Only	Tubewell Only
Days of Operation:			
Case IV*	222	128	15
Case V**	131	219	11
Duty (ac/cfs)	150	350	262
Supply Rate (cfs)	3.67	1.57	2.10
Water Supplied (AF):			
Case IV*	1615	399	62
Case V**	953	683	62

* Tubewell at 65% of capacity
** Tubewell at 40% of capacity

than average and the resultant potential benefits of preventing losses will be accordingly higher. In other instances the situation will be reversed.

These loss rates are developed to characterize an average for all fields in a watercourse. There will be little if any loss for fields adjacent to the mogha, while during delivery to the last fields near the tail, losses of twice the average figure are possible. Table 3 assumes that a linear relationship exists between initial discharge and loss rates within the range from normal to SCARP situations discussed above. Estimated loss rates for various intermediate situations are developed. Based on these estimates a more elaborate picture of average losses for the five cases being considered is presented in Tables 4 and 5.

Table 6 summarizes the water delivery situation for the five cases being examined. The final column gives estimated water supplies actually delivered to the field turn-out (nucca).

Two conclusions can be drawn at this point. First, for a given duty, the larger watercourses will deliver less to each acre because of the higher losses associated with greater initial discharges. Second, operating SCARP wells at only 40 percent of capacity instead of 65 percent reduces nucca supplies by one third of an acre foot per acre annually.

The Value of Water

Water saved through farm water management programs must be valued according to its subsequent use. Two principal uses may be expected under Pakistani conditions; more frequent irrigations of existing acreage and irrigation of new acreage. In the first instance, water is valued by its marginal value in crop response. In the second case, an average product net of variable costs is appropriate. The two estimates are combined to reflect our best judgement as to the distribution that would actually occur of additional water.

Values in this paper are taken from the value product of crop responses to irrigation. Local data do not exist to permit developing value estimates from the macro-impact of any particular irrigation project. Even in the case of crop responses, adequate data are not available for any crop except wheat. In particular, no estimation of crop-water response relationships on farmer's fields exists for other crops. Also, previous experimental data have not produced water response information suitable for economic analysis or representative of 1975 conditions, except in wheat.

Table 3. Percentages of Initial Discharge at Mogha Lost in Delivery to the Average Field

Supply Rate (cfs)	Representative Situation			Percent of Initial Discharge Lost		
	CCA (ac.)	Duty (cfs/ac)	Description	Total	Spillage	Seepage
1.15	400	1/350	"Normal" Watercourse - CASE I	25.0*	15.0	10.0
1.57	550	1/350	SCARP with canal only	27.5**	16.7	10.8
2.00	700	1/350	CASE II	30.0**	18.4	11.6
2.00	530	1/265	CASE III	30.0**	18.4	11.6
2.10	550	1/262	SCARP with tubewell only	30.7**	18.8	11.9
2.50	660	1/265	Heavy flow rate	33.0**	20.4	12.6
3.00	795	1/265	Exceptionally large mogha	36.0**	22.3	13.7
3.67	550	1/150	SCARP, tubewell and canal	40.0*	25.0	15.0

* Based on numerous field measurements
** Assuming a straight line relationship between high and low measured values

Table 4. Water Losses During Delivery in Three Typical Watercourse Situations

	Case I		Case II		Case III	
Duty	1/350		1/350		1/265	
CCA (acres)	400		700		530	
	Total	Per Acre	Total	Per Acre	Total	Per Acre
Water Supply (AF/yr)	800	2.0	1400	2.0	1400	2.64
Annual Losses						
Spillage (AF/yr)	120	0.3	258	0.4	258	0.5
Seepage (AF/yr)	80	0.2	162	0.2	162	0.3
Total (AF/yr)	200	0.5	420	0.6	420	0.8

Table 5. Water Losses During Delivery in SCARP Watercourses

	Case IV (Tubewell @ 65%)		Case V (Tubewell @ 40%)	
Maximum Flow Duty (cfs/ac)	1/150		1/150	
CCA (acres)	550		550	
	Total	Per Acre	Total	Per Acre
Water Supply (AF/yr)	2076	3.77	1698	3.09
Annual Losses				
Spillage (AF/yr)	482	0.88	364	0.66
Seepage (AF/yr)	292	0.53	224	0.41
Total (AF/yr)	774	1.41	588	1.07

Table 6. Summary of Annual Water Availability at the Field Turnout for Representative Watercourses (in acre feet)

Watercourse Type	Original Discharge	Delivery Losses	Nucca Supplies
(Watercourse Total)			
"Normal" (400 ac., 1 cfs/350 ac)	800	200	600
Two Cusecs (700 ac., 1 cfs/350 ac)	1400	420	980
Two Cusecs	1400	420	980
SCARP (tubewell at 65%)	2076	774	1302
SCARP (tubewell at 40%)	1698	588	1110
(Per Acre)			
"Normal" (400 ac., 1 cfs/350 ac)	2.00	0.5	1.5
Two Cusecs (700 ac., 1 cfs/350 ac)	2.00	0.6	1.4
Two Cusecs (530 ac., 1 cfs/265 ac)	2.64	0.8	1.84
SCARP (tubewell at 65%)	3.77	1.41	2.36
SCARP (tubewell at 40%)	3.09	1.07	2.02

For wheat, however, two separate studies are of use. The first is a survey of 77 growers of high yielding semi-dwarf wheat taken in 1968-69 in Shaiwal district (9). These data represent average farmer management capabilities plus the whole complex of actual field conditions that affect production response. No controls were imposed on other input levels or technology. However, all measurable inputs were quantified and their effects disaggregated as best possible with multiple regression techniques.

The second set of data comes from water-fertility response function experiments conducted at Punjab Agricultural Research Institute, Lyallpur in 1973-74 (19). In this instance, all inputs were carefully controlled and a limited number of measured irrigations were applied at the most critical stages of crop growth. These data, then approximate the highest possible water response surface with current varieties and optimum cultural practices.

Since plant growth reflects interactions between fertility and water as well as the independent levels of each, it is necessary to project the fertilizer application averages that will prevail throughout the project's duration. We estimate for a 25 year project beginning any time before 1979 that an average of 75 pounds of nitrogen and 25 pounds of phosphate will be applied per acre to irrigated, dwarf wheat. This represents a substantial improvement over 1975 levels which approximate 45 to 5 pounds per acre of nitrogen and phosphorus respectively.

While it is possible that fertilizer use could exceed an average of 75-25-0 by mid-project, it is considered unlikely in the absence of substantial changes in fertilizer distribution programs and pricing as well as radical changes in cropping techniques and possibly varieties. Our assumption here reflects as much forward progress in these spheres as is believed to be realistically feasible during the time frame being considered.

Figure 1 presents several water response curves for semi-dwarf wheat. Curve F is the response function achieved by farmers today with fertilizer applications averaging 45-5-0. F_a is the function one would expect with no change in the management of water or any other inputs except that fertilization is increased to 75-25-0 as projected above. Curve E, drawn from experimental data, shows the water response relationship possible with optimum water management practices and the projected fertilization levels. The difference between F_a and E represents the potential increases in yield for given amounts of irrigation that can be obtained from the many different components of a water management program.

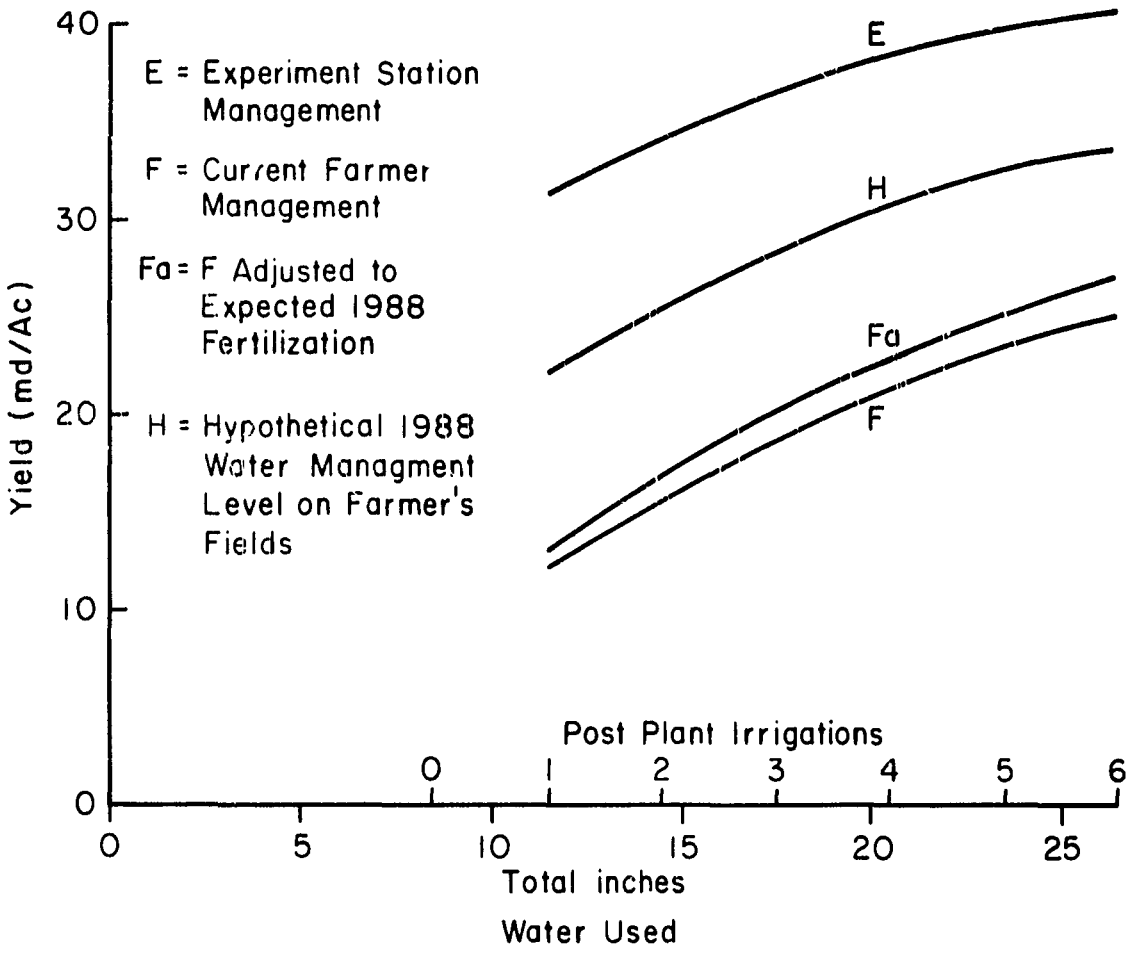

Figure 1. Total product curves for semi-dwarf wheat under various water management assumptions.

It is highly unlikely that all farmers would move immediately to optimum irrigation practices. The techniques are complicated and adoption will be slowed by the learning process, risk aversion behavior, cropping system rigidities, conflicting farm and household objectives and other factors. Even at the end of a project, some farmers will have made little progress.

We have assumed that, for the large numbers of farmers involved in project watercourses, the productive relationships that will characterize the average of the period are represented by a hypothetical curve (H) lying halfway between the management levels of F_a and E. The accuracy of this assumption depends to a large extent on the effectiveness of the irrigation extension component of the program. A highly effective extension effort could achieve widespread change in irrigation methods in, say, five years in which case a higher curve would prevail for the bulk of the project. To a certain extent a successful land leveling component is also required since knowledge alone cannot result in efficient irrigation where it is physically impossible due to field conditions. An ineffective extension program will produce little change in current methods and a curve much closer to F_a would be appropriate.

Table 7 presents the total, marginal and average products for curve H. Where necessary we have assumed that an irrigation equals three inches of water, an average generalization that requires precisely leveled fields. Average products are calculated after the entire irrigation has been given. Marginal products are measured at the mid-point of each three inch interval.

For water applied as extra irrigation to existing acreage we take the marginal product of the fourth irrigation to determine value. Pakistani farmers would rarely plant an acre of irrigated wheat for which only two irrigations were assured (and which would allow using the marginal productivity of the third irrigation). In fact, several studies have shown that normal practice is to irrigate five times or more (9, 11, 17). Valuing wheat at its 1975 market price of Rs. 40 per maund gives a value for supplemental water of Rs. 345.60 per acre foot.

For water applied to additional acreage, the concept used here is total value product minus variable costs divided by the quantity of water applied. Variable production costs (net of rent and returns to management) have been recently estimated at Rs. 643 per acre of wheat at the above assumed fertilization levels. Taking again the fourth irrigation the value attributable to irrigation water calculates to Rs. 366.38 per acre foot.

Table 7. Estimated Water Response Relationships for Average Farmers in Water Management Project Areas over a 25 Year Project Life

Water Inputs[1]		Total Products (Md/Ac)	Marginal Product (Md/Ac. in)	Average Product (Md/Ac. in)
Post-Plant Irrigations	No. of Inches[2]			
1	10.2	22.31	1.92	2.18
2	13.2	25.80	1.19	1.95
3	16.2	28.61	.91	1.77
4	19.2	30.73	.72	1.60
5	22.2	32.52	.68	1.46
6	25.2	33.88	.44	1.34

[1] Does not include 1.4 inches of rain

[2] Includes 7.2 inches of water obtained from that stored in profile at planting plus post-planting irrigations at 3 inches each

Several factors within the overall farming system serve as constraints to acreage expansion. Most studies show that additional water alone results in no more than a 20 percent increase in cropping intensity (1, 10, 20). Such an expansion will only utilize about half or less of the extra water anticipated. We have therefore assumed that water supplies generated by a water management program will be used equally for new and existing acreage. Hence, a simple average of the values pertaining in each case results in an overall value of water of Rs. 356 per acre foot, or Rs. 29.66 per acre inch.

These estimates derived from curve H rest on the rather high degree of water control, optimum timing and level fields implicit in the technology behind the response curve. Irrigations are three inches each under these conditions and even then there will be some overirrigation during the low water demand period in mid-winter. Season long application efficiency for the experiment that gave curve E was only 61 percent.

In many instances farmers cannot achieve a three inch irrigation, largely because of unlevel fields. Extensive measurements of field applications over the past eighteen months (3) have identified individual irrigations ranging from one to thirteen inches. On unleveled land a figure of four inches may be taken as a generalized minimum possible depth. Only with precision land leveling can this generalization be reduced to three inches or less.

In the unleveled case, the higher quantities applied are matched by higher losses through deep percolation. Consequently the extra water results in lower irrigation efficiencies rather than additional crop growth. Because of its less efficient use, the value of water applied to unleveled fields (averaging at least four inch irrigations) is Rs. 267 per acre foot or less.

The above estimates represent water values as viewed by private farm enterprise. We recognize that the social value may exceed these figures by a substantial amount as long as food grain shortages are met by more expensive imported supplies. However, due to the unpredictable nature of foreign debt management and the unknown future balance between quantities imported on concessional and commercial terms we have not attempted to estimate a social value for water applied to wheat production.

Watercourse Improvements

Several options exist for reducing or compensating for losses of water in delivery from the mogha to the field. Possibilities considered here include:

1. Lining part or all of the delivery channel,
2. Better maintenance and design of earth channels,
3. Tubewells discharging into the watercourse.

Channel Lining

Three options are discussed: 1) lining the entire watercourse, 2) lining the main channel only, and 3) lining the main channel plus significant branches. Theoretically, complete elimination of seepage and spillage can be achieved by lining when accompanied by leak proof turn out and juncture structures. We will assume, however, that operationally only 90 percent of total water losses will be prevented in lined sections since small leaks will persist and the system will not be operated perfectly.

Lining All Channels: We mention this option here only for conceptual completeness. It does not require exhaustive analysis to show that this option is totally uneconomic. Seventy percent of the delivery distance is in the main ditch, in which water flows most of the time. The closer one gets to individual fields the less water is conveyed by individual side ditch sections throughout the year. At the final extreme the ditch serving an individual field may carry only the water reaching that field. The ditch reaching a half acre field on a normal watercourse may convey only one acre foot of water per year, the losses from which will not pay for lining of that ditch. Preliminary calculations for an earlier draft of this paper showed a benefit:cost ratio ranging from .1-.4:1.0 for lining of entire watercourses. It has therefore been omitted as a viable option from this discussion.

Lining the Main Channel and Main Branches: In this option we have assumed a 90 percent reduction for the portion of the watercourse lined which, in this case, will cover 85 percent of total delivery distance. For this to be effective, a substantial land leveling program is assumed that will permit larger fields and longer irrigation runs. To achieve this approximately 25 percent (60 ft/ac) of the total length of channels within a watercourse must be lined. In this event, lining one quarter of the channel length reduces losses by .85 x 90 = 76.5 percent.

Lining Only Main Channels: The main channel in watercourse layouts common to Pakistan is estimated, based on watercourse case studies, to account for as much as 70 percent of total delivery distance to the average field, yet constitutes only 7.5 percent of the total channel mileage served by the mogha. Losses may be reduced by .70 x 90 = 63 percent through lining only the main channels.

The profitability of any combination of lining less than the full watercourse depends critically on the actual

relationship between feet of channel to be lined and the proportion of the delivery distance to the average field involved. We have used our best present generalizations in this paper based on critical examination of several watercourses. In reality, some measurements will have to be made on each watercourse and compared with certain loss criteria before it is determined whether to line any sections at all.

Cost of Lining

In estimating the costs of channel lining we have two points from test constructions. A non-linear relationship is assumed to complete the range of costs at relevant flows. At Lar 2000 feet of watercourse have been constructed with a capacity of 1.9 cfs. At today's input prices this channel would cost 28 Rs/foot. At Mona several thousand feet of various designs have been built. While an analysis of these data is still in preparation, it is safe to say that a 4 cfs channel (for a 550 acre SCARP watercourse) can be constructed for Rs. 40/foot.

Both of these examples assume a rectangular cross section with plastered 9 inch thick walls. Other designs being tested may prove cheaper when full results are available. Concrete trapezoidal channels look particularly promising and may cost only Rs. 30/ft for a 4 or 5 cfs channel.

For the present, the costs given in Table 8 are satisfactory, however, they should be reviewed as further data and new designs become available. It should be emphasized that these costs are only approximate and will vary with soil type, channel grade, number of drop structures and gates, location and other factors.

Table 8. Approximate Relationship Between Channel Capacity and Cost of Channel Lining, January 1975.

(Brick Construction, Rectangular Cross Section)

Channel Capacity - (cfs)	1	2	3	4	5
Rupees of Cost per Linear Foot -	20	30	35	40	45

In the calculations below both 10 and 25 year lengths of life have been presented as options. The former we assume requires annual maintenance expenditure equal to one percent of initial outlay; the latter case is assumed to require three percent. These are considered consistent with a

figure of four percent annually used by WAPDA for planning SCARP and other long term programs.

Three interest rates are also presented. Fifteen percent per annum is the rate of return now expected or required by foreign assistance agencies such as IBRD or USAID. Current institutional interest rates in Pakistan in the agricultural sector are 11% (ADBP) or 12% (National Bank, commercial banks). To these costs must be added the unofficial costs of gaining access to these sources of funds. According to credit specialists in the National Bank of Pakistan, 14-15 percent represents the cost of capital to agriculture in mid 1975 under present institutional arrangements.

Twenty percent is included to more nearly portray benefit:cost ratios with capital valued at its true cost to the nation. The Government is now paying 25 percent on 10 year defense bonds and 20 percent for seven year defense bonds. Interest on secured commercial loans in Karachi is ranging from 25-30 percent. Non-institutional commercial credit (money lenders) in rural areas are receiving between 18 and 36 percent annually. Hence 20 percent is probably a fairly conservative estimate of the real cost of capital in Pakistan.

Ten percent has been included only for comparison since funds are not presently available at this rate. The differences in profitability between the 15 and 20 percent rates are the benefits of being able to draw on foreign capital for these investments. Against the additional profitability one might envision under a 10 percent rate, the offsetting cost of the implicit interest subsidy must be considered. Clearly, the opportunity cost of capital is at least 15 percent per year.

Tables 9-11 develop the costs and benefits of watercourse lining for the five watercourse situations described earlier under two assumed life spans and three interest rates. Costs are calculated from the number of feet of channel that must be lined per acre times the cost per foot for the lining. This is annualized and added to the annual maintenance expenditures. Benefits are simply the number of acre feet of water saved per year divided by the acres in the watercourse times the value of an acre foot estimated earlier.

Discussion

The lining design evaluated above is a brick and mortar rectangular cross section ditch on a concrete base with plastered nine inch (one brick length) walls. Such a design can be constructed today for approximately the costs shown in Table 8. We have examined this design in depth for

Table 9. Estimated Benefit:Cost Ratios for Selected Water Channel Improvement Options
CASE I - (400 acres @ 1 cfs/350 acres) (all figures in current rupees per acre)

	Length of Life and Interest Rates					
	10 years			25 years		
Lining Main Channel and Branches (60 ft/ac)	10%	15%	20%	10%	15%	20%
a. Annualized Cost*	225	275	329	152	213	279
b. Annual Maintenance	14	14	14	41	41	41
c. Total Annual Cost	239	289	343	193	254	320
d. Annual Benefits	136	136	136	136	136	136
e. Benefit:Cost Ratio	.57	.47	.40	.70	.54	.42
Lining Only Main Channel (20 ft/ac)						
a. Annualized Cost*	75	92	110	51	71	93
b. Annual Maintenance	5	5	5	14	14	14
c. Total Annual Cost	80	97	115	65	85	107
d. Annual Benefits	112	112	112	112	112	112
e. Benefit:Cost Ratio	1.40	1.15	.97	1.72	1.32	1.05

*Assume cost of 23 Rs/ft. for 1.15 cfs channel derived from Table 8.

Table 10. Estimated Benefit:Cost Ratios for Selected Water Channel Improvement Options (Case II and CASE III - 2 cfs Moghas) (all figures in current rupees per acre)

	Length of Life and Interest Rates					
	10 years			25 years		
	10%	15%	20%	10%	15%	20%
Lining Main Channel and Branches (60 ft/ac)						
a. Annualized Cost*	292	359	429	198	278	364
b. Annual Maintenance	18	18	18	54	54	54
c. Total Annual Cost	310	377	447	252	332	418
d. Annual Benefits (CASE II)	163	163	163	163	163	163
e. Benefit:Cost Ratio (CASE II)	.53	.43	.36	.65	.49	.39
f. Annual Benefits (CASE III)	216	216	216	216	216	216
g. Benefits:Cost Ratio (CASE III)	.70	.57	.48	.86	.65	.52
Lining Only Main Branch (20 ft/ac)						
a. Annualized Cost*	98	120	143	66	93	121
b. Annual Maintenance	6	6	6	18	18	18
c. Total Annual Cost	104	126	149	84	111	139
d. Annual Benefits (CASE II)	135	135	135	135	135	135
e. Benefit:Cost Ratio (CASE II)	1.30	1.07	.91	1.61	1.22	.97
f. Annual Benefits (CASE III)	178	178	178	178	178	178
g. Benefit:Cost Ratio (CASE III)	1.71	1.41	1.19	2.12	1.60	1.28

*Assumed cost of 30 Rs./ft for 2 cfs channel from Table 8.

Table 11. Estimated Benefit:Cost Ratios for Selected Water Channel Improvement Options CASE IV and CASE V (SCARP Watercourse, 550 ac) (all figures in current rupees per acre)

	Length of Life and Interest Rates					
	10 years			25 years		
Lining Main Channel and Branches (60 ft/ac)	10%	15%	20%	10%	15%	20%
a. Annualized Cost*	391	478	572	264	371	485
b. Annual Maintenance	24	24	24	72	72	72
c. Total Annual Cost	415	502	596	336	443	557
d. Annual Benefits (CASE IV)	383	383	383	383	383	383
e. Benefit:Cost Ratio (CASE IV)	.92	.76	.64	1.14	.87	.69
f. Annual Benefits (CASE V)	291	291	291	291	291	291
g. Benefit:Cost Ratio (CASE V)	.70	.58	.49	.87	.66	.52
Lining Only Main Channel (20 ft/ac)						
a. Annualized Cost*	130	159	191	88	123	162
b. Annual Maintenance	8	8	8	24	24	24
c. Total Annual Cost	138	167	199	112	147	186
d. Annual Benefits (CASE IV)	316	316	316	316	316	316
e. Benefit:Cost Ratio (CASE IV)	2.29	1.89	1.59	2.82	2.14	1.70
f. Annual Benefits (CASE V)	240	240	240	240	240	240
g. Benefit:Cost Ratio (CASE V)	1.74	1.44	1.20	2.14	1.63	1.29

*Assumed cost of 40 Rs/ft for 4 cfs channel from Table 8.

two reasons; it is the type of construction that Pakistanis have experienced and can do without further training, and it is the design for which most data are available. Some thoughts about alternative designs are given below.

Lining the entire watercourse using this technology was so obviously infeasible that it was not evaluated in this section. At either 15 or 20 percent interest, lining of the main channel and branches with bricks did not pay for itself in any of the representative cases examined.

Lining only the main channel yields benefit:cost ratios in excess of 1.0 for all types of watercourses assessed here. In order of profitability the five cases are ordered as follows.

Table 12. Summary of the Benefit:Cost Ratios for Lining Main Channels Only

		Benefit:Cost*
1.	CASE IV SCARPs (TW @ 65%)	2.14
2.	CASE V SCARPs (TW @ 40%)	1.63
3.	CASE III Two cfs Mogha (530 ac @ 1 cfs/265 ac)	1.60
4.	CASE I "Normal" (400 ac @ 1 cfs/350 ac)	1.32
5.	CASE II Two cfs Mogha (700 ac @ cfs/350 ac)	1.22

* At 15% interest over a 25 year channel life.

Depending on the interest rates and channel lifetimes actually prevailing, lining may be justified for at least the main channel of some watercourse situations. However, planners must consider the opportunity cost of investing the same funds in other water management options. Subsequent sections develop comparable benefit:cost estimates for channel maintenance programs, reconstructed earthen channels, small tubewell augmentation and precision land leveling.

For watercourse lining the primary candidates are SCARP watercourses particularly if their tubewells are to operate on the basis of water demand (roughly 65 percent of capacity as farmers presently operate their cropping and irrigation system). However, as long as budget and electric rationing constrains tubewell operation to 40 percent of capacity or less, the justification for lining the main channel is weakened.

The profitabilities calculated in Tables 9-11 depend critically on several assumptions. Further research, new designs or changing price ratios may alter these assumptions sufficiently to require recalculation. For example:

1. We have assumed that 7½ percent of total ditch length is main ditch. This may be correct to represent watercourses as they are presently laid out. However, with relocation of channels into a more efficient layout, particularly in conjunction with land leveling, it may be possible on some watercourses to reduce the length of main channel per acre. On watercourses where length is no more than twice the width, an optimum design may require only 15 feet of main channel per acre rather than the 20 feet used above.

2. Similarly, the assumption that the main channel constitutes 70 percent of average delivery distance is crucial. Any change in this percentage will, when multiplied by 0.9, affect the benefits of lining directly.

3. Changes in the value of water will directly influence the benefit:cost ratios estimated here. It should be emphasized that the technology on which the value of water estimates were based requires significant progress by farmers and by the government machinery serving them as well as leveling of all fields in project areas. If these do not occur benefit:cost ratios could be reduced substantially.

4. Costs are underestimated in the above tables with respect to at least one factor. If lining is to prevent delivery losses for a major portion of the delivery distance, then the earthen channels leading from the main channel to fields will need improvement in order to handle the much larger flows they will receive. This will be particularly important in SCARPs where the large amount of water savings will mean much larger flows for the branches and side ditches. The method of calculation behind Tables 9-11 assumed that all of the losses prevented by lining the main ditch reached the field, an assumption that is clearly wrong without additional expenditure on side ditches.

One partial solution, already used unofficially by farmers at Mona on lined watercourses, is to subdivide the flow of the main channel to permit irrigating on more than one branch at a time. Even in this case, however, some additional reconstruction of lower ditches will be needed. If the water is not continuously subdivided, then at least some channels will have to be rebuilt to handle full flow.

5. On the other hand, additional benefits may accrue although current data are insufficient to permit their estimation. Crop losses due to "swamping" by spills along unimproved channels could be reduced. Control of delivery

losses would contribute to control of waterlogging and salinity, possibly preventing additional losses in production from this source. Operational losses would be reduced. Finally, preventing losses will add significantly to the reliability of water delivery and thus permit farmers to manage their irrigations with more sophistication, using higher yielding techniques which may presently be too risky.

6. All of the above calculations are for rectangular, brick watercourses. Some experience has been gained with trapezoidal cross section concrete channels in Mona. Preliminary indications show a cost function lower than that in Table 8. Concrete trapezoidal ditches can be constructed for different flows at the following costs today:

cfs	1	2	3	4	5
Rs/ft.	15	20	23.33	26.67	30

Further cost reductions may be obtained as experience is gained with soil cement plaster, soil cement bricks, slip form construction techniques, etc.

Table 13 compares benefit:cost ratios for brick ditches from Table 12 with those possible using the cost function from paragraph six above.

Table 13. Comparison of Benefit:Cost Ratios for Lining Main Channels with Alternative Designs

	Benefit:Cost Ratios*	
Watercourse Type	Brick Rectangular	Concrete Trapezoidal
CASE IV	2.14	3.21
CASE V	1.63	2.44
CASE III	1.60	2.44
CASE I	1.32	1.92
CASE II	1.22	1.85

* At 15% interest and a 25 year life.

Earth Channel Reconstruction and Maintenance

The other end of the technological spectrum from channel lining is renovated earth ditches which are well constructed so that they can convey the intended water flows without excessive loss. One recent examination of a

watercourse in the Mona Reclamation Experimental Project identified 148 leaks from one source or another in three miles of main channel, approximately one every 100 feet. These leaks were predominantly at nakka sites. More than 75 percent of the water was lost in this channel before reaching the fields being irrigated at the tail.

Sources of watercourse losses include:

a. Leaking nakkas and junctions.

b. Rat, root, and insect holes.

c. Inadequate watercourse capacity causing water to flow over channel banks.

d. Watercourse below ground level resulting in dead storage after irrigation.

e. Very high seepage rates especially through channel sides.

f. Unproductive use of water by channel bank vegetation.

g. Operational losses such as frequent rewetting of channels and refilling of dead storage as water is borrowed and sold back and forth among different branches of a watercourse.

Of these different types of losses, only the latter cannot be controlled to a large degree by reconstruction of a better earthen watercourse or by better maintenance.

To fully understand the importance of reconstruction and/or better maintenance of ditches, two general watercourse conditions need elaboration. Extensive field investigations show that the most important source of delivery loss is leaking nakkas and junctions in the watercourse. After an irrigation, nakkas are closed either with loose soil which passes water easily or with mud which can crack upon drying. In either case, leaks can develop either immediately or when water returns to the channel in a subsequent turn. In addition, nakkas are often not filled up to the level of the top of the ditch bank. They, therefore, constitute points of inadequate freeboard in the overall channel. An intensive study of one watercourse in the Shadab IRDP area identified 1237 nakkas on a watercourse commanding only 238 acres (10). This average of five nakkas per acre is at least indicative of the number of poential leaks on any watercourse. At junctions where the watercourse branches, the section not being used at a given time is closed off in the same manner as are nakkas and consequently has the same

propensity to leak. It is common to see the closed branch of a watercourse slowly filling from leaks at the junction yet irrigating nothing.

A second significant source of loss which has been recently identified is the high permeability of ditch banks. Careful measurements have shown loss rates through the banks of watercourses to be several multiples (10-12 times) as much as the infiltration rates of soils in the adjacent fields. Most of this loss appears to be through small holes and highly permeable soils in the upper portions of the banks. Holes in the lower portions tend to be self filling with the normal sediment load.

The high permeability of watercourse banks stems in part from the ideal conditions for plant growth thereon. Weeds and grasses are not generally harvested and their seeds, stems and roots furnish a rich food supply for ants, beetles, worms, and other insects and grubs which honeycomb the banks as they eat and nest. Attracted by food in the form of insects and larvae, rodents further damage the banks. In many areas, ditch banks are the only land high enough to escape complete inundation during irrigation. Finally, it is common practice when cleaning ditches to pile the silt directly on top of the sod of the banks. In time this creates a layered bank with strata of old sod and roots alternating with silt. These facts combine to make watercourse banks the most densely populated and most permeable soils in Pakistan (12).

Correcting the permeability of ditch banks requires replacement of the present root riddled sod banks with fresh compacted soil. In the process ditch banks can be reconstructed to more adequate hydraulic specifications, with ample thickness and freeboard and an efficient cross section. Existing vegetation will be removed along with its root mass. Once reconstructed, these banks will require routine maintenance to prolong the period of high efficiency.

Correcting the problem at nakkas will require inexpensive, relatively leak proof nakkas that can be widely adopted by small farmers. Research and testing is currently underway evaluating a wide range of alternative designs. An alternative approach is to better maintain existing earth filled nakkas so that they are more substantially filled each time and leaks that do occur due to cracking are quickly closed.

There are two ways to arrive at the desired end product of a hydraulically sound, relatively impermeable earth ditch. One is to remove the existing channel and construct a new one using soil from surrounding fields. The other method would be to institute a regular watercourse maintenance program with sufficient excess capacity to gradually

rebuild and improve existing ditches to meet prescribed specifications. Both options are discussed here. In either case, an element of routine maintenance is a permanent necessity if today's very large water losses are to be prevented in tomorrow's earthen channels. A third option, maintenance without reconstruction is also analyzed for comparison.

Mechanical Reconstruction with Maintenance

Where ditches are to be reconstructed mechanically it seems possible that this might have to be done every three to five years and that one (possibly two) maintenance men would be needed on a full time basis to minimize wear and tear on reconstructed channels. We envision a process where the old banks are removed and new soil brought to the watercourse site with tractor drawn scrapers. Bullock drawn scrapers or men with shovels are alternatives, although, they are more expensive and time consuming. A new bed would be built up and compacted with sheep's-foot rollers. Again tractor or bullock power are both possible. Finally a new ditch would be cut in the compacted bed using either a tractor drawn ditcher or men and shovels.

Since testing of these several techniques under local conditions is just beginning, no firm estimates of cost are yet available. However, based on very preliminary information it seems that earth channels can be constructed in this manner for somewhere between 5 and 15 rupees per linear foot including necessary nakkas, junctions and drop structures.

As an approximation, let us assume one man full time can handle the maintenance on the main ditch and main branches of a 400 acre watercourse if it has first been reconstructed to modern standards. At Rs.200/mo. his cost would be Rs.6/acre/year. For larger flow SCARP watercourses two men would be needed.

Table 14 approximates the annual cost per acre for several different assumptions. A cost of five rupees per foot is used for CASE I, II, and III watercourses and 7.5 Rs./ft. for CASES IV and V.

It is obvious from these figures that the most important variable is the initial cost of construction. The cost of maintenance, 6 Rs/acre/year/man, is only a fraction of the total. Such a program should be able to prevent 75 percent of all delivery losses in the portion of the delivery distance to which it is applied. As in earlier sections, the main ditch plus major branches account for 85 percent of the delivery distance. Table 15 estimates the benefit:cost ratios obtainable from reconstruction with a maintenance component using the costs from Table 14 for a five year life with one maintenance man.

Table 14. "Indicative" Costs of Mechanical Reconstruction of Earth Watercourses with a Maintenance Component Included (all figures in rupees/acre/year)

	Cost (assuming 15% interest)			
	5 Rs./ft.		7.5 Rs./ft.	
Length of Life	One*	Two*	One*	Two*
--------Main Ditch and Major Branches (60 ft/ac)----------				
Three Years	137	143	203	209
Five Years	95	101	140	146
Eight Years	**	79	**	112
----------Main Ditch Only (20 ft./ac)----------				
Three Years	50	56	72	78
Five Years	36	42	51	57
Eight Years	**	34	**	45

* Number of maintenance men
** Not considered a realistic combination

Table 15. Benefit:Cost Ratios for Mechanical Reconstruction of Earth Watercourses with a Maintenance Component Included (all figures are per annum)

	Watercourse Type				
	CASE I	CASE II	CASE III	CASE IV	CASE V
Main Ditch and Major Branches					
Water Saved (AF)*	127.5	267.8	267.8	493.4	374.8
Value: Total	45,390	95,319	95,319	175,659	133,446
Per Acre	113	136	180	319	243
Cost per Acre	95	95	95	140	140
Benefit:Cost	1.19	1.43	1.89	2.28	1.74
Main Ditch Only					
Water Saved**	105.0	220.5	220.5	406.4	308.7
Value: Total	37,380	78,498	78,498	144,660	109,897
Per Acre	93	112	148	263	200
Cost per Acre	36	36	36	51	51
Benefit:Cost	2.58	3.11	4.11	5.16	3.92

* 75% of delivery losses prevented for 85% of distance
** 75% of delivery losses prevented for 70% of distance

The methodology and assumptions underlying Table 15 are the same as for Tables 9-11 in order to facilitate direct comparison between the returns from alternate programs for, say, the main ditch. The two maintenance options that follow are developed to apply to the main ditch plus major branches and should be compared with the appropriate section of Table 15.

Maintenance and Manual Reconstruction

The second alternative is a program of routine maintenance with sufficient capacity to permit gradual reconstruction of ditch banks. Most of the spillage losses can be controlled to a significant degree by continuous maintenance performed by a laborer with some training and a shovel. Occasionally some additional soil must be moved to channel junctions to replace that washed away, but this can be obtained from surrounding fields with bullocks and a karah. These same men can also gradually reconstruct ditch banks with fresh soil to reduce their permeability. At a rate of 25 feet per day a man can reconstruct approximately 1.5 miles of ditch per year. Since there are approximately 4.5 miles of main ditch and major branches on a 400 acre watercourse, one man could reconstruct all of these reaches every three years. Two men could do the same and spend half their time on routine maintenance, three men could spend 2/3 of their time on maintenance.

Simple maintenance cannot be expected to completely prevent spills because of the difficulties of finding them at night and the lengths of some reaches involved. And, of course, the amount of labor and the length of the watercourse will affect the results. In Table 16 we have assumed that two laborers working half time each on maintenance and reconstruction can save half of all losses from the main ditch and branches and that three men can prevent 60 percent of the water loss from the same channels. Their cost is Rs. 200/mo. each to which is added a total of Rs. 50/mo. for two days of bullock services to scrape soil up to junction points.

Routine Maintenance

A third alternative is to simply maintain the ditch without reconstructing it in the process. Two men on a 4-500 acre watercourse should be able to control 75 percent of the spillage losses but none of the seepage losses on the main ditch and major branches. Table 17 presents the amount and value of water that may be saved with this type of effort alone.

In all three of these options the payoffs are greatest in SCARP areas. This is due to the much higher losses occurring in this situation of augmented flows and high

Table 16. Benefit:Cost Ratios for Watercourse Maintenance with a Manual Reconstruction Component Applied to Main Ditch and Major Branches (figures are per annum)

	Watercourse Type				
	CASE I	CASE II	CASE III	CASE IV	CASE V
With Two Men					
Water Saved (AF)*	85	143***	178	329	250
Value: Total	30,260	50,260	63,546	117,106	88,964
Per Acre	76	73	120	213	162
Cost per Acre	13.5	7.7	10.2	9.8	9.8
Benefit:Cost	5.6	9.4	11.8	21.7	16.5
With Three Men					
Water Saved (AF)**	128	268	268	493	375
Value: Total	45,390	95,319	95,319	175,659	133,447
Per Acre	113	136	180	319	243
Cost per Acre	19.5	11.1	14.7	14.2	14.2
Benefit:Cost	5.8	12.3	12.2	22.5	17.1

* 50% of all delivery losses for 85% of the delivery distance
** 75% of all delivery losses for 85% of the delivery distance
*** Reduced to 40% due to length of watercourse

Table 17. Benefit:Cost Ratio for Simple Routine Maintenance of Earthen Watercourse Main Channel and Major Branches

	Watercourse Type				
	CASE I	CASE II	CASE III	CASE IV	CASE V
Water Saved*	76.5 AF	164.5 AF	164.5 AF	307.3 AF	232.0 AF
Value (Rs):Total	27,234	58,553	58,553	109,390	82,610
Per Acre	68	84	110	1[illegible]9	150
Per Acre Cost	13.50	11.14**	10.19	9.82	9.82
Benefit Cost	5.0	7.5	10.8	20.3	15.3

* 75% of spillage losses controlled over 85% of delivery distance, seepage unaffected

** Three men full time because of larger watercourse size.

initial discharge. By extension it is suggested that in areas with a high private tubewell density where tubewells are used to augment canal flows these programs would also repay investment handsomely. But in any circumstance some type of option where routine ditch maintenance becomes a permanent part of village life seems absolutely essential for Pakistan.

A maintenance component fits into the overall program in at least two ways. First, wherever a watercourse is involved in the water management program, whether the channels are lined or tubewells installed, a precondition for government assistance should be the establishment of a permanent maintenance program within the village or watercourse. Second, if the benefits possible from proper channel maintenance can be made known, most watercourse users in Pakistan should find sufficient incentive to institute a routine maintenance program whether they are involved in other water management programs or not. Managing such a maintenance program would necessitate a water users association. This type of organization is discussed more fully in a subsequent section.

One might well ask why farmers do not maintain their ditches better if the payoffs are as great as suggested here. The primary cause is that farmers do not perceive the losses that actually occur as being significant. Frequently, when shown a leak and asked why it isn't fixed farmers respond with, "It is nothing, only a small leak." They do not see that small leaks every 100 feet can add up to large losses.

Also, holes in the ditch bottom often do not vent on the surrounding surface so losses are not directly visible. Finally, when they are aware that flows at their fields are much less than flows at the mogha, their tendency is to ascribe the difference to seepage which they feel is beyond their ability to control. Hence, they take no action at all except periodic silt-removal efforts.

Tubewell Supplementation

Water supplies at the nucca can be substantially enhanced by the installation of tubewells discharging into the watercourse. Two such wells, one at the mogha and one approximately halfway down the main channel, have been suggested. The wells contemplated are the size of private tubewells, powered by a 12-20 hp. diesel engine, delivering 1.1-1.3 cfs and costing Rs. 30,000 each. Initial capital cost would run Rs. 60,000 per watercourse. A survey of private tubewells operating in the Mona area suggests that water from private diesel tubewells costs about Rs. 35 per

acre foot when operated at 65 percent of capacity (adapted from 12 to approximate 1975 costs).

Spillage losses have been observed to increase significantly when canal flow is augmented by the discharge of a well, whether it is a SCARP well or a private tubewell. In SCARPs, where flows are 3-5 cfs at the mogha, characteristic losses total 40 percent; 25 percent spillage and 15 percent seepage. In normal watercourses no adjustment in channel size is made so seepage losses probably do not increase appreciably when flows are augmented. However, spillage increases suggest that if a program of this type is implemented, farmers on earthen watercourses should be required to renovate their channels, bringing them to satisfactory specifications and demonstrate that they have institutionalized within the village a system of routine maintenance.

Table 18 estimates the increase in water supplies at the nucca from two 1.1 cfs tubewells located as described above. We assumed spillage and seepage losses of 25 and 10 percent respectively when tubewell and canal water are mixed and 15 and 10 percent when for tubewell water only. These were then weighted for the amount of time each condition prevailed and the percentage of the acreage involved.

There are two primary impacts of this possible program. The first is to more than double the quantity of water reaching the field. This occurs with or without maintenance. The second is to more equitably distribute water supplies. The tubewell in the middle of the watercourse means that for at least this source of water the farmers at the tail are not penalized for losses that occur in the first half of the watercourse. A third point can be made from Table 18. Combining a routine maintenance program with this program increases the overall benefits substantially.

Precision Land Leveling

One of the three primary dimensions of the proposed farm water management program is precision land leveling (PLL). Precision land leveling consists of grading and planing land to a smooth level field to facilitate efficient irrigation and water use. Irrigation practices currently in use in Pakistan require a smooth level field with no slope. With proper farm water management practices, efficient applications can be made with surface variations $\pm$ .05 foot from the designed level. As new cropping patterns and cultural practices are introduced, other water control methods such as corrugations, bed shaping, and furrows may warrant designing with some slope. However, for the present and in this paper PLL shall be conceived as attempting to achieve a

Table 18. Estimated Discharges, Losses and Supplies at the Field for Watercourses Augmented by Small Communal Tubewells[a]

	Total Discharge (AF/yr)	Losses (AF/yr)	Delivered at Field Total (AF/yr)	Delivered at Field Per Acre (AF/yr)
Unaugmented Watercourse				
Without Maintenance	800	200	600	1.5
With Maintenance	800	110	690	1.7
Augmented Watercourse				
Without Maintenance	1874	542	1332	3.3
With Maintenance	1874	267	1607	4.0

	Total	Per Acre	Benefit:Cost
A. Cost of additional water 1074 AF @ Rs. 35 each	Rs. 37,590	Rs. 94	---
B. Value of additional water without maintenance 732 AF @ Rs. 356 each	260,592	651	6.9
C. Value of additional water with maintenance 917 AF @ Rs. 356 each	326,452	816	8.7
D. Value of Maintenance 185 AF @ Rs. 356 each	65,860	165	12.2[b]

a Assuming a 400 acre "normal" watercourse with a mogha discharge of 1.15 cfs, 350 days/years.

b. Assuming two beldars full time plus Rs. 50/mo for earth moving Total cost = Rs. 5400 or Rs. 13.50/ac.

level, smooth irrigation field as described above so that irrigations may be given efficiently by basin flooding techniques.

Benefits of Precision Land Leveling

There are numerous benefits which result from precision land leveling. Among them are the following:

1. Improved irrigation application efficiencies.
2. Uniform soil moisture for germination.
3. Improved fertilization efficiency.
4. Higher yields.
5. Lowered probability of salt accumulation.
6. Increase in cultivable land.
7. Reduced delivery losses.

A discussion of each of these major benefits follows with commentary on the possible magnitude of each.

Improved Irrigation Application Efficiency - Generally the Pakistani farmer will apply irrigation water until all of the field is covered including any high spots. This practice results in very little water covering the high areas while excessive amounts cover low areas. Actual intake differentials are even greater since differences in hydraulic head result in faster infiltration in low areas and possible salt accumulation can reduce infiltration on higher areas (15). The additional time required to cover the high areas are of major concern to the irrigator. He attempts to improve the levelness of his field by moving soil from the high to the low areas and by making smaller bunded areas so that variations in level within an irrigation unit are minimized. Unfortunately, he does not have engineering technology available to him and has to rely on his memory of field elevation and on inefficient field equipment and considerable labor to achieve any success. This trial and error method if pursued long enough will result in a fairly level area. However, it is extremely difficult with this method to acquire much precision over fields of one-half to one acre or larger in size, or over long, narrow irrigation borders. Therefore, Pakistani irrigated fields have been subdivided not only by social factions and inheritance, but as an attempt to improve field levelness.

Extensive field measurements in the Mona Reclamation Experimental Project have shown that the median irrigation application efficiency throughout most of the irrigation season lies between 20 and 30 percent (3, 4). Only about one-fourth of the water applied during an irrigation is stored in the crop root zone, the remaining three-fourths penetrates to deeper levels contributing to the rising water table. There is a strong supposition that from 10 to 60% of

of the fertilizer applied may be removed from the crop root zone by this water movement (16).

In many instances early in the crop growing season or at planting time, there is need for only a light irrigation in order to replenish the soil moisture. However, the minimum depth of irrigation water that can be applied is often four to five inches in order to cover the entire surface of the field since the fields are not properly leveled, and adequate water flow is often not available and farmers' knowledge of irrigation techniques is limited. Overirrigated fields and low application efficiencies result.

In a previous section on the value of water, the productivity of irrigation water applied to wheat is estimated at Rs. 356 per acre foot on leveled land. If farmers are incapable of applying less than a four inch irrigation, as often occurs on unleveled fields in Pakistan, the value of an acre foot is only Rs. 267. It has been shown repeatedly that with good leveling, irrigations of three inches can be applied to large fields. The first benefit, then, from leveling is to raise the value of water by Rs. 89 to a total of Rs. 356 per acre foot. This occurs because application efficiencies increase by approximately one-third from 25 to 33 percent. Through more efficient water application, four irrigations are obtained per foot of water instead of three. At some times during the season only two inches are needed. There is no question but that a very level field is necessary to avoid overirrigating in this situation. If, however, it can be achieved through leveling and modern field layout the value of water rises to Rs. 534 acre foot, twice its value in a typical unleveled situation.

As an example of what can be achieved, nine acres on tubewell 78 in Mona Reclamation Experimental Project have been leveled and arranged in borders, 40 feet wide and extending 660 feet from the watercourse in length. These are now growing their third crop. By actual measurement, the entire nine acres can be irrigated with only 40 percent of the water formerly required. In one recent set of measurements, although the borders are 660 feet in length, each was irrigated completely with only two inches of water (8).

Uniform Soil Moisture to Promote Better Germination - Poor crop stands are common in Pakistan and can often be attributed to inadequate soil moisture to achieve good germination particularly in the kharif season. The problem is usually due to the short period the soil is in proper moisture condition for seeding, locally called wattar, and the unlevel nature of the fields. It is not uncommon for the higher areas of the fields to have lost the moisture essential for germination before the lower areas are dry enough to cultivate. Often not more than 0.2 foot difference in elevation

is sufficient to create a marked difference in the field conditions so that soil preparation traffic and seeding operations cannot be accomplished over the entire field at the same time. Consequently, the farmer is forced to wait and plant when the lower portions are sufficiently dry for performing the necessary cultural practices. Poor or spotty crop stands are the common result.

These factors are difficult to value for lack of widely representative data on the incidence of poor stands. The phenomenon is undoubtedly more prevalent in summer due to the more rapid drying conditions. However, as a plausible example, if poor stands reduce yield by 50 percent on one-fifth of a given field, total yield is reduced by ten percent. The level of technology in use determines the value of this reduction. With wheat it could range from 80-160 rupees per acre depending on whether the field and the farmer were capable of producing 20 or 40 maund wheat yields.

In the kharif season the effect of soil moisture on plant population is markedly increased since the time when the soil moisture is in wattar condition is much shorter because of the intense heat. In the Sind there is generally a strong breeze adding to this problem. Under present water management practices it is physically impossible to apply a light irrigation to replenish that lost moisture. Therefore, in the process of replenishing a one inch moisture depletion in the surface half foot of soil, at least three inches and often four or five inches are applied. The result is a gross waste of valuable water and a five to ten day delay in planting.

Improved Fertilization Efficiency - Another benefit related directly to irrigation efficiency is the efficiency with which fertilizer is used. Overirrigation such as occurs on unleveled fields most of the year leaches applied nutrients out of the root zone, resulting in lower recovery rates. It is estimated that from 10-60 percent of the applied nitrogen may be lost for this reason. This is a value of improved farm water management that must be recognized and efforts made to prevent this loss. When 2, 3 or 4 inches of excess irrigation water are applied each time a crop is irrigated, it becomes impossible to maintain adequate nitrogen in the root zone. We assume below that 30 percent of the applied nitrogen is lost in this manner. Unfortunately, data do not exist that would indicate how much of the total over-irrigation is due to unlevel fields and how much due to other factors, but all are related to poor farm water management.

Higher Yields - In the same vein, yields can be reduced on both the high and low spots for reasons that cannot be ascribed to poor germination or fertilizer leaching. Most

important is the increased probability of moisture stress occurring in the underwatered high spots. This is the reason behind reduced germination mentioned above, but it also affects per plant yields if moisture stress occurs during other important stages of growth.

Similarly, low areas are prone to excessive ponding of irrigation or rainwater which can reduce yields in several ways. Lack of oxygen in the root zone, destruction of soil structure and an increased probability of lodging are among these.

Data reported for the United States suggest a 20 percent increase in yield from land leveling for wheat (2). We are unable to determine from this reference, however, just how much of this yield increase might be attributed to the several individual sources described herein. No quantitative estimate is included here of the value of this factor in Pakistan for this reason.

Reduced Probability of Salt Accumulation - The combination of unlevel fields and the criterion of irrigating until the high spots are covered frequently results in both over and underirrigation occurring within the same fields. Underirrigated high spots do not receive enough water to accommodate normal leaching of accumulated salts. In addition, shortly after irrigation the high spots are again exposed and evaporating, even while lower areas are still inundated, with the result that even greater accumulations occur as salts are carried by capillarity from surrounding areas to the surface of the high spot.

To value the current crop losses due to this source, and hence the benefits possible from correcting it by leveling, data are needed that associate yield reductions with accumulated salinity and the propensity for salt problems to develop must be related to differences in elevation, soil type, water quality and water table depth. Unfortunately, these relationships are not yet quantified.

The inability to apply uniform amounts of water that results from unlevel fields also affects the cost of reclamation programs which rely on leaching to remove salts. If a certain amount of leaching is required, then effective reclamation programs must plan to apply this much water to the high spots. Variations in level and infiltration rate can result in two to four times as much water being applied to low areas, most of which is wasted in that it is unnecessary if the field were only level.

Increased Cultivatable Land - A prevalent farmer adaptation to unlevel fields is to subdivide and make smaller irrigation units so that the differences in level within the

irrigation unit (khet) are minimized. As a result, few irrigation units exist that are an acre or larger in size; half and quarter acres predominate (3). This irrigation unit size necessitates an extensive farm watercourse system in order to convey water to each of these areas. A mile of watercourse is required to adequately serve each twenty acres of land with these small fields. With improved farm water management systems it is practical to increase the area served by a mile of watercourse to 50 acres.

Water channels preempt an average of 15 square feet of crop land per foot of length in Pakistan. If, in an ideal situation, a whole 400 acre watercourse could be redesigned with 50 acres per mile of channel, an additional 21.8 acres (5.4%) could be added to cropped area. While completely redesigning all the channels in a watercourse will be impossible, substantial benefits from this source are possible. Additional land can be put into cultivation as fields are made larger and fewer bunds are required. Further benefits come from eliminating many field corners that occur with each field. It is physically impossible to maintain the level of a field or to plant well in corners even when utilizing animals for tillage.

As an extreme example, five acres of crop land as typically subdivided in Pakistan will require 1,320 feet of delivery ditch and will contain from 40-80 field corners in which there is little or no crop. With modern leveling and an adequate water flow, five acres can be managed as one field with only four permanent corners, temporary guide borders and as little as 330 feet of ditch.

Reduced Delivery Losses - A reduction in the mileage of channels to serve a given area will also reduce the losses to seepage and spills in delivery. In fact, other than channel lining, this is the only method that can have a significant impact on the seepage portion of delivery loss.

In the analyses of the foregoing sections no attempt was made to relate delivery losses to delivery distance for lack of data. The relationship used was a function of flow rates at the watercourse head. In truth, delivery losses are a complex function of both, plus other factors. Losses are highest near the outlet. Sources of loss in the main channel and branches are most important since water flows in these sections most often. Again in an ideal situation, the entire watercourse would be leveled and total ditch length would be reduced by 60 percent, from one mile per 20 acres to one mile per 50 acres. It is more realistic, however, to assume that realignment will bring the area served by one mile of ditch only up to 35 acres. This would be a reduction of 43 percent. Most, if not all, of this reduction would come from farmer ditches serving a few

individual fields each. It was shown above that these ditches account for 15 percent of the delivery distance. The simplistic methodology used in this paper assigned 15 percent of the delivery losses to these ditches. A 43 percent reduction in total ditch length if concentrated only in farm ditches would reduce their length by .55 percent. Losses from watercourses would therefore, be reduced by .15 x 55 = 8.25 percent.

Summary of Benefits - A synopsis of benefits is offered here even though the figures underlying most of them are only assumptions. Further research is needed to more accurately specify the full extent of these benefits.

1. Improved application efficiency - Data from a previous section indicate that water deliveries at the field range from 1.4 - 2.36 acre feet per acre annually for the several representative situations analyzed. If higher application efficiency through leveling raises the value of water by Rs. 89/AF, benefits range from Rs. 125-210 per acre.

2. Better germination - On fields where poor germination as a result of variations in elevation reduce yields in the amount discussed above, production losses range between Rs. 80-160 per acre. Taking the midpoint, Rs. 120, and assuming this occurs on 1/4 of the fields to be leveled gives an average benefit of Rs. 30 per acre.

3. Improved fertilization efficiency - Nutrient consumption averages 25 pounds per irrigated acre in Pakistan. If fertilization levels are twice this on fields to be leveled, the grain:nutrient ratio is 10:1, and a 30 percent loss is assumed to result from overirrigation. The added income from this source at current grain prices would be Rs. 73 per acre.

4. Increased cultivatable land - Redesigning watercourses so that a mile of ditch serves 35 leveled acres instead of 20 will add 3 percent to cultivatable acreage. With cropping intensity of 120% and a gross value per crop of about Rs. 1200 (net value added figures are not available), the value of additional production would be at least Rs. 43 per acre just from land formerly in ditches. We are unable to estimate the amount of land that would be recaptured from bunds since this depends on quantity of water and other management factors.

5. Decreased delivery losses - Again, data from a previous section show that annual delivery losses in different situations range from 0.5 - 1.4 acre feet per acre. If delivery losses were cut by 8.25 percent as estimated above through reductions in total channel length and channels were redesigned to serve 35 acres per mile, the value of the water saved would range from 15-41 Rs./Ac.

6. Reduced salt accumulation - We do not have the data to even guess what the value of this benefit might be nor the probability of its incidence.

7. Higher yields - Similarly we are unable to assign a value to increased yields from sources not summarized above for lack of data.

Cost of Precision Land Leveling

Basin irrigation, the irrigation practice used in Pakistan, ties uniformity of water distribution directly to the physical levelness of the field. The amount of soil required to level these fields is generally not excessive and level fields can be achieved at a relatively low cost. Considerable research and practical field experience in Pakistan has shown that moving of 200 m^3, or approximately 260 yds^3, would make most fields adaptable to efficient irrigation applications.

A technique has been developed and proved in Pakistan utilizing a standard farm tractor and engineering technology for effectively leveling irrigated lands. The farm tractor powers a locally fabricated soil scraper and land plane to achieve the end result required for improved water management practices. The soil scraper is fabricated in widths from 5 to 8 feet, capable of efficiently moving from 1 to 2 m^3 of soil per trip depending on tractor horsepower and soils. Any program, however, should allow for moving soil by any means available. The ongoing Precision Land Leveling Project is designed to teach technicians to properly engineer systems and advise farmers in improved irrigation practices. The cadre trained during 1975 will be a base on which a program can be developed.

Soil Conservation Service personnel have developed the cost structure of hypothetical contractor operations utilizing farm tractors and locally fabricated equipment. It is estimated that a contractor can move soil for Rs. 3.00 per m^3, or approximately Rs. 600 per acre (7). A field, once leveled, will remain in that condition providing proper cultural practices are used and periodic touch-up maintenance is done. If five percent of initial costs are spent on annual maintenance at 1974-75 prices this would allow one or two days annually with a pair of bullocks and indigenous scraper blade to maintain each acre. Total annual costs therefore, would be as shown in Table 19.

Table 20 develops the benefits for the five typical watercourse cases and estimates the benefit:cost ratios assuming a 25 year life and 15 percent interest rate. The benefit:cost ratios shown are based on the actual loss and delivery situations prevailing in unimproved watercourses.

Table 19. Annualized Costs and Maintenance for Precision Land Leveling (Rs./acre)

	15 years			25 years		
	10%	15%	20%	10%	15%	20%
Annualized Cost	79	103	128	66	93	121
Maintenance	30	30	30	30	30	30
Total Annual Cost	109	133	158	96	123	151

Table 20. Benefit:Cost Ratios for Precision Land Leveling Without Watercourse Improvements (Figures are in Rupee/acre/year)

	Watercourse Type				
Benefits	CASE I	CASE II	CASE III	CASE IV	CASE V
Higher water value	133	125	164	210	180
Better germination	30	30	30	30	30
Fertilizer savings	73	73	73	73	73
Increased land area	43	43	43	43	43
Decreased delivery losses	15	18	23	41	31
Total	294	289	333	397	357
Costs*	123	123	123	123	123
Benefit:Cost	2.39	2.35	2.71	3.23	2.90

* 25 year life and 15% interest rate assumed.

A subsequent section combines the benefits and costs of various watercourses improvement options with those of land leveling to derive the returns to be expected from an integrated program.

Irrigation Extension

The third major dimension of a water management program is irrigation extension, meaning the transfer to the farmer of knowledge concerning modern irrigation techniques plus complimentary cultural practices for irrigated cropping. It does little good to provide the physical basis for modern water management if drastic inefficiencies prevail after the water has been stored in the root zone.

Recent surveys have discovered that most farmers do not understand soil moisture deficiencies, believe plant roots are confined to the top few inches of soil and have little or no knowledge of plants' varying sensitivity to moisture stress at different times of the season (15). As already mentioned overirrigations are common as farmers apply water in excess of available root zone moisture holding capacity. Current cultural practices almost necessitate a pre-planting (rauni) irrigation. Conventionally this is conceived as a "soaking dose" and is one of the heaviest irrigations given (4 - 10 inches). It is also one of the most wasteful since soil moisture depletion is frequently only 1 to 2 inches at the time. Furthermore, trying to manage a sequence of pre-plant irrigations, plowings and plankings to obtain good soil moisture at seeding depth is sufficiently complicated in the monsoon season that planted acreage of maize and possibly cotton is reduced.

If farmers use any criteria for irrigating other than the calendar, it is visual and textural symptoms of plant wilting, even though yield reductions may be incurred before wilting symptoms appear. Farmers do not understand nutrient movement in the soil and have no appreciation of the relationship between overirrigation and nitrogen loss. Incredibly, after 23 years of chemical fertilizer availability almost none of the farmers deal with fertilizer in terms of pounds of nutrients per acre. Few of them even understand the differences in nutrient content between bags of urea, DAP, MAP, Nitrophos, K_2S, and ammonium sulphate, all of which are available in Pakistan.

The above is by no means a complete list but it is indicative of the fact that plant-soil-water-nutrient relationships remain largely a mystery to Pakistani farmers. Without better knowledge, modern irrigated farming will remain impossible and if it does, the investments made in channel lining, routine maintenance, tubewells or leveling will earn only a fraction of their potential.

The above is not meant to imply that the Pakistani farmer is, of necessity, a poor manager. What it does mean, however, is that there are serious limits to his knowledge of factors affecting his irrigation and cropping efficiency. Farmers have never been educated to the concepts and practices involved in modern irrigated farming. To a very large extent this is because these practices are not used or understood by research scientists who develop recommendations or by the staffs of the government departments who should be conveying the message to the farmers or implementing programs in the field.

Figure 1 on page 13 emphasizes the magnitude of possible change with better control of inputs and knowledge of when and how to apply them. The differences between present farmer conditions (F) and the best available technology (E) are dramatic. On the experiment station, irrigations were applied at critical crop stages and were measured to minimize overirrigation. Seedbed preparation was optimum, planting and germination was excellent with the result that an optimum plant population was established for converting water and nutrients into yield. Simply raising fertilization levels on farmers' fields will not do the job as is shown by the small differences between F_a and F.

$E - F_a$ represents the magnitude of yield increases possible through better managing of the water input. At the four irrigation level, poor input control and lack of knowledge reduce yields by 15.6 maunds which at today's prices is worth Rs. 622. At the risk of over-simplification, this difference between the two total product curves may be viewed as the potential benefit of good irrigation extension.

A shift from one response surface to the other will not happen instantaneously, but a considerable portion of the shift might be expected after a reasonably short period of concentrated, technically correct irrigation extension. In developing the value of water we assumed that a water management technology which would characterize the average farmer capabilities in project watercourses over a 25 year period. This was given by the response curve H in Figure 1 and provided an estimate of Rs. 29.66 per acre inch as the value of water applied to leveled fields. With no change in farming techniques except increased fertilizer levels, the value of water would be Rs. 23.55 per acre inch, or 21 percent less than that assumed by H. Benefits attributable to the value of water saved discussed in other sections of this paper would be adjusted downward accordingly.

At another level an extension effort will be necessary to achieve widespread adoption of a water management program. As mentioned earlier, farmers do not correctly perceive the sources or magnitudes of their water losses. This is

particularly true with respect to application losses but is also true for delivery losses. When they do notice serious problems they often are mistaken about the cause. Finally, they do not know how to correct the situation or even that solutions are within their grasp.

Education for the farmer in this respect will be a necessary precursor to having watercourses who are ready to invest in a water management program. Secondly, extension of irrigation and cropping techniques is necessary if satisfactory benefits are to be obtained by the program. Both of these processes require staff who understand modern irrigation and farm managers well enough to convey the message to farmers. This in turn will necessitate a training program for irrigation extension personnel and for those irrigation engineers who will be responsible for eliciting interest and investment in water management from the villages.

Water Users' Associations

All of the suggested means of watercourse improvement evaluated above require group interaction among farmers with lands served by the same watercourse. Communal decisions are needed to select a plan, agree with Government authorities for a cooperative effort, provide labor from all farmers, accumulate funds from watercourse members, hire personnel for maintenance, and many other reasons. In order to achieve these purposes satisfactorily, farmers will have to be organized into some form of Water User Association having the powers to apportion the cost, ensure compliance by all members, enter into contracts, own assets, supervise innovative water allocation programs and ensure that each farmer receives his fair share of the benefits.

Water User Associations should be quite feasible in irrigated portions of Pakistan particularly because such an association can focus on a specific set of issues for which the rewards to cooperative action are considerable. However, current types of rural organizations especially those registered under the Cooperative Societies Act seem to have severe drawbacks that impede their effectiveness. An analysis of existing legislation presently being finalized will show whether current Acts can be used with some modification or whether new legislation is necessary. Preliminary conclusions are that some specific new legislation is necessary (21).

Once a satisfactorily constituted Water User Association is established it will serve as the primary means of organizing farmers for participation in a farm water management program and as the point of contact between farmers and the relevant government agencies. After the initial development

phase of land leveling and watercourse renovation, there are a number of additional services that a Water User Association could provide on a continuing basis for its constituents. The most significant is to organize and operate a system of routine maintenance for the watercourse. To do this the necessary men must be identified, contracted with and supervised. The latter, supervision, is particularly important. Payment could either be in kind direct from the farmer, or the Water User Association could accumulate a small assessment to finance cash contracts.

Another possibility lies in providing the services of improved water management equipment to all members. The cost of equipment such as siphons, bund makers, earth movers and levelers, special seeders and ridgers can be very high for the farmer with only a few acres. However, these equipment items are shareable and their purchase by groups of farmers or perhaps the Water Users' Association as a whole could greatly decrease the cost per farmer. The Water Users' Association might itself become an agency which could own and rent equipment needed by the farmers at nominal costs.

As stated earlier two possible organizational units suggest themselves as nuclei for organization; the farmers served by one watercourse or the village as a whole which may contain several watercourses. In the first instance the size of the constituent body would normally range from 30 to 50 farmers, in the second it may be as high as 120 farmers. Realistically, organizing at the village level will encounter problems where a village contains more than one agricultural caste. Sociological research in Punjab and NWFP has shown that caste lines form barriers which constrain effective cooperative action (22). However, a recent study at Shadab indicated that the land holdings of each different caste were relatively contiguous. The lands farmed by one caste, in general, fell on a single branch of the watercourse as a result of the historical pattern of inheritance (15). To the extent this pattern prevails throughout Pakistan organizing watercourse users around individual watercourse units may be feasible in that not only are the numbers smaller but caste differences are minimized.

On the other hand field research presently underway has identified many types of water management issues for which the interactions are on a village wide basis (16). In order to permit a Water User Association to play its full potential role in village water management, there is a strong case for organizing at the village level. Until further results are in this issue must remain undecided.

Summary and Integration
(Putting It All Together)

The foregoing sections separately evaluate several different water management program alternatives for Pakistan. Some of the suggested programs such as maintenance may well warrant investment by themselves. Others when actually implemented should be a combination of several different components. This section draws on the earlier analysis to assess some of the possible packages and to show the conditions and locations under which each is relevant.

The tabulations developed in earlier sections were done consistently under one set of assumptions regarding the value of water. Two of these assumptions which are important are examined here to determine the effects of altering them. These assumptions are:

1. That all of the water saved from delivery losses is applied to leveled fields.
2. That water lost either in delivery or application was charged off at its full value without considering that it might have been recovered by a lower cost technique.

Also, an element of cost was also uniformly ignored in earlier sections. Any program of watercourse reconstruction or land leveling will disrupt water deliveries and/or cropping while it is being completed. The extent of disruption will vary with the different programs and will also reflect the efficiency and methods with which the process is completed. We have ignored these costs because data are not available to measure them and because we feel that careful planning of the programs' operation can reduce them to relatively minimal levels.

Table 21 summarizes the benefit:cost ratios estimated in preceding sections for several alternative programs with all the water placed on leveled fields. These rates of return, then, fit a program where ditch renovation options are instituted on already leveled watercourses.

Assuming all land was already leveled is a simplistic technique allowing the use of Rs. 356/AF as the value of water saved. The figure if this water is to be applied to unleveled fields is only Rs. 267, twentyfive percent less. By applying the percentage of land leveled one could interpolate between these two figures to determine the actual value pertaining to a particular case. For example, if only half the watercourse is leveled the benefit:cost figures of Table 21 for any of the lining or maintenance options are reduced by .5 x .25 or 12.5 percent. If none of the watercourse is leveled, the rates of return are reduced to 75

Table 21. Summary of Benefit:Cost Ratios for Various Water Management Options

Improvement Program	Watercourse Type				
	CASE I	CASE II	CASE III	CASE IV	CASE V
LINED CHANNELS					
Brick, Rectangular*	1.32	1.22	1.60	2.14	1.63
Concrete, Trapezoidal*	1.92	1.85	2.44	3.21	2.44
IMPROVED EARTH					
Rebuilt w/maintenance*	2.58	3.11	4.11	5.16	3.92
Rebuilt w/maintenance**	1.19	1.43	1.89	2.28	1.74
Maintained w/rebuilding**	5.8	12.3	12.2	22.5	17.1
Maintained only**	5.0	7.5	10.8	20.3	15.3

* Main ditch only
** Main ditch and major branches

percent of those in the table. In fact, this is the most realistic valuation if these ditch renovation techniques are to be completed on normal watercourses in the absence of other programs such as precision land leveling.

Cropping patterns, farmer reticence and cash limitations, time lags in the program and other factors may limit the portion of a given watercourse that will be leveled. Many villages may wish to consider watercourse improvement programs even though precision land leveling services are not available in their area. Finally, some of the suggested programs are better not tied to a land leveling component so that they may be spread nationwide more rapidly. Therefore, in many instances renovation programs may be considered in the absence of precision leveling. For situations where renovation can be combined with other components, different pictures emerge. These are elaborated in later sections of this paper.

Finally, the assumption that water losses are not recoverable holds only where ground water is too saline for use. In other areas water lost can be pumped again to the surface at an additional cost. Net benefits to the farmer equal the value of the water pumped minus the cost of pumping minus the amount of deterioration in quality minus other losses such as swamping of crops or nitrate leaching that occur in the process of losing water to the water table. An appropriate evaluation framework is to consider the costs of delivering an acre foot to the nucca with alternative techniques. In many areas pumping water may be the most economical, highest priority program. For this reason tubewell supplementation is included as an option considered in this paper.

Precision Land Leveling

Table 20 shows that this program has a relatively uniform return regardless of the type of watercourse to which it is applied. Benefit:cost ratios will, in fact, exceed those in this table by the amount of those benefits that we could not estimate for lack of data. One fact not shown in the earlier analysis is that application efficiencies are particularly low in SCARPs. This would result in a lower value for water applied to unleveled land and consequently a return exceeding Rs. 89/AF for leveling. Present information indicates that this added benefit could, in fact, be quite substantial in SCARPs.

It should be recognized, however, that the government's ability to mount a precision land leveling program will have certain size limitations for the foreseeable future. Engineers must be trained, equipment obtained, operations sequenced, etc. Realistically, only a few hundred

watercourses will be completed in a year even after the program has been fully launched. Because of this limited feasible capacity, it is suggested that the land leveling program be concentrated in watercourse command areas where lining or reconstruction of the watercourse is being done. In several of the sections below precision land leveling is integrated with watercourse improvement options for analysis.

Watercourse Renovation Options

Several programs have been proposed for reducing delivery losses by various types of improvements in the delivery ditches. All of them have been evaluated on a farm production technology level expected to prevail in the mid 1980s. Whether or not the assumed technology level, indicated by curve H in Figure 1, is achieved depends on the effectiveness of extension efforts. Curve H assumes a rather high degree of effectiveness. In addition, at several other points in the foregoing analysis farmers were assumed to have learned new techniques. We have implicitly assumed that there would be a concentrated irrigation extension effort applied directly to project watercourses during the renovation and leveling process and continuing indefinitely. For this reason, although no specific analysis of the impact of extension is made below, it should be understood that a concentrated, effective program is assumed.

Watercourse Maintenance

Maintenance programs proved to have the highest benefit: cost ratios of any option considered although they do not save as high a percentage of delivery losses as do reconstructed earth or concrete channels. Losses by seepage, in particular, cannot be controlled by maintenance of the banks, however, field observations indicate a high control of spillage losses can be obtained. Maintenance programs require a rather minimal investment per acre, can probably be handled by the villages without elaborate government or industry bureaucracies and should be a profitable investment in all watercourses in Pakistan.

Two possible forms of this program were presented. In the first, two men were employed full time maintaining the ditch banks. Their functions would include strengthening the closures of nuccas and junctions, building up an adequate freeboard, strengthening ditch banks, straightening alignments and controlling vegetation. They will probably not be able to alter the slope of various sections but will have to work within the natural slope of the commanded area. The second alternative was to add the function of gradually replacing permeable ditch banks with new soil at a rate that would rebuild the main ditch and major branches once every three years. To achieve this some excess capacity beyond mere maintenance needs is required.

In either case, the men involved should probably be hired by the village from within its own population. Payment could be in cash or in kind. The latter is probably most consistent with village practices. It is recommended that these men be drawn from the landless labor class, who presently average only 11 days of work per month at low wages (23) and are thus the rural group most desperately in need of extra employment. There are several of these men in every village and they possess the necessary skills.

Tables 16 and 17 evaluate these options under the assumption that all land is leveled. In this case, leveling is not necessary in order to have very attractive returns. Furthermore requiring leveling would constrain the spread of routine maintenance to the pace at which land could be leveled.

Instead, it is strongly recommended that routine watercourse maintenance be initiated and institutionalized within the village on all watercourses as soon as possible. Either of the two versions described above are acceptable. However, if gradual reconstruction of the banks is included, more water will be saved per acre and the program will, among other things, make a greater contribution to containing waterlogging. While the benefits and costs are not precisely known, there is no doubt that the program would be very beneficial to every farmer and to Pakistan as a nation.

It is further recommended that a routine maintenance program, institutionalized within the village, be a precondition to qualify for participation in other government supported watercourse programs.

Table 22 compares benefit:cost ratios for these two programs with and without leveling. Even without leveling both are highly attractive.

Table 22. Benefit:Cost Ratios for Maintenance of Main Ditch and Branches With and Without Precision Land Leveling

Program	Watercourse Type				
	CASE I	CASE II	CASE III	CASE IV	CASE V
100% Leveled					
Maintained Only*	5.0	7.5	10.8	20.3	15.3
Maintained & Rebuilt**	5.8	12.3	12.2	22.5	17.1
No Leveling					
Maintained Only**	3.8	5.6	8.1	15.2	11.5
Maintained & Rebuilt**	4.4	9.2	9.2	16.9	12.8

* From Tables 16 and 17

** Seventyfive percent of leveled figure.

Watercourse Reconstruction

Again two basic techniques are feasible although with differing levels of return on investment. Of the lining techniques, concrete trapezoidal designs are considerably more economical than brick but we do not yet know how cheaply they can be constructed or how the cost will vary for different flows. We choose concrete trapezoidal designs for the combination programs below.

The second type of reconstruction is an earth ditch cut to proper grade and cross section in a compacted bed with concrete or masonry turnouts, junctions and drop structures. This design will not control seepage as well concrete lining but it is an improvement over a maintained and manually rebuilt channel to the extent of the structures, nuccas, and controlled channel slope. Because testing of this option is in its initial stage the exact costs of this type of channel built in Pakistan are unknown. Also not known with precision is its effectiveness in controlling losses or how much maintenance is required to keep it operational.

Tables 23-26 assume a 25 year life and 15 percent interest rate.

Discussion

Among the above renovation options are several with sufficient returns to justify investment. In all cases SCARP watercourses have the highest payoffs. SCARP areas have higher water losses and higher deliveries per acre than any other watercourse environment. Only the watercourse supplemented with two communally owned private tubewells as discussed on page 33 delivers more water to the average acre.

Consequently, SCARP areas are the general category with highest justification for watercourse renovation. Benefit:cost ratios in SCARP are sufficiently attractive under most assumptions that one can conclude that watercourse improvement should be a mandatory part of the program to expand SCARPs.

Watercourse lining or reconstruction, except when done gradually as part of a maintenance program, is of questionable return in the lower flow watercourses. Benefits do exceed costs in most instances estimated here but the margin is sufficiently narrow that unexpected cost overruns or other factors could negate the profits. Maintenance, however, remains a highly profitable option for CASE I, II and III watercourses.

Maintenance and manual reconstruction can save a substantial portion of delivery losses. The more permanent

Combination I - Lined Main, Reconstructed Branches, Maintenance on Mains and Branches, Land Leveling and Extension

In this combination we assume a concrete trapezoidal lining to control 90% of the losses for 70% of the distance and mechanical reconstruction to control 75% of the losses on the 15% of delivery distance in branches. Furthermore, we assume that there is no change, increase or decrease, in losses on the 15% of delivery distance in farmers fields. The value of water originally reaching the nucca is raised by Rs. 89 due to leveling. All water saved by these modifications, is valued at the Rs. 356/AF which applies to leveled fields. The other quantifiable benefits of Precision Land Leveling are also included. Table 23 summarizes the results.

Table 23. Benefits and Costs of Combination I; Lined Main, Reconstructed Branches, Precision Land Leveling, Maintenance and Extension

	Watercourse Type				
Costs/Acre	CASE I	CASE II	CASE III	CASE IV	CASE V
Lining Main Channel	64	74	74	98	99
Reconstructed Branches (40 ft/ac)	60	60	60	89	89
Maintenance (1-2 men)	6	6	6	12	12
Precision Leveling	123	123	123	123	123
TOTAL	253	263	263	323	323
Benefits					
Higher Value of Original water	133.5	124.6	164.6	210.7	179.6
Water Saved (AF)	148.5	311.8	311.8	574.7	436.6
Value: Total	52,866	111,019	111,019	204,591	155,426
Per Acre	132	159	209	372	283
Other Benefits?ac.	161	164	169	187	177
TOTAL	426	448	543	769	640
Benefit:Cost	1.68	1.70	2.06	2.38	1.98

Combination II - Reconstructed Main and Branches, Maintenance on Mains and Branches, Land Leveling and Extensions

In this alternative we assume that the combination of reconstruction and maintenance saves 75% of all losses in 85% of the delivery distance and no change in losses on the 15% that are farm ditch. All water is valued as if applied to leveled fields and the additional benefits to leveling are also included. Table 24 presents the analysis.

Table 24. Benefit:Cost Ratios for Combination II: Reconstructed and Maintained Mains and Branches, Precision Leveling and Extension

	Watercourse Type				
Cost/Acre	CASE I	CASE II	CASE III	CASE IV	CASE V
Reconstruction w/maintenance	95	95	95	140	140
Precision Leveling	123	123	123	123	123
TOTAL	218	218	218	263	263
Benefits/Acre					
Added Value for Existing Deliveries	134	125	165	211	180
Value of Extra Water	93	112	148	263	200
Other Benefits	161	164	169	187	177
TOTAL	368	401	482	661	557
Benefit:Cost	1.69	1.84	2.21	2.51	2.12

Combination III - Reconstructed Mains, Maintained Mains and Branches, Land Leveling and Extension

This is the same as Combination II except that the branches are only maintained with gradual manual reconstruction instead of being mechanically rebuilt in program. Table 25 presents the analysis.

Table 25. Benefit:Cost Ratios for Combination III - Reconstructed Main, Maintained Branches, Land Leveling and Extension

	Watercourse Type				
Cost/Acre	CASE I	CASE II	CASE III	CASE IV	CASE V
Reconstruction	36	36	36	51	51
Maintenance	19.5	11.1	14.7	14.2	14.2
Precision Leveling	123	123	123	123	123
TOTAL	178.5	170.1	173.7	188.2	188.2
Benefits/Acre					
Added Value for Existing Deliveries	134	125	165	211	180
Value of Extra Water	113	136	180	319	243
Other Benefits	161	164	169	187	177
TOTAL	408	425	514	717	600
Benefit/Cost	2.29	2.49	2.96	3.81	3.19

Combination IV - Lined Main Ditch, Branches Maintained with Gradual Reconstruction, Precision Leveling and Extension

This combination is essentially the same as Combination I except that the major branches are maintained and only gradually reconstructed by hand. We have assumed three men are involved in maintenance and that they will control 75 percent of the losses in the branches. Lining controls 90 percent in the section lined.

Table 26. Benefit:Cost Ratios for Combination IV: Lined Main Ditch Branches Maintained with Gradual Reconstruction, Precision Leveling and Extension

	Watercourse Type				
Cost/Acre	CASE I	CASE II	CASE III	CASE IV	CASE V
Lining Main	64	74	74	99	99
Maintenance with Manual Rebuilding of Branches	19.5	11.1	14.7	14.2	14.2
Precision Leveling	123	123	123	123	123
TOTAL	206.5	208.1	211.7	236.7	236.2
Benefits/Acre					
Added Value for Existing Deliveries	134	125	165	211	180
Value of Extra Water	132	159	209	372	283
Other Benefits	161	164	169	187	177
TOTAL	427	448	543	770	640
Benefit:Cost	2.07	2.15	2.56	3.25	2.71

methods such as lining or mechanical reconstruction save a higher percentage of the water but at a higher cost per acre foot. This suggests that lining and mechanical reconstruction are best concentrated in those areas where it is most important to control losses.

First priority among these are areas with saline ground water in which water, once lost, is not retrievable in useable form at any cost. A second high priority area for maximum loss control is where the water table is near the surface. Losses here not only waste the farmer's water resource but they can reduce yields on all surrounding crops by contributing to a further rise in ground water level.

One point needs to be made with emphasis. Under many of the current water duties in Pakistan there are times during each season when the allotted flow will not support crops on every acre even if every drop is delivered and stored in root zones. In low duty areas the first priority then is to increase water supplies. One such option, supplementing watercourse flows with two tubewells has been evaluated. This type of program with the assumptions used delivers more water to the average nucca than even CASE IV watercourses.

Watercourse maintenance with or without manual reconstruction makes a very logical additional component to include with small tubewell supplementation. Combined flows may not be large enough to have the loss characteristics that would justify lining. But maintaining the watercourse should be a mandatory minimum to achieve maximum benefits from the tubewells. Finally, because of the higher flows reaching the nuccas, precision land leveling will have its highest returns in this situation.

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