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OPERATIONAL IRRIGATION EVALUATION OF PAKISTAN WATERCOURSE CONVEYANCE SYSTEMS

By Thomas Trout
and S. A. Bowers

Water Management Research Project
Colorado State University
Fort Collins, Colorado
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OPERATIONAL IRRIGATION EVALUATION OF PAKISTAN WATERCOURSE CONVEYANCE SYSTEMS

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Prepared by

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Water Management Research Project
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ABSTRACT

Five Pakistan watercourse systems, selected from various geographical areas of the Indus Basin, were evaluated during complete irrigation turn rotations while operating normally. This allowed a quantification of the various types of water losses, including transient condition losses such as dead storage, bank wash-outs, outlet leakage, and high initial seepage into dry channel banks.

Flow measurement was made with Cutthroat flumes and water volumes were determined through integration of the flow hydrographs.

Total conveyance losses ranged from 38% to 56% and averaged 45%. Six to eight percent of the inflow was consistently lost to transient conditions of which about half was dead storage. Transient losses depended primarily on the length of channel filled and drained.

Steady-state conveyance loss rates were significantly higher in the farmers' branches than in the main channels, and increased rapidly as the flow rates increased.

Seepage rates into watercourse banks were much higher than intake rates into the surrounding fields on three watercourses, indicating a potential for conveyance loss reduction utilizing only improved earthen channels.

Application efficiencies, monitored on three of the studied watercourse command areas varied widely, and averaged 63%. Farmer water application did not correlate with measured antecedent soil moisture deficiencies.

ACKNOWLEDGEMENTS

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Naveed Ahmed, CSU-WMRP programmer efficiently carried out the data analysis work.

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Thomas Trout and S. A. Bowers[2]

SECTION 1

INTRODUCTION

The primary goal of the Colorado State University (CSU) Water Management Research Project (WMRP) is to improve irrigated agriculture in Pakistan through better on-farm water management practices. An important component of the on-farm irrigation system is the network of small conveyance channels which carry the water from the canal outlet to the irrigated fields.

In the past six years, many measurements of water losses from these watercourse systems have been made by CSU engineers and their Pakistani counterparts. These measurements have indicated that 30 to 50% of the water which enters the watercourse at the head is lost from the conveyance system before it reaches the fields (Ashraf, et al., 1978; Lowdermilk, et al., 1978; Punjab On-Farm Water Management Development Project, 1978; and Trout, 1979).

These measurements, which were obtained by both the inflow-outflow method using flumes and by the ponding method (Brockwell and Worstell, 1968, Robinson and Rohwer,

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1/This study was a joint effort of the Water Management Research Project, Mona Reclamation Experimental Project and WAPDA Master Planning.

2/Agricultural Engineer and Agronomist, Water Management Research Project Field Team, Lahore, Pakistan.

1957), were designed to measure losses which occur while a conveyance system is operating under steady-state or constant flow conditions. They fail to measure the additional transient losses which occur in watercourses under operational conditions. Transient losses include, in addition to steady-state leakage:

1. excess infiltrated water which wets up dry channel banks;
2. water seepage and leakage during the time water is being transferred from one field to another;
3. dead storage water left lying in the bottoms of channels after drainage of channel storage into the fields is complete; and
4. losses resulting from short term watercourse breaches and outlet breaks.

These additional losses are constantly changing over time and are not measured by ponding or steady-state inflow-outflow measurements.

This report describes operational water loss studies on five Pakistan watercourse systems. Although the measurements were primarily designed to evaluate and better understand the water conveyance systems, evaluations of field applications and of farmer understanding of his irrigation system were also made.

The primary objectives of the study were to:

1. determine the extent of transient condition watercourse conveyance losses so that past steady-state measurements can be adjusted to reflect total operational losses; and

2. to better understand the watercourse system and the reasons for water losses so that techniques to reduce losses can be proposed.

SECTION 2

DESCRIPTION OF INDUS BASIN WATERCOURSE SYSTEMS

In order to fully understand the procedures used in this study, as well as the results and consequent implications, a basic understanding of the watercourse system is required. Although there is wide variability among the approximately 78,000 watercourse systems in the Pakistan portion of the Indus Basin, the majority of them are laid out and do operate in similar ways, and generalized descriptions can be made. Watercourses are the network of small channels which lead from the outlet (mogha) of the government controlled and maintained irrigation canal (distributary) to the individual fields. The basic layout and working of the system is prescribed in the Canal and Drainage Act of 1873 (Jahania, 1973), and the Manual of Irrigation Practice, (Government of West Pakistan, Public Works Department, 1943).

A watercourse system usually commands between 80 and 350 hectares (ha) of land and was originally designed to provide enough water for an annual cropping intensity over two seasons of about 75%. Water was designed to be a production constraint. Although the original holding sizes of the farmers were fairly large (10 to 20 ha), the subdivision of land has led to present average holding sizes of about 4 ha. Holding sizes vary widely between farmers on one watercourse and between watercourses. Many holdings are even further fragmented into separate plots scattered around the command area.

The watercourse conveyance system can be basically divided into two portions: the sarkari khal, or government laid out and constructed portion; and the farmers' branches which lead from the sarkari khal to the individual plots. The original intent of the sarkari khal was to deliver water to a side or corner of each farmer's land. Each farmer was given an outlet (nucca) from this channel from which he built his own branches leading to the individual fields.

Over time, with land ownership changes and subdivision, the strict differentiation between sarkari khal and farmer's branch has broken down on some watercourses, and even sarkari khal alignments are often found to be different from the original records. Several farmers often will share the use of one sarkari khal outlet and the main farmers' branches. However, there is still an understanding among the farmers between which portion of the watercourse system belongs to the community or government and which portions are their own branches.

The mogha (canal outlet) has no gate, and flows whenever water is in the canal. Mogha flows are often determined based on the amount of commanded land, at the rate of about one liter per second (lps) per five hectares, and usually range from 20 to 80 lps. Farmers have no control over their irrigation water supply. The water is generally divided among the farmers on a turn rotation, called a warabundi. Each farmer receives a turn time each week proportional to the amount of land he owns on the watercourse. A man with 0.5 ha might receive water for 20 minutes each week, while a farmer with 10 ha would receive all of the water in the watercourse for about 7 hours. The water passes turn-by-turn to farmers whose land lies progressively farther down each sarkari khal branch, and also rotates between the various sarkari khal branches. The rotation is completed each week (although in some cases 10 or 14 day rotation periods are used) and then starts again from the head of the watercourse.

Farmers generally divide their land into small level diked basins, varying in size from very small vegetable plots up to about 0.4 ha in size. Average field size is less than 0.2 ha. A farmer will irrigate about 15 to 20% of his land each week with 5 to 10 centimeters (cm) depth of water.

About 120-160 m of watercourse channel per hectare of land is required to irrigate the level basins, of which about 15% of the total is sarkari khal. However, about 80% of the channel utilized to reach any one field is sarkari khal. All of the sarkari khal and about 40 to 60% of the farmers' branches are utilized each week.

A watercourse can be typified as a complex system of small water channels, the primary portion of which is government authorized and communally maintained, through which 20 to 80 lps of water rotates every week to each of 20 to 80 farmers who irrigate fractional hectare plots.

Description of the Five Studied Watercourses

The five studied watercourses were located in central and southern Punjab Province and in central Sind Province.

Locations are shown in Figure 1. All were perennial watercourses, or received flow for both summer and winter cropping seasons. One watercourse was augmented by a Salinity Control and Reclamation Project (SCARP) tubewell (well), while another watercourse was augmented by two private tubewells. Brief descriptions of each studied watercourse are given. Maps of each command area showing the irrigation channel layout are given in the Appendix.

Tubewell 81-R Watercourse (TW 81-R)

Tubewell 81-R watercourse is located in the Mona Reclamation Experimental Project (MREP) area near Bhalwal in central Punjab. It is part of the SCARP II area and is served by part of the flow of SCARP Tubewell #81. The canal inflow through mogha #31574/R to the watercourse was about 30 lps. The tubewell added 40 lps to the system, giving a combined inflow of 70 lps.

The watercourse commands 148 culturable hectares. Primary crops in the area are wheat, fodder, sugarcane, and citrus. The cropping intensity for the 1975-76 cropping year (two seasons) had been 174%, which is higher than the average in the Mona area of 138%.

There are a total of 23,000 meters (m) of watercourse channels in the command area (154 m/ha) of which 3350 m are sarkari khal. Figure A-1 in the Appendix shows the layout of TW 81-R watercourse command area.

There are 20 land holdings listed on the watercourse warabundi list. Land holding sizes varied from 2.6 to 18.9 ha with a median size of 6 ha.

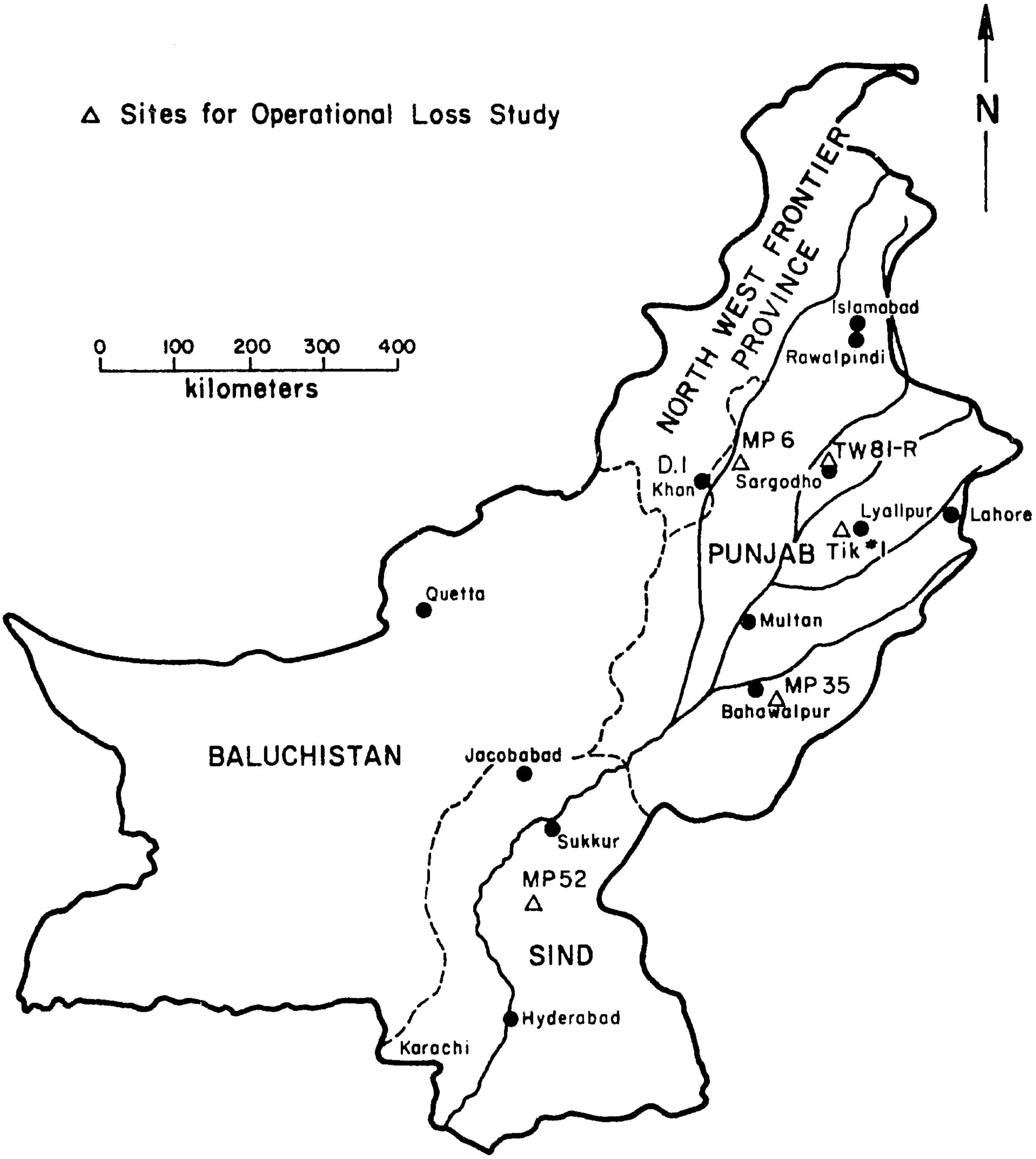


Figure 1. Map of Pakistan showing the locations of the five operationally studied watercourses.

There was little indication of maintenance or cleaning of the watercourse channels, although the farmers had shown an interest in, and later did complete, a watercourse earthen improvement program proposed by the MREP staff. There was evidence of more than 50 nucca cuts through the sarkari khal banks, or one for about every 60 m of length. One irrigator was usually present during a farmer's irrigation turn. He generally was a hired laborer.

In response to questioning on the number of irrigations required by their crops compared to the number given, the farmers indicated that they needed 54 percent more water to fulfill their crop irrigation needs (without increasing their cropping intensity).

The operational loss study was carried out from the 7th to the 14th of December, 1976. Much of the irrigation water was applied to newly germinated wheat. The canal was scheduled to be closed one week after the study ended for cleaning and maintenance work.

Tikriwala #1 Watercourse (Tik #1)

The second watercourse system studied was that served by mogha #RD89480/L of the Jhang branch. It serves the farmers of Tikriwala village, located 11 miles from Faisalabad on the Jhang road, and will be called Tikriwala #1 (Tik #1) watercourse.

The canal inflow to the watercourse varied between 38 and 45 lps and averaged 41 lps during the week it was being studied. The design inflow to the watercourse was 35 lps based on requirements for a 75 percent cropping intensity (according to district Irrigation Department personnel), but the mogha had recently been enlarged.

There were two private tubewells located near the head of the watercourse, each jointly owned by groups of about 10 cultivators. The tubewells, which each pumped 40 lps, were reported to have good quality water. They are run extensively, but never mixed with the canal water. All farmers bought tubewell water for Rs. 4/hr. (Rs. 1 ≈ U.S. $0.10), or about Rs. 2.8/ha-cm (Rs. 35/ac-ft), but during high use periods, nonowner farmers sometimes expressed difficulty getting tubewell water. During the studied week, one tubewell was out of order and the other ran every day during the daylight hours.

The watercourse commands 166 culturable hectares. Major crops are sugarcane, wheat, and fodder. The cropping intensity for the 1976-77 crop year was 174 percent. The high intensity was made possible by the presence of the private tubewells, and is much higher than is generally found in the Faisalabad area.

There are a total of 30,000 m of watercourse channels leading from the mogha to the fields (180 m/ha), of which 4880 m are sarkari khal. The layout of Tikriwala #1 is shown in Figure A-2 of the Appendix.

There are 91 land holdings in the watercourse command area. The average holding size is about 1.8 ha, with the largest holding size being 5.3 ha. Only 6 farmers own more than 3 ha of land on the watercourse.

The farmers indicated they needed 15 percent more irrigation water in order to adequately irrigate their crops. In response to a question regarding their use of a 50 percent increase in water supply, the replies were evenly divided between cropping more land, getting higher yields, and utilizing less tubewell water, with many farmers giving two of the responses.

The watercourse had been relatively well maintained and cleaned. Farmers often cleaned their branches before their irrigation turn began. Half of the time, two men were present during the irrigation, one of which was nearly always the cultivator, and much time was spent patrolling the watercourse checking for leaks. There were only 23 nuccas cut into the sarkari khal, or one for each square (land division containing about 10 ha), as was authorized in the original design. As a result, sarkari khal leakage was reduced, but longer farmer branches were required. Farmer branch banks were often very thin and freeboards were very small, which was largely the result of carving away the bank soil in order to enlarge the field sizes slightly. The farmers showed an interest in watercourse improvement, and later did rebuild their sarkari khal sections based on the design provided by the staff of the On-Farm Water Management Development Project (OFWMDP).

The watercourse was studied from March 21 to 28, 1977. Most of the sugarcane had been harvested, and fodder, wheat, and new sugarcane received most of the irrigation water.

Master Planning Watercourse #6 (MP 6)

Watercourse #6 of the WAPDA Master Planning Watercourse Survey, flows from outlet D21000-L, and serves the farmers of Chak 35 ML, Tehsil Bhakkar, District Mianwali. It is located within the Thal Development Scheme. The watercourse layout is shown in Figure A-3.

The watercourse, laid out during the 1960's, is very regular with one straight main sarkari khal channel 3260 m long serving land on both sides divided into 6 ha rectangular holdings. The area is composed of uncommanded sand dunes where gram is grown during the rabi (winter) season, with 150 ha of commanded culturable land between the dunes. There are 34 operators served by the watercourse, most of whom own the original 6 ha holding of land. Fifteen thousand meters of farmers' branches are utilized to serve the various fields.

The cropping intensity during the 1976-77 cropping year was 119 percent, with 89 percent of the land cropped during the rabi season and 30 percent during kharif (summer) season.

The perennial mogha flowed between 30 and 70 lps during the study period with an average of 56 lps. The design discharge is 33 lps. There are no tubewells in the command area.

During the study period (the final three weeks of April, 1978) final irrigations were given to the wheat crop and kharif pre-planting irrigations were being applied.

The soil in the command area is sandy with infiltration rates around 25 cm/hr. However, the fields near the head of the watercourse have been overlain with silt from the canal water, thereby reducing the infiltration rates significantly. Also, the first 2/3 of the sarkari khal and often-used farmers' branches near the head had a silt layer which greatly reduced infiltration rates. Farmers' branches near the tail had banks and beds of sand.

Master Planning Watercourse #35 (MP 35)

Watercourse MP 35 is located in the Bahawalpur district near the town of Dera Bakka. The farmers of village 31/BC receive their perennial water from a mogha which has a design discharge of 35 lps. The average inflow during the study period was 38 lps. There are no tubewells present.

One hundred nineteen culturable hectares are commanded by the watercourse. The area, shown in Figure A-4, is regularly laid out and quite compact, with the most distant field lying only 1830 m from the mogha. During the study, only the 975 m of main channel was considered to be sarkari khal, although probably from 600 to 1200 m of branches are also sarkari khal. The main channel was uniform, clean and well maintained. Only authorized nucca cuts were found leading to major branches. There are 13,200 m of total channels, or 111 m/ha.

Uncommanded sand dunes lay on the fringes of the command area, and the irrigated land is sandy loam, although the measured infiltration rate was only 2.3 cm/hr.

Twenty-two operators are served by the watercourse, giving an average holding size of about 5.2 ha. The 1976-77 cropping intensity was 117 percent, with 60 percent of the land cropped in the rabi season and 57 percent during kharif.

During the study period (April, 1978), farmers were harvesting wheat and cutting sugarcane. Most of the irrigation water was applied to fallow fields in preparation for cotton sowing.

Master Planning Watercourse #52 (MP 52)

Master Planning Watercourse #52 is located near the city of Moro in central Sind, and is within the command area of the Rohri canal. One hundred twenty-nine culturable hectares are commanded by outlet #8AR/52. Forty-two operators cultivate the land, giving an average holding size of about 3.2 ha.

The layout of the watercourse, depicted in Figure A-5, is irregular and no distinct sarkari khal exists. There is a 3020 m main channel and a 1220 m channel branching from the mogha which serves most of the cultivators. Both were taken as sarkari khal. The total length of channels is 16,300 m, or 126 m/ha.

The mogha, whose design discharge is 26 lps, flowed an average of 37 lps during the study, but was reported to have significantly higher discharges during other periods. (The canal was flowing lower than normal during the study period.) The higher flow rate has led to a 136 percent cropping intensity. Eighty-one percent of the land was cropped during the previous rabi, and 55 percent during the previous kharif.

During the study period of late April and early May, 1978, the farmers were busy threshing their wheat and paid little attention to their irrigation turns, so the warabundi was not followed closely. On two occasions the mogha was completely blocked to stop the water, sometimes it was partially blocked, and occasionally the water simply ran to the tail where it drained into a farmer's field or into a roadside pond. Irrigation was carried out haphazardly with farmers sometimes opening several nuccas and returning to the village. By the third week, the irrigation schedule had begun to return to normal as the cultivators were irrigating their fodder crops and applying pre-tillage irrigations and first irrigations to the kharif cotton crop.

A summary of the description of all watercourses is given in Table 1.

Table 1. Summary descriptions of the five studied watercourses.

	Watercourse					
	TW 81-R	TIK #1	MP 6	MP 35	MP 52	Ave.
Mogha Number	31574/R	RD89480/L	RD21000/L	4500-R	8AR/52	
Location (District)	Sarghoda	Faisalabad	Mianwali	Bahawalpur	Moro	
Commanded Culturable Area (ha)	148	166	150	119	129	142
Sarkari Khal Length (m)	3350	4880	3260	980*	4240	3342
Farmer's Branch Length (m)	19,650	25,120	15,000	12,220	12,060	16,810
Total Channel Length (m)	23,000	30,000	18,260	13,200	16,300	20,152
Percent Sarkari Khal (%)	15	16	18	7*	26	17
Length of Channel Per CCA (m/ha)	154	180	122	111	126	139
Number of Farmers	20	91	34	33	42	42
Average Holding Size (ha)	6.0	1.8	4.4	5.2	3.2	4.1
Annual Cropping Intensity (%)	174	174	119	117	136	144
Mogha Design Discharge (lps)	≈30	34	33	35	26	32
Average Measured Discharge (lps)	70**	41***	56	38	37	48
CCA per Design Discharge (ha/lps)	4.9	4.7	4.5	3.4	5.0	4.5
CCA per Measured Discharge (ha/lps)	2.1	4.0	2.7	3.1	3.5	3.1
Tubewells	1 (SCARP)	2 (Private)	None	None	None	
Soil Type	Silty Loam	Silty Loam	Sandy	Sandy Loam	Silty Loam	
Average Field Infiltration Rate (cm/hr)	≈1.0****	≈1.0****	26	2.3	7.1	

*Main channel length - sarkari khal was not delineated.
**30 lps from the mogha + 40 lps from the SCARP tubewell.
***Not including tubewell water which was not mixed with the canal water.
****Estimated from data in Precision Land Leveling Project (1974).

SECTION 3

PROCEDURE

Flow rates were measured with Cutthroat flumes (Skogerboe, et al., 1973) at the head of each watercourse below the mogha, at the outlet where the water flowed from the sarkari khal into the farmer's branch, and upstream of the nucca outlet to the field. Those flow measurements were collected continually during the complete warabundi turn rotation. Thus water which flowed into each watercourse was measured three times before it entered the irrigation field. The turn rotation cycle was one week on each watercourse. On MP 6, MP 35, and MP 52 watercourses, the measurement was continued for three consecutive warabundi cycles.

Flow readings were recorded approximately every five minutes during transient flow conditions and about every 15 minutes while the channel was flowing steadily. An attempt was always made to install the flume before the water arrived and to continue readings until channel drainage was complete.

The flume flow rate data for all three flumes was plotted on a flow hydrograph such as is shown in Figure 2. The plots were graphically integrated using a planimeter to determine the total volume of water passing through each flume over a given time period. Summing up the volume of water which entered the head of the watercourse, passed from the sarkari khal into the farmers' branches, and entered the field, allowed a direct volumetric calculation of the

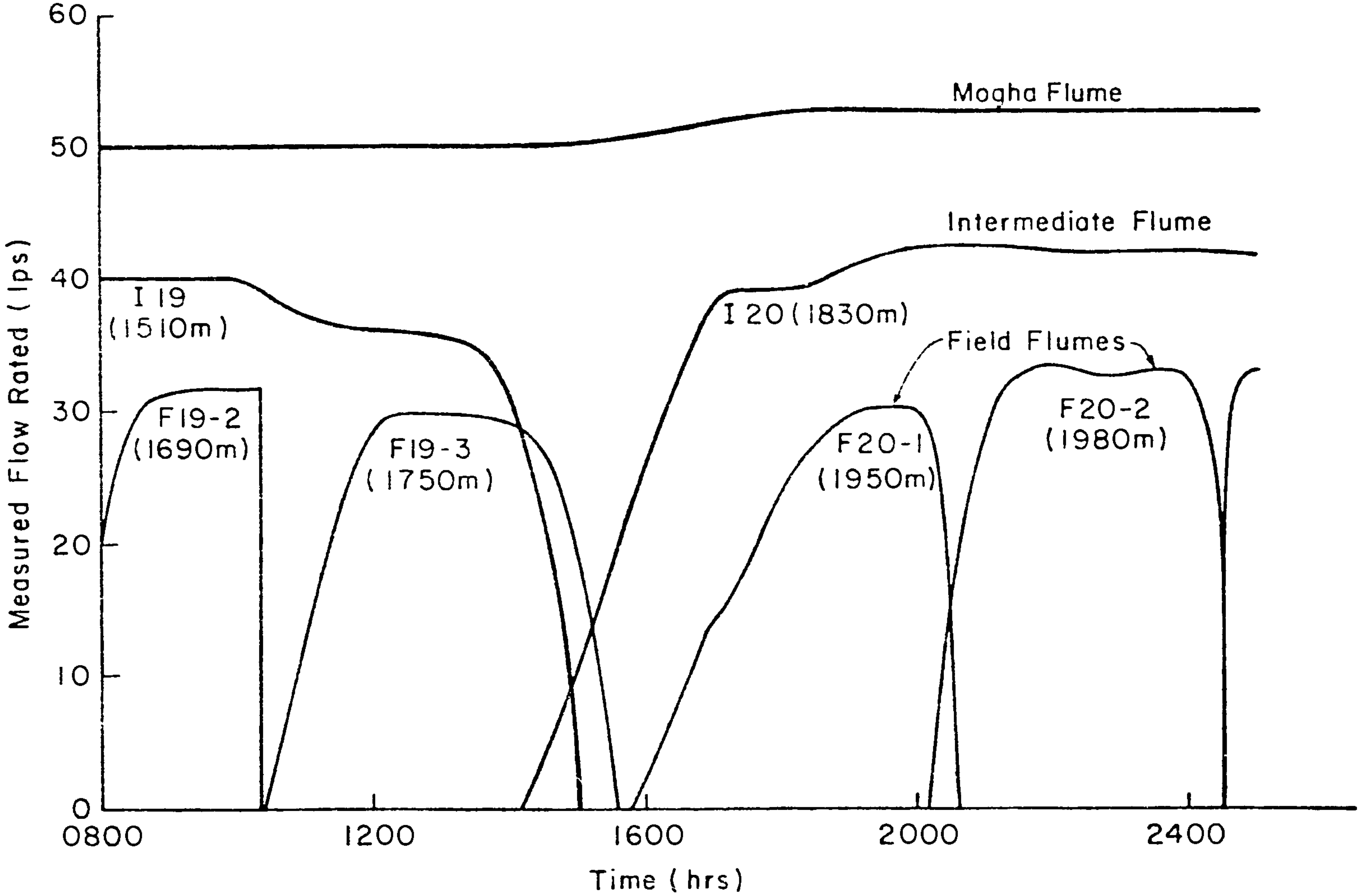


Figure 2. Flow hydrograph showing discharge through the mogha, intermediate, and field flumes over time during an operational loss study.

losses and conveyance efficiencies in each section of the watercourse.

Because one field flume was sometimes set to measure flow into more than one nearby field, the flumes were occasionally set as far as 150 m from the field nucca. Consequently, in such cases, there were additional conveyance losses beyond those measured in the field flume. The conveyance loss rate in the section above the field flume was determined and, when multiplied by the length of channel between the field flume and nucca, produced an estimate of the additional unmeasured water losses. These adjustments in the operational losses to the field resulted in an overall efficiency decrease of from 1 to 3 percentage points (percent of the inflow).

Any flow measuring device which creates a head loss in an open channel will raise the water level upstream of the device. Ponding loss measurements (Trout, 1979) indicate that loss rates in watercourse channels are sensitive to changes in flow depth. A flume installed in a watercourse channel would thus be expected to increase the water losses above the actual value which occurs in the channel without the flumes, especially in low gradient systems such as Indus Basin watercourses. The amount of this effect depends upon: a) the head loss in the flume (or other flow measuring device); b) the extension of the raised water level upstream, termed the backwater curve, which is a function of the channel hydraulic characteristics of flow rate, cross-sectional shape, roughness, and especially slope, and; c) the sensitivity of loss rates to depth changes.

To better understand the effect of flume head loss on water losses in a section, a theoretical analysis of flume induced losses was made utilizing iterative backwater calculations (Chow, 1959, p. 262) and an empirically derived exponential relationship, presented by Trout (1979), between loss rate and changes in flow depth. Thus, in a channel with specific hydraulic characteristics (which determine a certain backwater curve) the ratio of the measured to normal loss rate can be predicted in a channel section of a given length and a flume setting with a given head loss. The results of such an analysis for a channel with a typical cross-sectional shape described by a power curve shown in Figure 3, a flow rate (Q) of 45 lps, and three slope and head loss values, are given in Table 2. It can be seen from the table that watercourse loss measurements can be greatly affected by head loss in the flow measurement device, and this factor must be considered when making inflow-outflow measurements.

For analyses of inflow-outflow data which were sensitive to the flume induced losses, these effects were calculated and subtracted out by the same theoretical methods as were used to generate Table 2. A graph was generated of the ratio of measured (including flume induced) to normal loss rates vs. section length for a flume head loss of 6 cm and a slope of 0.5 m/km and the same hydraulic characteristics

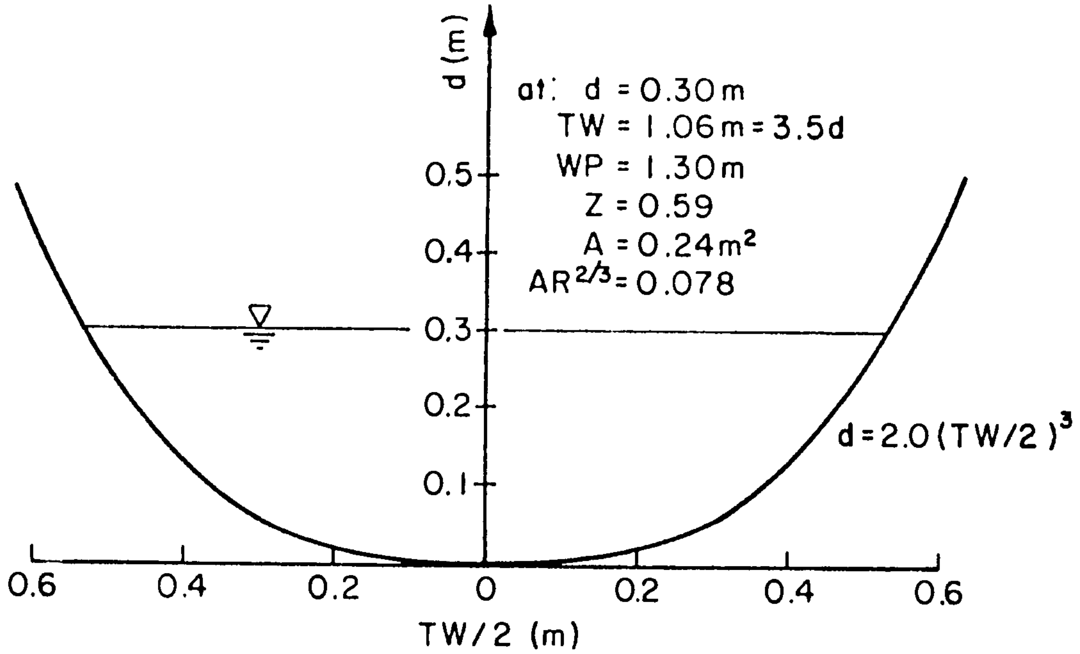


Figure 3. Channel cross-sectional shape used in the calculations for Table 2.

Table 2. Ratio of the measured water losses (including induced losses resulting from the head loss through the flume) to normal losses for a channel with the cross section shown in Figure 3, for varying channel slopes, flume head loss values, and measured section lengths (from Trout, 1979)*

Head Loss in Flume (cm)	Channel Slope (m/km)	Section Length (m)					
		200	500	1000	1500	2000	3000
3.3	.2	1.50	1.36	1.24	1.17	1.14	1.09
	.5	1.36	1.19	1.10	1.07	1.05	1.03
	.8	1.26	1.12	1.06	1.04	1.03	1.02
6.7	.2	2.36	1.98	1.63	1.34	1.23	1.16
	.5	1.99	1.53	1.28	1.18	1.14	1.09
	.8	1.71	1.35	1.18	1.12	1.09	1.06
10.0	.2	3.73	2.96	2.26	1.90	1.68	1.46
	.5	2.94	2.04	1.54	1.36	1.27	1.18
	.8	2.45	1.66	1.33	1.22	1.17	1.11

*For normal depth = 0.3 m, flow rate = 45 lps, roughness coefficients varied with slope to maintain a normal depth (d) of 0.078, and exponential coefficient value of the loss rate vs. depth relationship (Trout, 1979) of 0.15 cm^{-1}.

and cross-sectional shape as was used to generate Table 2. After testing several equations, it was decided that an exponential equation with an added constant factor best fit the curve, so through combined regression and trial-and-error techniques, an equation which minimizes the squares of the deviations in the commonly encountered section length range was derived. The best fit equation was:

$$\frac{Q_{LM}}{Q_{LN}} = 1.11 + 1.044e^{-0.209D} \tag{1}$$

where:

Q_{LM} = measured loss rate (lps/100m)

Q_{LN} = normal loss rate (lps/100m)

D = channel section length (100m)

The measured loss rates were thus adjusted for flume effects by the formula:

$$Q_{LA} = Q_{LM} \left(\frac{1}{1.11 + 1.044e^{-.209D}}\right) \tag{2}$$

where:

Q_{LA} = loss rates adjusted for flume induced losses (= Q_{LN}) (lps/100m).

Conveyance efficiencies were also adjusted by:

$$E_{CA} = 1 - (1 - E_{CM}) \left(\frac{1}{1.11 + 1.044e^{-209D}}\right) \tag{3}$$

where:

E_{CM} = measured conveyance efficiency, or the ratio of the measured outflow to the measured inflow

E_{CA} = conveyance efficiency adjusted for flume induced losses.

Although the actual adjustment required in each case will actually depend upon the particular channel conditions and flume setting, the flume adjustment (Eqs. 2 or 3) will at least allow an evaluation of the importance of the flume effects on the tested relationships.

Cutthroat flumes were chosen as the flow measurement device because they have been calibrated under submerged flow conditions and flow measurements can be made with less head loss than in most other devices. Engineers and field technicians were trained to set the 0.91 m (3 foot) length Cutthroat flumes used in collecting the data according to the channel conditions. If slopes and freeboards were small, and channel conditions were poor, the flumes were set to minimize the head loss and the flume induced excess losses. If channel conditions were good and slopes were greater, then the flume could be set for larger head losses in order to obtain a more accurate flow measurement. Flume head losses usually varied from 3 to 10 cm.

Regression analyses were made to relate the steady-state inflow-outflow loss measurements to fluctuations in the flow rate in the upstream flume, the length of the measured section and the relative slope of the section, as determined by the average channel slope from the watercourse head to the field.

Transient conveyance losses were defined as the difference between the losses which would have occurred had the system flowed constantly at steady state, and the actual measured losses. They were calculated by taking the difference between the product of the steady-state flow rate into a field and the rotation turn time utilized in irrigating that field, and the actual volume of water which entered the field. This calculation is shown graphically in Figure 4. Regression techniques were used to relate transient losses to lengths of channel filled and drained and the normal inflow rate.

One type of transient loss, dead storage, was estimated by measuring the top width and center depth of the water lying in the bottom of channels from which the inflow had been diverted, as soon as possible after drainage of the section was complete. Two readings were taken per 60 m length and the readings were averaged. The cross-sectional area of the sections were estimated by multiplying the product of the two dimensions by 0.75. This simplified method, which assumes the area is about half-way between a triangle and a rectangle (as indicated in Figure 5), was used as an approximation of the real, irregular cross-sectional shapes, since further accuracy would have demanded much more measurement and calculation time.

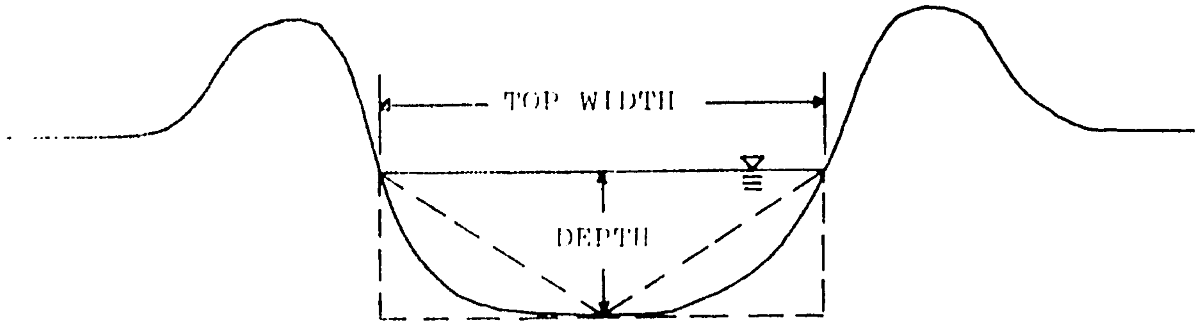
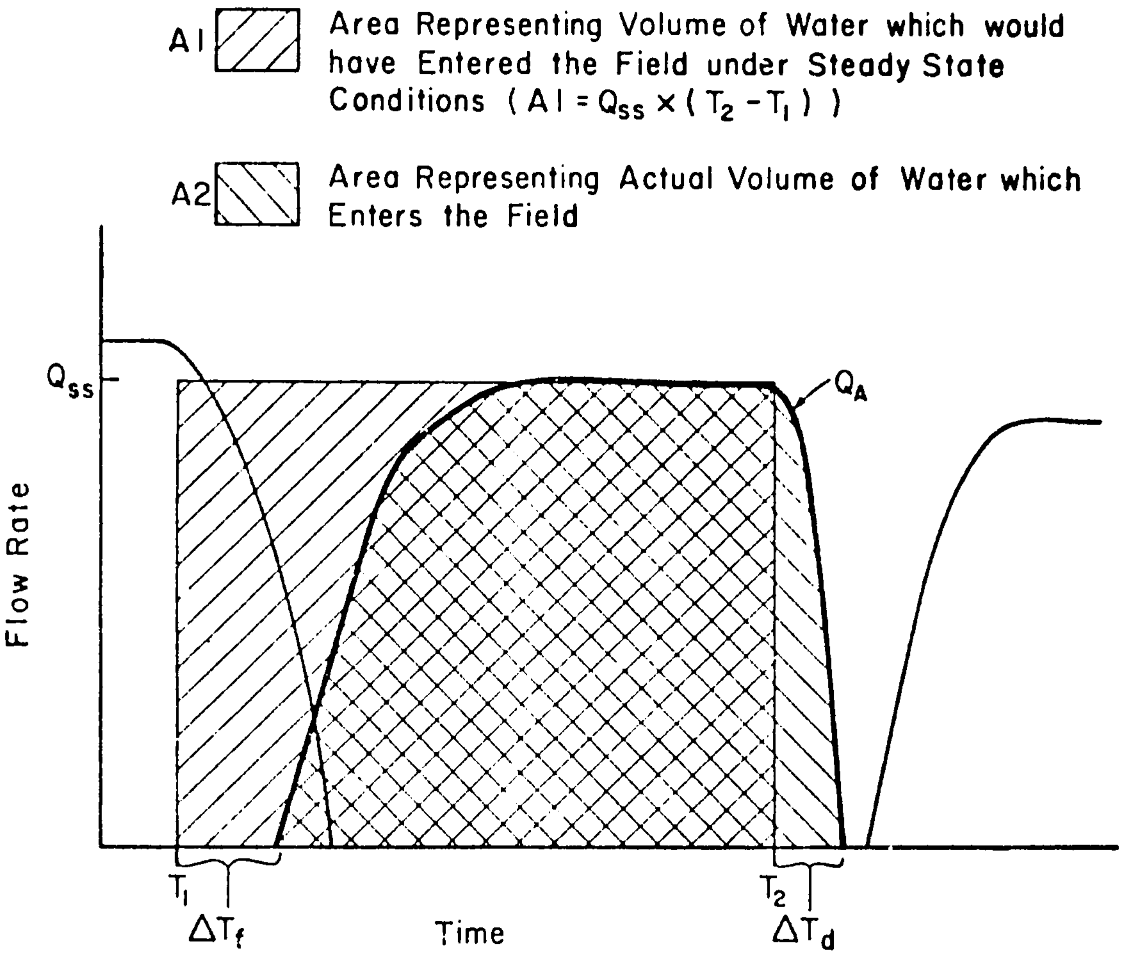


Figure 5. Illustration of the dead storage calculation simplifying assumption.



T_1 = Time Water Flow is Turned from Previous Field

ΔT_f = Time Consumed in Filling the Channel Leading to the Present Field

T_2 = Time Water Flow is Turned to the Following Field

ΔT_d = Drainage Time of Channel into the Field

Q_{ss} = Steady State Flow Rate

Q_A = Actual Flow Rate

Transient Loss (V_{TL}) = A1 − A2

Figure 4. Graphical depiction of the transient loss calculation.

Water volumes lost from short term outlet or bank breaks were estimated from the drop in the hydrograph (Fig. 2) from the steady-state flow rate during the time of the break. Infiltration tests were made in short channel sections to attempt to define the intake rate vs. time curve for watercourse channels so that volumes of water initially absorbed into the wetted perimeters of dry channels could be estimated, but the variability in the loss rates and antecedent moisture conditions was so great that no conclusions could be drawn.

Visible leakage through insect and rodent holes, poorly closed nuccas, and weak, thin banks were observed, and sometimes measured. Measurements were made by collecting a volumetric sample in a pan or by observing the increase in depth of a small known bunded area with time.

Evaporation from the flowing water surface was calculated utilizing estimates of water surface top widths and measurements of lengths of channels used, and pan evaporation rates measured at nearby meteorological stations.

Locations of each irrigated field and of the flumes were noted on maps. Also, the lengths of sarkari khal and farmers' branch channels utilized and filled or drained were recorded, so that channel usage could be determined.

A water use and cropping pattern survey of the farmers on TW 81-R and Tik #1 watercourses was made to determine their cropping patterns, yields, and perceived water usage and needs. The results of the survey were then compared to the physical measurements.

Soil moisture deficiencies were estimated for each irrigated plot on MP 6, MP 35, and MP 52 watercourses immediately preceeding each irrigation. One soil sample was collected from each plot up to a five foot depth and soil moisture deficiency was estimated for each one foot depth increment by the touch and feel method (Early & Clyma, 1976). This method was chosen because of the large number of evaluations involved (about 600 per watercourse) and the lack of available time. This moisture deficiency was then compared with the depth irrigated to determine the amount of over- or underirrigation for each field.

Application efficiency (E_a) in this study was defined as the total amount of water stored in the root zone divided by the total application, or

$$E_a = \frac{\text{Total Stored}}{\text{Total Applied}} = \frac{\text{Total Applied} - \text{Total Overapplication}}{\text{Total Applied}} \times 100 \qquad (4)$$

This value will give a measure of the total amount of water which is stored in the root zone, and that amount which percolates below the root zone (deep percolation).

In many cases, sufficient water is not applied to fully fill the crop root zone (i.e., the application is less than the soil moisture deficiency). Under these conditions, the application efficiency will be 100%, and a different parameter, called application completion (R) is used as an evaluative measure where:

$$R = \frac{\text{Total Volume Applied}}{\text{Volume Required to Fill the Root Zone}} \times 100 \qquad (5)$$

A water budget was constructed for each watercourse which graphically depicts where the water went which entered each watercourse and enables portions of the budget which could not be measured to be estimated.

In order to better understand the irrigation system and the relationship between various watercourse parameters and water losses, regression analyses were made between several of the measured values. These regressions were run on an individual field basis and all the data from each watercourse were analyzed together. Only linear relationships were sought, except in a few cases where the data, or theoretical considerations, indicated otherwise.

Because of the repetitive nature of the required calculations, and in order to insure against computational error, a Fortran computer program was written and utilized to do most of the data analysis. A description of the program is given by Trout and Naveed (1978).

Five watercourses were studied by these monitoring techniques. Tubewell 81-R watercourse was studied for one week with the assistance of engineers from the Mona Reclamation Experimental Project (MREP). Tikriwala #1 watercourse was also studied for one week with the assistance of students from the Department of Irrigation and Drainage at the University of Agriculture, Faisalabad (UAF), along with MREP engineers. The final three watercourses, MP 6, MP 35, and

MP 52, were each studied during three consecutive weeks by personnel of the Survey and Research Organization, Master Planning and Review Division, Water and Power Development Authority (WAPDA). Data listed in the following section of this report are the average of the three weeks of measurements. Weekly data is listed in the Appendix.

SECTION 4

RESULTS

During the weeks when the five watercourses were studied, an average of 55 percent of the inflow reached the fields. The most efficient watercourse, Tik #1, delivered 63 percent of its inflow to the fields, while TW 81-R, the SCARP tubewell supplemented watercourse, delivered only 44 percent of its inflow to the field nuccas. About 55 percent of the losses were from the sarkari khal channels. Watercourse conveyance efficiencies and losses are given in Table 3.

Farmers utilized an average of 1090 m of sarkari khal and 310 m of farmer's branch channels to deliver the water to their fields. Thus, 80 percent of the total channel used to reach the average field was sarkari khal. The average farmer's branch channel was full only 2 percent of the time and just over 50 percent of all branch channels were utilized during a one-week warabundi cycle. Nearly all sarkari khal channels were used each week, and the average sarkari khal section was full 36 percent of the time. Channel usage for each monitored watercourse is summarized in Table 4.

The percentage of the total sarkari khal length which was full a given percentage of the rotation time is shown in Figures 6, 7, 8 and 9 for four of the studied watercourses. The figures show that, when the sarkari khal is subdivided into several branches, each channel section is used less. On MP 6 watercourse, which has one main channel and a rectangular command area, channel usage is high, while on Tik #1

Table 3. Volumes of inflows and losses and conveyance efficiencies on the five operationally studied watercourses.

Watercourse Section	Volume of Inflow (m^3)	Conveyance Efficiency (%)	Volume of Losses (m^3)	Distribution of Losses (%)
TW 81-R				
Sarkari Khal	42,970	63	15,340	66
Farmers' Branches	27,130	70	8,080	34
Total to Fields	19,070	44	23,920	
TIK #1				
Sarkari Khal	24,970	84	4,020	44
Farmers' Branches	20,950	76	5,110	56
Total to Fields	15,840	63	9,130	
MP #6*				
Sarkari Khal	34,070	81	6,380	47
Farmers' Branches	27,690	74	7,150	53
Total to Fields	20,540	60	13,530	
MP #35*				
Sarkari Khal	23,290	80	4,560	50
Farmers' Branches	18,740	76	4,480	50
Total to Fields	14,260	61	9,040	
MP #52*				
Sarkari Khal	20,280	66	6,810	66
Farmers' Branches	13,470		3,580	34
Total to Fields	9,890	49	10,390	
Average				
Sarkari Khal	29,120	75	7,520	55
Farmers' Branches	21,600	75	5,680	45
Total to Fields	15,920	55	13,200	

*Average of three weeks (3 warabundi cycles) of data. Weekly data is given in Tables A-1, A-2 and A-3 of the Appendix.

Table 4. Utilization of watercourse channels on the five operationally studied watercourses.

Watercourse Section	Length of Channels Utilized (m^3)	Percent of Total Channels Utilized (%)	Weighted Average Channel Length Utilized (m)	Distribution of Usage (%)	Percent Time of Channel Usage (%)
TW 81-R					
Sarkari Khal	3400	100	1310	80	39
Farmers' Branches	7900	41	330	20	2
Total	11300	49	1640		7
TIK #1					
Sarkari Khal	4900	100	1155	80	24
Farmers' Branches	16800	67	290	20	1
Total	21600	72	1450		5
MP #6*					
Sarkari Khal	3260	100	1340	87	41
Farmers' Branches	8390	55	196	13	1
Total	11650	64	1535		8
MP #35*					
Sarkari Khal	980	100	436	50	44
Farmers' Branches	8480	69	445	50	4
Total	9450	72	875		7
MP #52*					
Sarkari Khal	3660	92	1220	80	31
Farmers' Branches	3350	27	300	20	2
Total	7010	43	1520		9
Average					
Sarkari Khal	3240	98	1090	75	36
Farmers' Branches	8980	52	310	25	2
Total	12200	60	1400		7

*Average of three weeks' (3 warabundi cycles) of data. Weekly data is given in Tables A-1, A-2, and A-3 of the Appendix.

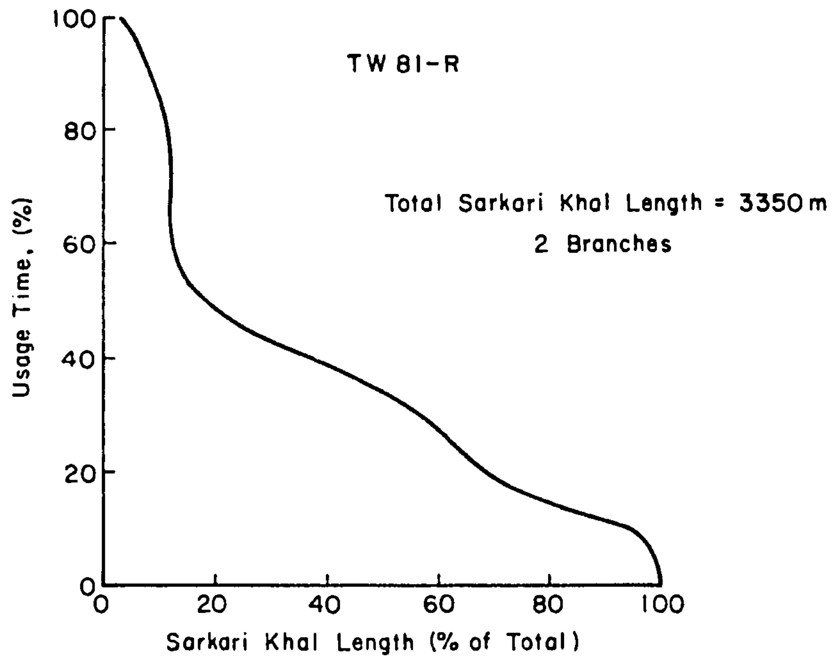


Figure 6. Normalized usage time vs. sarkari khal length for TW 81-R watercourse.

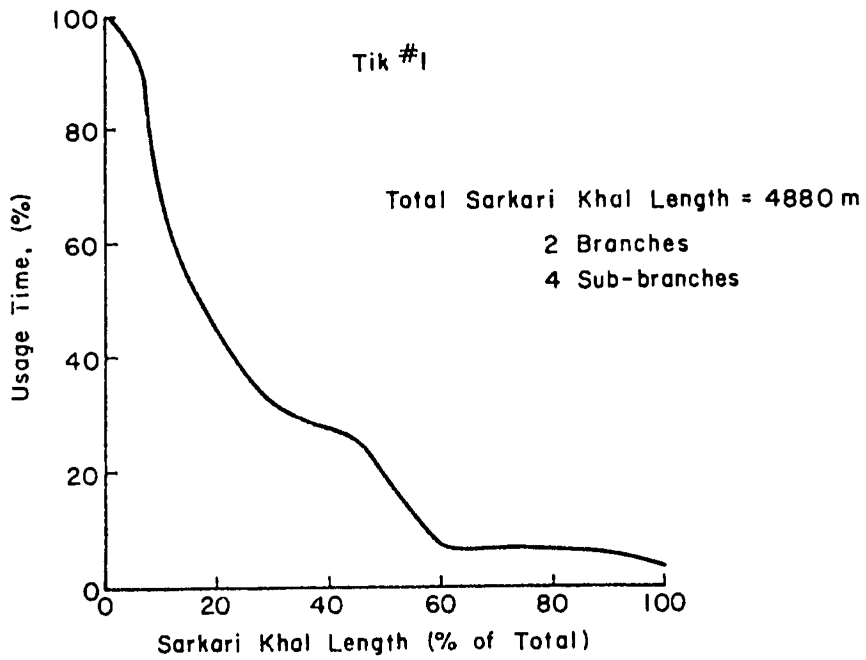


Figure 7. Normalized usage time vs. sarkari khal length for Tik #1 watercourse.

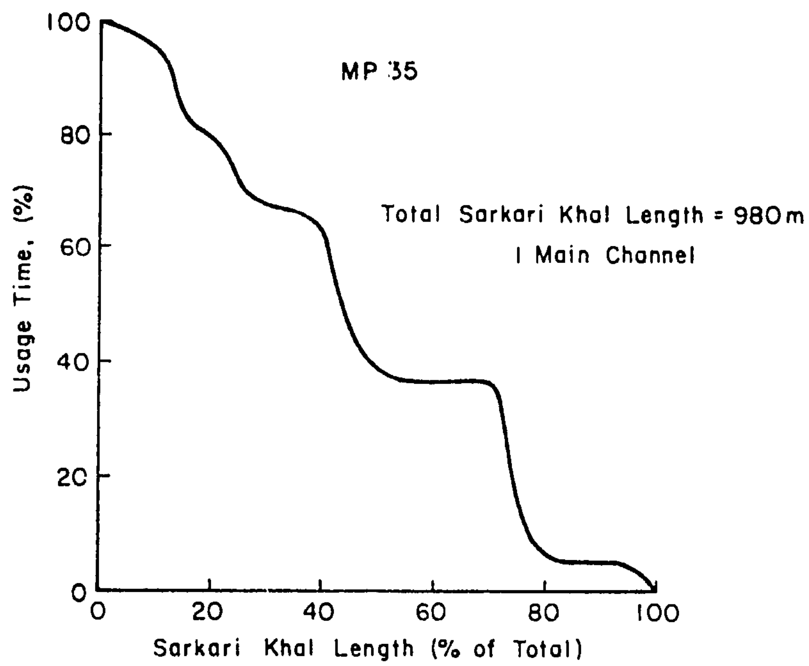


Figure 8. Normalized usage time vs. sarkari khal length for MP 35 watercourse.

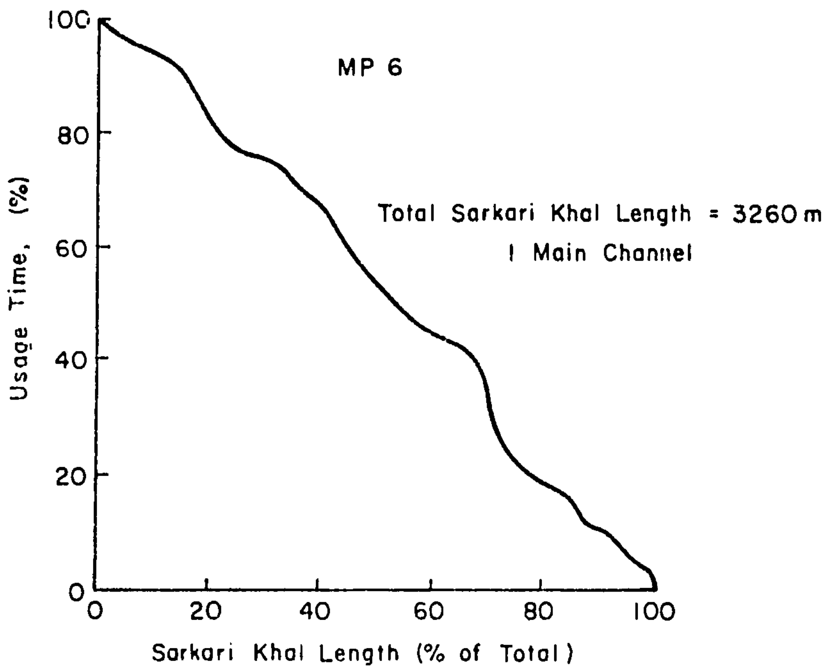


Figure 9. Normalized usage time vs. sarkari khal length for MP 6 watercourse.

watercourse which subdivides into several branches only 20 percent of the sarkari khal is full during at least half of the rotation period.

Steady-State Losses

Thirty-eight percent of the inflow, or 84 percent of the total losses, were steady-state type losses. Ninety-five percent of the sarkari khal losses were steady-state losses.

Weighted average steady-state loss rates in the farmers' branches were higher than in sarkari khal sections on four of the five watercourses, and averaged about double the water losses in the sarkari khal. On MP 6 watercourse, which irrigates sandy soil, the loss rate in the sandy branches was six times greater than the loss rate in the more often filled and silt-covered sarkari khal channels. Since the inflow rate to the farmers' branches is less than the watercourse inflow rate, due to the losses in the sarkari khal, the difference in percent losses per unit distance between the two types of channels is even greater than the absolute loss rate differences. Table 5 summarizes the steady-state losses for the studied watercourses.

One type of steady-state loss, evaporation from the water surface, can be estimated from measured pan evaporation data from the study areas. Table 6 gives the calculated water surface evaporation for each watercourse during the study period. Evaporation accounts for less than one percent of the total losses. Variability between surface evaporation values is due primarily to the varying pan evaporation values in different seasons and geographic locations.

Table 5. Steady-state losses on the five operationally studied watercourses.

Watercourse Section	Steady State Losses (%)	Weighted Average* Inflow Rate (lps)	Weighted Average* Steady State Loss Rate (lps/100m)	Weighted Average* Steady State Loss Rate (%/100m)
TW 81-R				
Sarkari Khal	34	71.0	1.86	2.5
Farmers' Branches	23	46.6	2.88	6.4
To the Field	49	36.1	2.13	2.9
TIK #1				
Sarkari Khal	16	41.2	0.56	1.2
Farmers' Branches	13	34.7	1.58	4.6
To the Field	28	30.5	0.74	1.9
MP #6**				
Sarkari Khal	19	56.3	0.79	1.3
Farmers' Branches	14	45.8	4.85	10.5
To the Field	33	39.3	1.16	2.0
MP #35**				
Sarkari Khal	17	38.5	1.69	3.9
Farmers' Branches	15	31.1	1.10	3.6
To the Field	33	26.3	1.40	3.6
MP #52**				
Sarkari Khal	34	37.1	1.07	2.8
Farmers' Branches	15	24.9	1.36	5.5
To the Field	45	21.2	1.12	3.0
Average				
Sarkari Khal	24	48.8	1.19	2.3
Farmers' Branches	16	36.6	2.35	6.1
To the Field	38	30.7	1.31	2.7

* Time weighted average.

**Values are the average of three weeks (3 warabundi cycles) of data. Weekly data is given in Tables A-4, A-5 and A-6 of the Appendix.

Table 6. Water surface evaporation from the five watercourses.

Watercourse	Total Channel Usage (m-hrs)	Pan Evaporation in/day	Pan Evaporation m/hr	Surface Evaporation[4] (m^3)	Percent of Inflow (%)	Percent of Losses (%)
TW 81-R	276,000	0.09[1]	.00010	37	0.1	0.1
TIK #1	243,000	0.23[2]	.00024	59	0.2	1.5
MP #6	258,000	0.37[3]	.00039	101	0.3	0.7
MP #35	147,000	0.55[3]	.00058	86	0.3	0.9
MP #52	230,000	0.47[3]	.00050	114	0.5	1.0
Average					0.3	0.8

[1]The average potential evapotranspiration measured at Mona during the first week in December.

[2]Pan evaporation at Faisalabad from March 21 to 28, 1974.

[3]1966-76 average pan evaporation data for April and May from Mianwali, Bahawalpur, and Sakrand meteorological stations, respectively.

[4]Assumes an average channel water surface width of 1 meter except at the larger TW 81-R watercourse where the average measured top width was 1.4 m.

Visible leakage which passes through watercourse banks or closed nuccas and wets the surface of surrounding fields or branch channels, was highly variable but never amounted to more than 5 percent of the total losses, or 3 percent of the inflow on any watercourse. The most visible leakage was observed on TW 81-R watercourse, where, in one poorly maintained 60 m section, 20 leaks losing nearly 3 lps of visible leakage was measured. Most observed leakage through watercourse banks were through small ant and worm holes which leak about 0.03 lps each. Occasionally, leakage through rat holes amounting to as much as 0.5 lps were observed. Nucca leakage often resulted from the cracking upon drying of the soils used to fill the outlet cuts. This was especially a problem on MP 52 watercourse, which was built from heavier textured soils, where 2 lps or 30 percent of the steady-state losses were measured leaking from 13 nuccas on one branch.

Both Tik #1 and MP 35 watercourses were well maintained and little visible leakage was observed. Any leakage through sandy MP 6 banks quickly washed out the bank.

The remaining steady-state losses infiltrate into the watercourse channel wetted perimeter. The steady-state loss rates can be converted to intake rates if the wetted perimeter lengths are known. On TW 81-R watercourse, wetted perimeter lengths were measured and averaged 1.8 m. On the other four watercourses, wetted perimeter lengths were estimated from a regression equation presented in Trout (1979):

$$WP = 3.9\left(\frac{Qn}{\sqrt{S}}\right)^{0.4} , \qquad (6)$$

where:

WP = wetted perimeter length (m),

Q = flow rate (m^3/sec),

n = roughness coefficient, and

S = slope.

Slope values of 0.0006 and n values of 0.04 were used in Equation 6 to calculate the wetted perimeter lengths listed in Table 7.

The calculated watercourse wetted perimeter average intake rates show no relationship with the intake rates of the surrounding fields. For example, on MP 6, the sandy fields have a very high water intake rate, while the silt-covered main channels have much lower rates. On TW 81-R watercourse, built in silty loam soils with very low intake rates, the average leakage rate into poorly maintained watercourse bed and banks was four times that into the field soils.

The weighted average values of loss rates given in Table 5 hides the wide variability which existed in loss rates on each watercourse. The large amount of data collected in these studies allowed loss rates to be correlated with other measured factors so that functional relationships with parameters which may affect loss rates could be determined.

Loss Rate as a Function of Inflow Rate Fluctuations

Inflow rates fluctuated sufficiently during the measurement period on three operationally studied watercourses (MP 6, MP 35, and MP 52), that the relationship between average loss rates over the measured section and inflow rates could be analyzed. Linear regressions of the data indicated that the

Table 7. Intake rates of the wetted perimeter soils on the five studied watercourses.

Watercourse	Average Flow Rate (m^3/sec)	Wetted Perimeter Length (m)*	Steady State Loss Rate (lps/100m)	Average Watercourse Intake Rate (cm/hr)	Intake Rate of Surrounding Fields (cm/hr)**
TW 81-R	.054	1.8	2.13	4.3	1
TIK #1	.036	1.3	0.74	2.0	1
MP #6	.048	1.5	1.16	2.8	26
MP #35	.032	1.2	1.40	4.2	2
MP #52	.029	1.2	1.12	3.4	7

*Estimated from Equation 6, except for TW 81-R which was measured.

**From Table 1.

relationship is direct, with a negative intercept. Table 8 lists the regression analysis results for the 3 data sets.

The consistently negative intercepts and positive slope values indicate that, since loss rates must approach zero at zero inflow rate, the true relationship must be curvilinear with a positive second derivative (concave upwards). So the loss rate data was logarithmically transformed and linearly regressed in order to fit it to exponential and power curve models. For two of the three operationally studied water-courses, regression of the transformed data resulted in higher coefficients of determination (r^2) than the linear regressions. The coefficient of the derived exponential equations listed in Table 8 have no physical meaning since Q_L must approach 0 at $Q_M=0$. However, the exponent coefficient does not depend on the chosen origin and should indicate the fractional change in loss rate with a unit change in inflow rate. Derived exponential coefficients vary from 0.029 to 0.091 and average 0.07. This indicates an average 7 percent increase in loss rate with each liter per second increase in inflow rate. The exponents of the derived power curve relationships, which will indicate the percent change in loss rate with a percent change in inflow rate were 4.35, 4.05, and 1.13, on MP 6, MP 35, and MP 52 watercourses, respectively.

Although the flume effect adjustment factor is a function only of distance, the adjustment (when made in the data) did consistently increase the coefficients of determination and probability of significance of the loss rate vs. inflow rate

Table 8. Derived linear and exponential regression equations relating steady-state loss rates (Q_L) to changes in the inflow rate (ΔQ_M).

Watercourse	Linear: Regression equation	Linear: r^2*	Linear: Sig.**	Exponential: Regression equation	Exponential: r^2*	Exponential: Sig.**
MP #6	$Q_L =-2.13+.061(\Delta Q_M)$	.269	>99%	$Q_L =.0042e^{.087(\Delta Q_M)}$	.149	>99%
	$Q_{L-A}=-1.13+.033(\Delta Q_M)$	.304	>99%	$Q_{L-A}=.0033e^{.083(\Delta Q_M)}$	.157	>99%
MP #35	$Q_L =-6.75+.220(\Delta Q_M)$	.480	>99%	$Q_L =.037e^{.091(\Delta Q_M)}$	.559	>99%
MP #35-ADJ	$Q_{L-A}=-3.64+.130(\Delta Q_M)$	.618	>99%	$Q_{L-A}=.017e^{.098(\Delta Q_M)}$	.622	>99%
MP #52	$Q_L =-0.70+.057(\Delta Q_M)$	.120	>99%	$Q_L =.400e^{.029(\Delta Q_M)}$	.140	>99%
MP #52-ADJ	$Q_{L-A}=-0.58+.045(\Delta Q_M)$	.214	>99%	$Q_{L-A}=.306e^{.031(\Delta Q_M)}$	.229	>99%

*Coefficient of determination.
**Level of significance.
***ADJ refers to data adjusted for flume effects by Equation 2.

fluctuation relationships. However, it did not have a large effect on the derived equation coefficients. Figure 10 shows the loss rate vs. inflow rate fluctuation data plus the derived regression curves for MP 6 watercourse.

Loss Rate as a Function of Distance from the Mogha

The relationship between average loss rate per unit distance (lps/100 m) and the length of the section was determined for all five operationally studied watercourses. Since each inflow-outflow measured channel section began at the mogha, the section length is also a measure of the average distance of the section from the watercourse head.

The analyses consistently indicated that loss rates decrease as distance from the mogha increases. The derived linear regression equations are given in Table 9. All of the equations are significant at the 95 percent level and indicate that loss rates decrease from 3 to 15 percent from the mean with each 100 meter increase in section length.

The measured inverse relationship could result from:

1. flume effects which cause more losses in shorter sections;
2. the biasing effect of shorter sections tending to include a higher proportion of farmers' branches which tend to have higher loss rates;
3. decreasing flow rates with distance from the mogha and the direct relationship between flow rates and loss rates; and/or
4. a tendency for reduced seepage rates into channels which lie farther from the mogha.

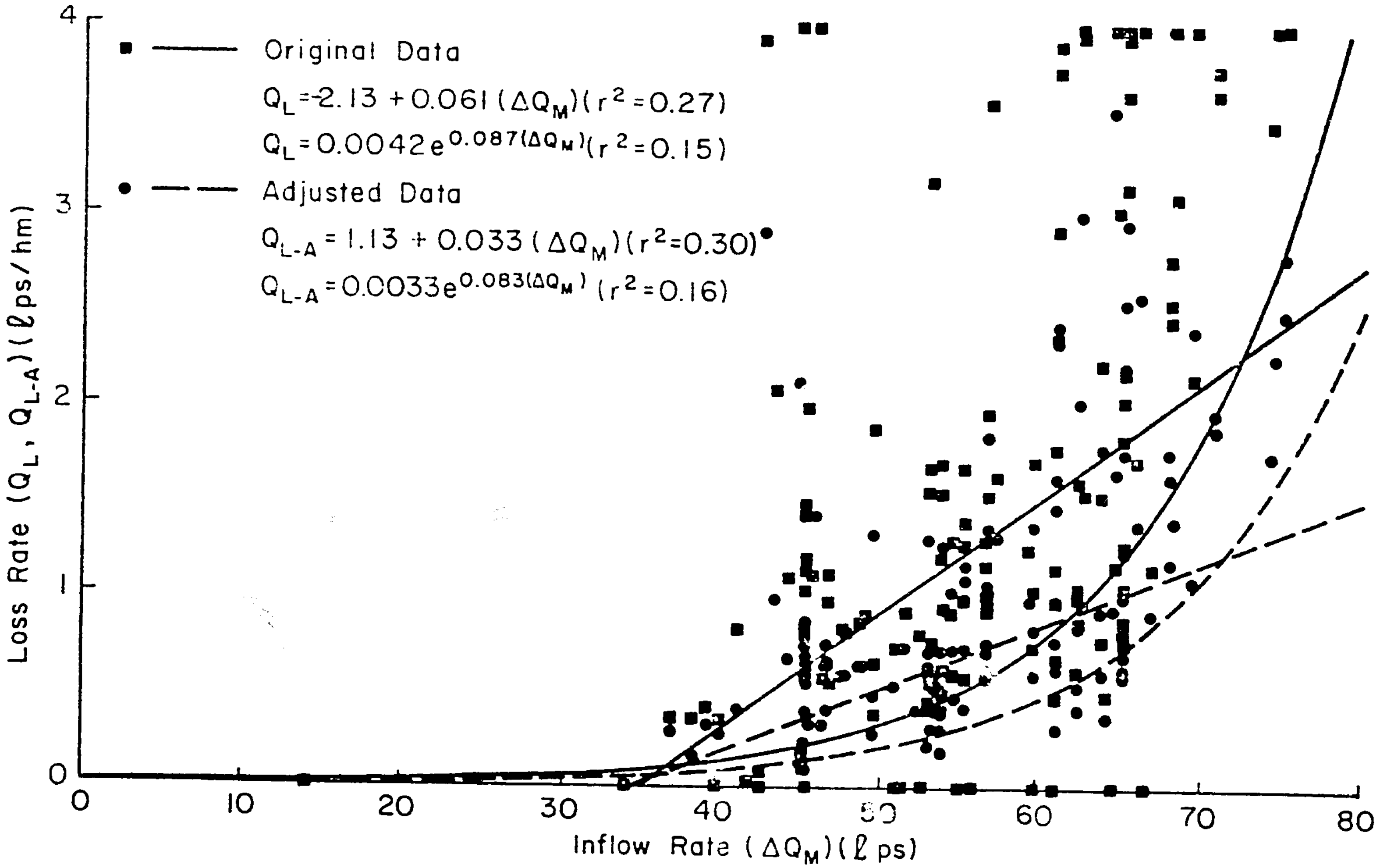


Figure 10. Steady-state loss rate (Q_L) vs. inflow rate changes (ΔQ_M) for MP 6 watercourse including derived linear and exponential regression curves.

Table 9. Average steady state loss rate (Q_L) as a function section length from the mogha (D).

Watercourse	Regression Equation Q_L (lps/100 m) D (100 m)	r^2	Sig.* (%)
TW81-R	[illegible]	[illegible]	> 99%
TW81-R-ADJ**	Q_{L-A}=4.07-.114D	[illegible]	> 99%
TW81-R-SK	Q_L=3.37-.102D_{SK}	.274	> 99%
TW81-R-SK-ADJ	Q_{L-A}=2.04-.033D_{SK}	.053	
TIK 1	Q_L=2.32-.093D	.250	> 99%
TIK 1-ADJ	Q_{L-A}=1.53-.054D	.244	> 99%
TIK 1-SK	Q_L=1.69-.076D_{SK}	.276	> 99%
TIK 1-SK-ADJ	Q_{L-A}=1.06-.041D_{SK}	[illegible]	> 99%
MP 6	Q_L=1.61-.030D	.029	> 95%
MP 6-ADJ	Q_{L-A}=0.65+.007D	.006	
MP 6-SK	Q_L=1.48-.050D_{SK}	.016	
MP 6-SK-ADJ	Q_{L-A}=0.63-.015D_{SK}	.006	
MP 35	Q_L=4.51-.304D	.150	> 99%
MP 35-ADJ	Q_{L-A}=2.61-.151D	.133	> 99%
MP 52	Q_L=2.62-.079D	.295	> 99%
MP 52-ADJ	Q_{L-A}=1.70-.041D	.232	> 99%
MP 52-SK	Q_L=8.74-.411D_{SK}	.229	> 99%
MP 52-SK-ADJ	Q_{L-A}=4.48-.209D_{SK}	.221	> 99%

*Level of significance.

**ADJ refers to data adjusted for flume effects by Equation 9.

In order to determine whether seepage rates really decrease with distance from the mogha, the effects of the first three factors must be cancelled out. First, the flume adjustment factor (Eq. 2) was applied to the data. This adjustment reduced the r^2 values and the coefficients of all the loss rate vs. distance from the mogha (Q_L vs. D) relationships. The flume adjustment reduced the coefficients relating Q_L to D by at least 40 percent, indicating that the relatively greater losses caused by flumes on short sections was a major factor in the derived Q_L vs. D relationship.

Second, the loss rates in different lengths of only sarkari khal sections were linearly regressed with section length on four watercourses: TW 81-R, Tik #1, MP 6, and MP 52. In all four cases, the r^2 value was reduced from the value derived with both sarkari khal and farmers' branch sections included. The coefficient relating Q_L to D was reduced by one-third to one-half compared to values derived utilizing flow in both types of sections on TW 81-R and Tik #1 watercourses, but on MP 52 and MP 6 watercourses, very high loss rates measured in short sarkari khal sections caused the coefficient to increase.

When both measurement biases are cancelled out, the slope coefficients on three of the watercourses are reduced to less than 50 percent of their initial value, but a significant inverse relationship still exists on 3 of the 5 watercourses.

In order to analyze the effect of decreasing flow rates with distance on loss rates, two relationships were assumed;

one where loss rate is proportional to flow rate, and the other where flow rate has no effect on loss rate. Since the data were collected on sections of various lengths which began at the mogha, the two relationships were integrated so that measured conveyance efficiencies could be correlated with the section length.

If loss rate ($Q_L = dQ/dD$) is proportional to flow rate (Q), then

$$\frac{dQ}{dD} = -K_1 Q. \tag{7}$$

Integrating:

$$\int_{Q_o}^{Q_F} \frac{dQ}{Q} = \int_0^D -K_1 dD,$$

$$\ln Q_F - \ln Q_o = -K_1 D,$$

$$Q_F/Q_o = e^{-K_1 D}, \tag{8}$$

where:

$\frac{dQ}{dD}$ = change of flow rate with distance, or loss rate,

K_1 = instantaneous fractional loss rate ($100m^{-1}$),

Q_o = initial flow rate (lps),

Q_F = final flow rate (lps), and

Q_F/Q_o = steady-state conveyance efficiency (E_c).

If flow rate is assumed not to affect loss rates, then:

$$\frac{dQ}{dD} = -K_2. \tag{9}$$

Integrating:

$$\int_{Q_o}^{Q_F} dQ = \int_0^D -K_2 dD,$$

$$Q_F - Q_o = -K_2 D,$$

$$(Q_F - Q_o)/Q_o = -(K_2/Q_o)D,$$

$$Q_F/Q_o = 1-(K_2/Q_o)D, \qquad (10)$$

where:

K_2 = loss rate (lps/100m), and

K_2/Q_o = loss rate as a fraction of initial flow rate ($100m^{-1}$).

Data for conveyance efficiency (and conveyance efficiency adjusted for flume effects) were regressed both linearly and exponentially with distance (D) to determine whether Equation 8 or Equation 10 best described the data. The results of the regression analyses are given in Table 10. The two models described the data equally well, with each giving higher r^2 values for some of the cases. This implies either that loss rate is between being constant and proportional to the normal flow rate; or that there is some other factor which tends to increase seepage rates at longer distances from the mogha and counters the effect of decreasing flow rates. Figure 11, which depicts the data and derived equations for watercourse MP 52, illustrates that the variability between values predicted by the two models is not great in the applicable distance ranges. This finding indicates that decreasing flow rates could explain a portion of the tendency for loss rates

Table 10. Derived linear and exponential regression equations relating conveyance efficiency (E) to distance from the mogha (D).

Watercourse	Linear Regression Equation	Linear r^2	Linear Sig.*	Exponential Regression Equation	Exponential r^2	Exponential Sig.*
TW 81-R	$E=.58-.005D$	.027		$E=.62e^{-.020D}$	.046	
TW 81-R-ADJ**	$E_A=.70-.009D$	.075		$E_A=.73e^{-.019D}$	.078	
TW 81-R-SK	$E=.91-.018D_{SK}$	.194	95%	$E=1.02e^{-.035D_{SK}}$	.154	> 95%
TW 81-R-SK-ADJ	$E_A=.96-.018D_{SK}$	.242	95%	$E_A=1.03e^{-.020D_{SK}}$	.190	> 95%
Tik 1	$E=.81-.005D$	.044	99%	$E=.80e^{-.006D}$	.035	> 95%
Tik 1-ADJ	$E_A=.88-.007D$	.124	99%	$E_A=.88e^{-.009D}$	.122	> 99%
Tik 1-SK	$E=.87-.003D_{SK}$	.026	95%	$E=.86e^{-.003D_{SK}}$	.018	
Tik 1-SK-ADJ	$E_A=.92-.004D_{SK}$	.096	99%	$E_A=.92e^{-.005D_{SK}}$	.085	> 99%
MP 6	$E=.93-.013D$	.242	99%	$E=.96e^{-.023D}$	.231	> 99%
MP 6-ADJ	$E_A=1.01-.013D$	.431	99%	$E_A=1.05e^{-.019D}$	.396	> 99%
MP 6-SK	$E=.99-.012D_{SK}$	.269	99%	$E=1.02e^{-.017D_{SK}}$	.325	> 99%
MP 6-SK-ADJ	$E_A=1.01-.011D_{SK}$	.325	99%	$E_A=1.04e^{-.016D_{SK}}$	.301	> 99%
MP 35	$E=.92-.011D$	.168	99%	$E=.92e^{-.015D}$	.178	> 99%
MP 35-ADJ	$E_A=.98-.012D$	.314	99%	$E_A=.99e^{-.015D}$	.329	> 99%
MP 52	$E=.77-.012D$	.516	99%	$E=.80e^{-.023D}$	.400	> 99%
MP 52-ADJ	$E_A=.86-.013D$	.665	99%	$E_A=.89e^{-.023D}$	.637	> 99%
MP 52-SK	$E=.81-.012D_{SK}$	.398	99%	$E=.82e^{-.022D_{SK}}$	.377	> 99%
MP 52-SK-ADJ	$E_A=.90-.015D_{SK}$	.619	99%	$E_A=.93e^{-.023D_{SK}}$	.583	> 99%

*Level of significance.

**ADJ refers to data adjusted for flume effects by Equation 10.

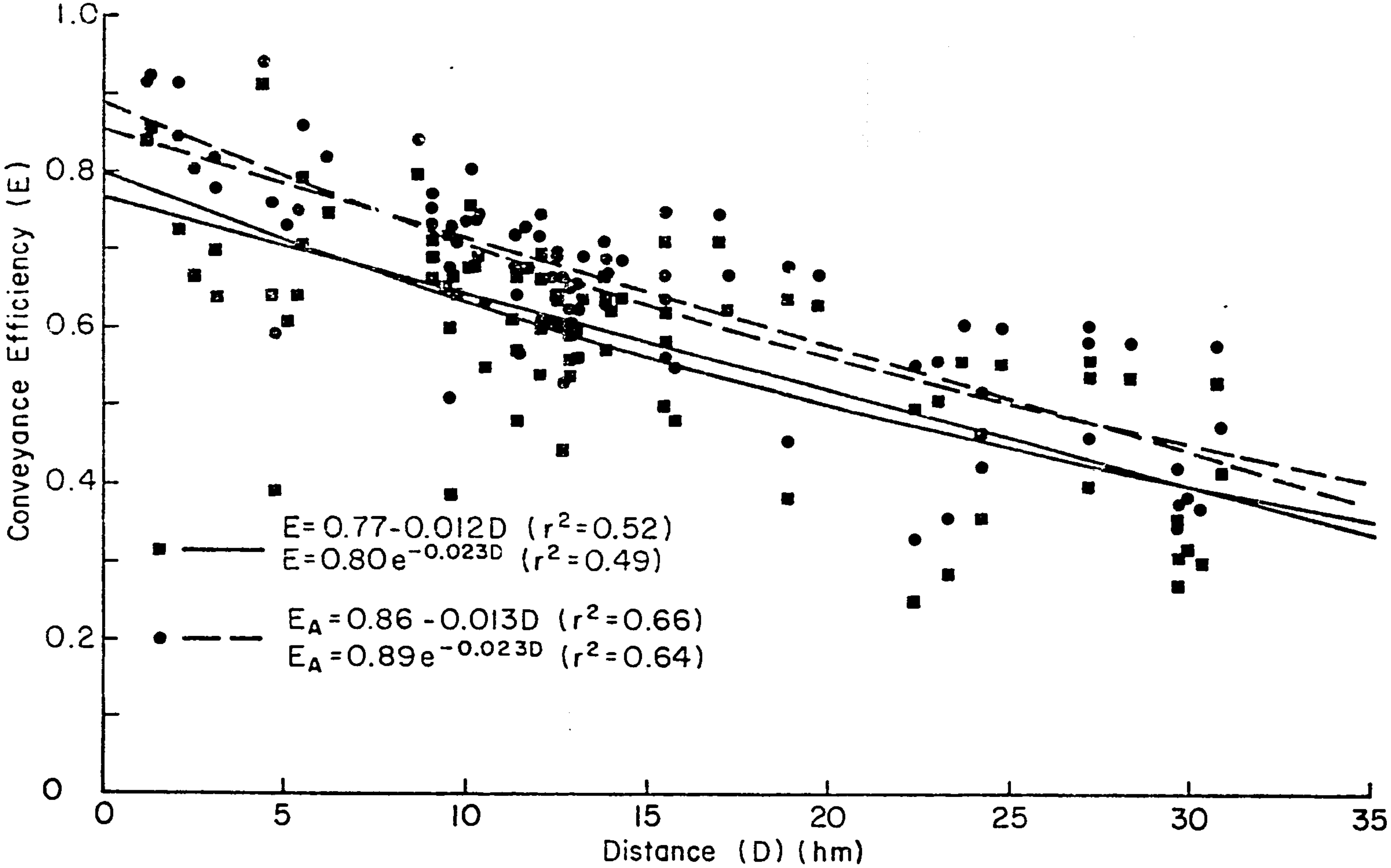


Figure 11. Conveyance efficiency (E) and conveyance efficiency adjusted for flume effects (E_A) versus conveyance distance (D) for MP 52 watercourse.

to decrease with distance, but doesn't prove that the effect is significant.

Trout (1979), found that the relationship between loss rates and normal inflow rate is best described by a power curve of the form:

$$Q_L = KQ^P, \qquad (11)$$

where K is an empirical coefficient and the exponent, P, indicates the percent change in loss rate with a percent change in normal flow rate. When loss rates are related to flow rates by this power curve with P values of 0.7 to 0.9 as derived by Trout (1979), loss rates decrease about 0.02 to 0.04 lps/100 m for each 100 m decrease in D.

One unexpected but consistent finding is that both the derived linear and exponential equations relating conveyance efficiency to distance predict efficiencies significantly below 1.0 (100%) at zero distance. The average derived intercept value from the linear correlation is 0.80, while the intercept of the exponential model averages a slightly higher value (as would be expected) of 0.82. The fact that the intercepts are significantly below 1.0 indicates that the loss rates would decrease with distance even if conveyance efficiencies do decrease linearly with distance, since the slope of a line connecting the value 1.0 at the intercept and a point at a distance, D, on the line depicting conveyance efficiency vs. distance will give the negative of the average loss rate ($100m^{-1}$) to that distance.

Flume effects would tend to cause the intercepts to be less than unity, and when the data is adjusted for flume induced losses, the mean intercepts are raised to 0.89 and 0.91 for the linear and exponential models, respectively. When the biasing effect of shorter section lengths containing a higher proportion of farmer's branch, is also cancelled out, by considering loss rates only on sarkari khal sections, the intercepts again increased with the average being 0.95 and 0.98 for the linear and exponential cases, respectively.

In summary, the indication of the inflow-outflow data that loss rates decrease with distance is concluded to be primarily the result of the projected conveyance efficiencies at 0 distance being less than 1.0. Flume effects and channel type (sarkari khal vs. farmer's branch) biases in the measurement process is seen to explain much of this result, which also reduces the significance of the loss rate-distance relationship. The decreasing flow rates with distance which should, according to Equation 11, tend to cause loss rates to decrease with distance, can explain a portion of the remaining decrease. The portion of the inverse relationship left unexplained on some watercourses could be the result of a high loss rate in the initial sections below the mogha. It also indicates the possibility that the flume effects are larger than has been assumed. In the light of the derived relationships shown in Table 10, it is not believed that seepage rates into watercourse wetted perimeters decrease with increasing distance of the channel section from the mogha.

Loss Rate as a Function of Channel Slope and Elevation Drop

An additional factor which could tend to affect steady-state loss rates and which was monitored during the operational studies, is the relative elevation drop from the mogha to the field. This factor will affect both the average slope of the water channel to the field; and the increased flow depth in a channel resulting from the backwater effects of a relatively high field being irrigated. Table 11 lists linear regression equations derived for the five operationally studied watercourses relating loss rate to average slope from the mogha to the field, S(m/km), and absolute elevation drop from the mogha to the field, EL(m). Since distance from the mogha to the field, D, is, as would be expected, highly correlated with EL, and loss rate has been seen to be inversely related to D, the distance factor was added to the correlations to separate out the indirect effects of the distance factor.

Although loss rates consistently decrease as the elevation drop to the field increases, most of this result on three of the five watercourses is seen to result primarily from the intercorrelation with distance, since adding the EL factor to the relationship between Q_L and D tends to increase the r^2 value very little.

The slope factor is directly related to loss rates for four of the five watercourses, although the one inverse relationship is highly significant. Again, only in two of the five cases does slope add significantly to the predictability of Q_L after distance effects have already been taken into account.

Table 11. Derived linear regression equations describing the relationship between loss rate (Q_L) and slope (S), elevation drop (EL), and distance (D), for the five operationally studied watercourses.

Watercourse	Independent Variable	Regression Equation	r^2	Sig.*
TW 81-R	S (m/km)	Q_L=4.27-2.88S	.35	> 99%
	EL (m)	Q_L=4.17-0.113EL	.66	> 99%
	D (hm)	Q_L=4.18-0.116D	.49	> 99%
	S and D	Q_L=6.40-2.46S-.125D	.69	> 99%
	EL and D	Q_L=4.17-0.133EL+.003D	.66	> 99%
Tik 1	S (m/km)	Q_L=0.91+0.245S	.003	
	EL (m)	Q_L=4.73-0.731EL	.186	> 99%
	D (hm)	Q_L=2.51-0.135D	.275	> 99%
	S and D	Q_L=2.01+0.770S+0.106D	.307	> 99%
	EL and D	Q_L=7.68-1.796EL-0.161D	.294	> 99%
MP 6	S (m/km)	Q_L=1.20+0.280S	.008	> 90%
	EL (m)	Q_L=1.78-0.670EL	.051	> 99%
	D (hm)	Q_L=2.19-0.061D	.102	> 99%
	S and D	Q_L=2.13+0.093S-0.061D	.103	> 99%
	EL and D	Q_L=2.25-0.274EL-0.061D	.109	> 99%
MP 35	S (m/km)	Q_L=1.37+0.984S	.037	> 99%
	EL (m)	Q_L=6.32-8.037EL	.173	> 99%
	D (hm)	Q_L=4.51-0.304D	.150	> 99%
	S and D	Q_L=5.66-0.696S-0.365D	.160	> 99%
	EL and D	Q_L=6.93-6.089EL-0.213D	.236	> 99%
MP 52	S (m/km)	Q_L=0.37+1.438S	.639	> 99%
	EL (m)	Q_L=2.11-0.578EL	.017	> 95%
	D (hm)	Q_L=3.16-0.091D	.290	> 99%
	S and D	Q_L=0.68+1.355S-0.030D	.643	> 99%
	EL and D	Q_L=3.04+0.187EL-0.121D	.292	> 99%

*Level of significance.

It is concluded that local relatively high fields tend to increase loss rates, probably the result of increasing the water level in the channel, but that the overall effects of the topography on loss rates are more complicated than can be described by slope or elevation drop.

Transient Losses

On each of the watercourses, between 5.7 and 8.4 percent of the inflow, or 12 to 23 percent of the losses, were transient-type losses. This amounted to an average of 0.16 m^3 per meter of channel filled and drained. Weekly transient loss totals for each watercourse are listed in Table 12.

Transient losses which occurred during the irrigation of a particular field were closely related to the amount of channel filled or drained in the process. Linear regression equations relating transient losses to these lengths for each watercourse are given in Table 13. The r^2 values indicate that between half and three-fourths of the variability in transient losses can be explained in terms of these lengths for a given watercourse. The equation coefficients indicate that from 0.14 to 0.31 m^3 of water is lost for each meter of watercourse that a farmer has to fill in order to reach his fields, and as much as half of that water is regained when the channels are drained.

Variability in transient losses per unit channel filled between watercourses can best be related to the watercourse inflow rate. The two coefficients of each of the derived equations listed in Table 13 were regressed with the average inflow rates to the watercourse. The resulting predictive relationships are:

Table 12. Transient losses on the five operationally studied watercourse systems during one warabundi turn rotation.

	Watercourse					Average
	TW81-R	Tik 1	MP 6*	MP 35*	MP 52*	
Total transient losses:						
Total volume (m^3)	2975	2086	2296	1271	1271	1980
Percent of inflow (%)	6.9	8.4	6.7	5.7	6.3	6.8
Percent of total losses (%)	12.4	22.[illegible]	17.0	14.0	12.2	16.4
Per channel length (m^3/m)	0.263	0.096	0.197	0.132	0.127	0.163
Per channel length per unit inflow ($m^3/m/(m^3/sec)$)	3.70	2.32	3.50	3.43	3.78	3.35
Dead storage:						
Total volume (m^3)	1308	1283	494	827	1073	997
Percent of inflow (%)	3.0	5.1	1.4	3.6	5.3	3.7
Percent of total losses (%)	5.5	14.0	6.8	10.9	9.8	9.4
Percent of transient losses (%)	44.0	61.5	17.0	65.0	84.4	55.1
Per channel length (m^3/m)	0.116	0.059	0.040	0.086	0.101	0.080
Per channel length per unit inflow ($m^3/m/(m^3/sec)$)	1.63	1.43	0.71	2.23	3.01	1.80
Major Bank and Nucca Breaches:						
Total volume (m^3)	nm**	0	822	38	86	237
Percent of inflow (%)		0	2.4	0.2	0.4	0.7
Percent of losses (%)		0	6.0	0.4	0.8	1.8
Percent of transient losses (%)		0	35.8	3.0	6.7	11.4

*Values are the average of three weeks (three warabundi cycles) of data collection. Weekly data is given in Tables A-4, A-5, and A-6 of the Appendix.

**Not measured.

Table 13. Regression equations describing the relationship between transient losses (V_{TL}) and the length of channel filled (L_W) and drained (L_D) to irrigate each field.

Watercourse	Regression equation	Coefficient of determination (r^2)
TW81-R	$V_{TL} = -15.0 + 0.31\ L_W - 0.10\ L_D$	0.58
Tik 1	$V_{TL} = 3.1 + 0.14\ L_W - 0.06\ L_D$	0.52
MP 6	$V_{TL} = 0.3 + 0.21\ L_W - 0.04\ L_D$	0.59
MP 35	$V_{TL} = 2.6 + 0.16\ L_W - 0.07\ L_D$	0.77
MP 52	$V_{TL} = 21.0 + 0.15\ L_W - 0.08\ L_D$	0.70

$$b_{LW} = -.03 + .0047\ Q_M \qquad (r^2=.94),$$

$$b_{LD} = \ \ .05 + .0005\ Q_M \qquad (r^2=.10),$$

$$\Delta b_L = -.08 + .0042\ Q_M \qquad (r^2=.96),$$

where:

b_{LW} = the L_W regression slope coefficient (from Table 13) - the volume of loss per unit length of channel filled (m^3/m)

b_{LD} = the L_D regression slope coefficient (from Table 13) - the volume of water regained per unit length of channel drained (m^3/m)

Δb = $b_{LW} - b_{LD}$ = the volume of water loss per length of channel filled and drained (m^3/m)

The intercept of the first equation, which has a very high r^2 value, is relatively small compared to the second term, thereby indicating that the transient losses per unit length of channel filled is nearly proportional to the flow rate. The poorly correlated second equation's intercept value is relatively large compared to the second term, indicating that the water regained by draining a certain length of channel is much less sensitive to the inflow rate. Channel storage water regained will be strongly affected by the local topography, which influences how much of the water drains into the field and what portion remains in the channel as dead storage.

During a complete rotation turn on a watercourse, the length of channel filled and drained will be equal; therefore, the third equation will be most useful in predicting watercourse transient losses. According to the highly-correlated regression equation, watercourse transient losses can be estimated by:

$$V_{TL} = (-.08 + .0042\ Q_M)L, \tag{12}$$

where:

V_{TL} = transient losses (m^3),

Q_M = normal inflow rate (lps), and

L = length of channel filled and drained (m).

This derived equation underestimates the measured transient losses listed in Table 12 by 5 to 40 percent (with an average of 25%) due to the fact that the constants of the original equations (Table 13) were ignored. The linear equation is not valid at low flow rates (<20 lps) where no transient losses are predicted.

Additional variation between values given in Table 2 for transient loss per meter length per lps inflow for each watercourse can be explained by the difference in steady-state loss rates for each watercourse. As the steady-state loss rate increases by one percentage point, the average slope coefficient value of Eq. 12 increases by 1½ percent of its value.

An average of 55 percent of the transient losses were dead storage on the five watercourses. Watercourse MP 6 was a sandy watercourse with high seepage rates in the farmers' branches, allowing much of the dead storage water to seep away before measurements could be made, so the value for MP 6 is an underestimation of the true dead storage. Generally, less than 5 percent of the watercourse inflow is lost to dead storage, which would usually amount to less than 7 percent of the water delivered to the farmers' branch. The average cross-sectional area of dead storage on the five watercourses was 800 cm^2. Dead storage losses for the studied watercourses are listed in Table 12.

Dead storage cannot be explained as well as transient losses in terms of length of channel utilized, inflow rate, or loss rate. It is highly dependent upon the topography of the watercourse command area. If slopes are large and fairly uniform, most water will drain from the channels into the fields.

Losses resulting from short-term bank and nucca breaks were a major form of transient loss on MP 6 watercourse. This was primarily due to the sandy bank soils which easily washed out and made washouts difficult to repair. Sixteen times during the three study weeks major breaks, which often required an hour to repair, were recorded.

Two major breaks occurred on MP 52 watercourse which amounted to 7 percent of the transient losses. No bank or nucca breaks were recorded on Tik #1 watercourse. Such losses averaged about 10 percent of the total transient losses and less than one percent of the inflow.

The remaining transient losses were the result of high infiltration rates into dry watercourse banks and losses which occurred during the movement of water from field to field.

Field Irrigation Applications

Farmers irrigated 16 percent of their land with an average depth of 7.6 cm of water during each week's warabundi cycle. Data for each watercourse is presented in Table 14.

Table 14. Field irrigation application data for the five operationally studied watercourses.

	TW 81-R	TIK #1	MP #6*	MP #35*	MP #52*	Average
Total Area Irrigated (ha)	22.7	33.6	20.6	21.1	14.8	22.6
Percent of CCA[1] Irrigated (%)	15	20	14	18	11	16
Number of Bunded Units Irrigated	99	150	402	201	116	194
Average Size of Bunded Units (ha)	0.23	0.23	0.05	0.11	0.13	0.15
Average Water Depth Applied (cm)	8.7	5.7	10.0	6.8	6.8	7.6
Total Volume Irrigated (m^3)	19070	15840	20540	14260	9890	15920
Total Volume of Over-Irrigation (m^3)	nm[2]	nm	14570	3370	1560	6500
Total Volume of Under-Irrigation (m^3)	nm	nm	140	1590	3430	1032
Application Efficiency (%)	nm	nm	29.1	76.2	84.4	63.2

*Values are the average of three weeks (3 warabundi cycles) of data. Weekly data is given in Table A-7 of the Appendix.
[1]Commanded culturable area.
[2]Not measured.

Soil moisture deficiencies were estimated on each field before irrigation on MP 6, MP 35, and MP 52 watercourses, allowing an estimation of the over- and underirrigation on each field. Application efficiencies varied from 29 percent on sandy MP 6 watercourse, to 84 percent on MP 52 watercourse where 58 percent of the fields were underirrigated.

Figures 12, 13 and 14 depict the distribution of fields which were over- and underirrigated by given percentages of the soil moisture deficiency.

On watercourse MP 6, more depth of water was applied on 90 percent of the fields than was required to fill the root zone to field capacity. The average overirrigation on a per field basis was 37 percent and the true overall application efficiency (as defined by Eq. 4) was 29 percent. On watercourse MP 35, 64 percent of the fields were overirrigated. Total application efficiency was 76 percent, while the average percent irrigation completion on the underirrigated fields was 74 percent. On watercourse MP 52, 42 percent of the fields were overirrigated. Total overirrigation was 16 percent of the nucca inflow, giving an application efficiency of 84 percent. The average percent irrigation completion (R in Eq. 5) was 62 percent. Overall, on the three watercourses over the studied weeks, 13 percent of the fields were irrigated within 10 percent of the soil moisture deficiency (application efficiency or percent completion greater than 90 percent), 26 percent of the fields within 20 percent, 41 percent within 30 percent, and 53 percent within 40 percent above or below the soil moisture deficiency.

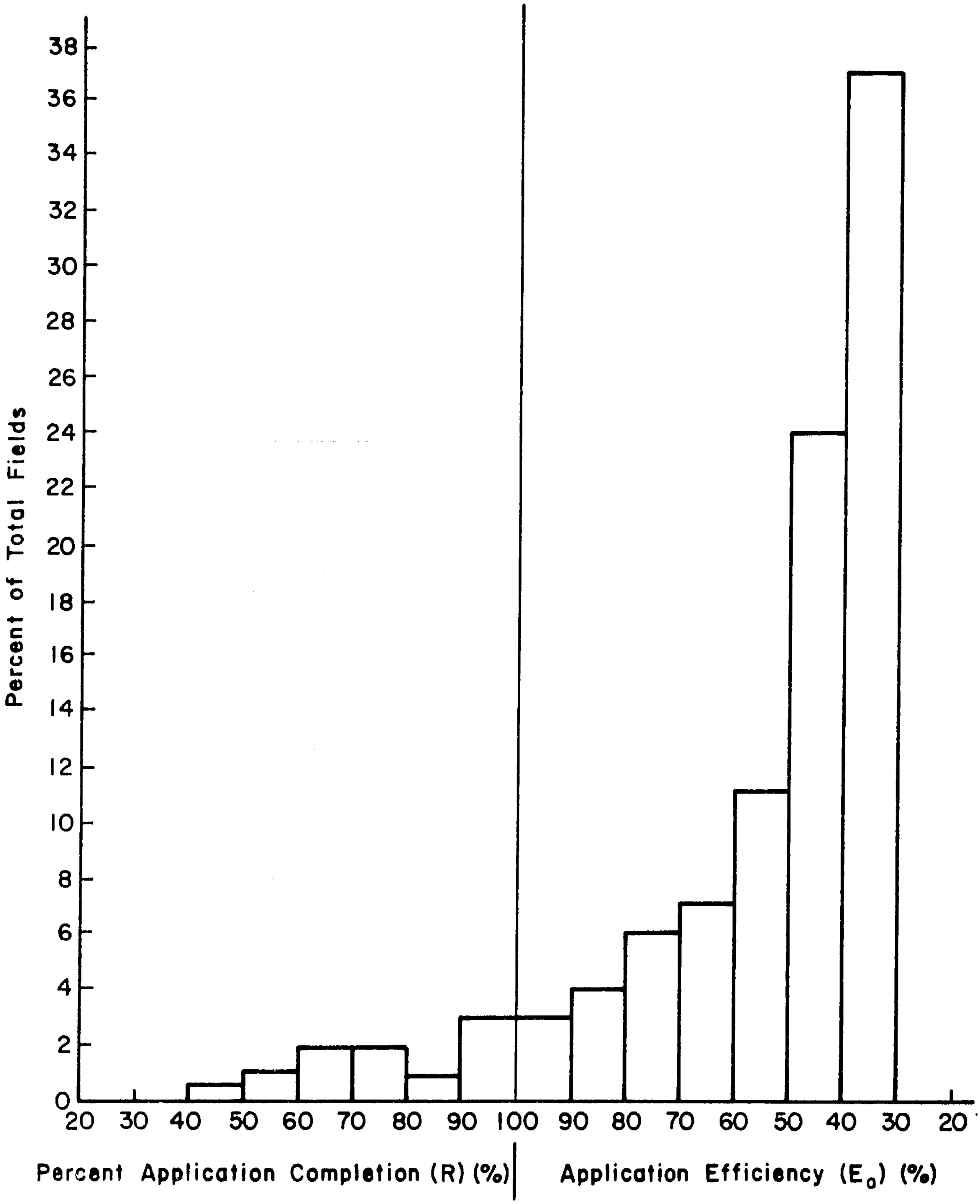


Figure 12. Percentage of the total irrigated fields on MP 6 watercourse which were irrigated within given ranges of Application Efficiency (E_a) or Application Completion (R).

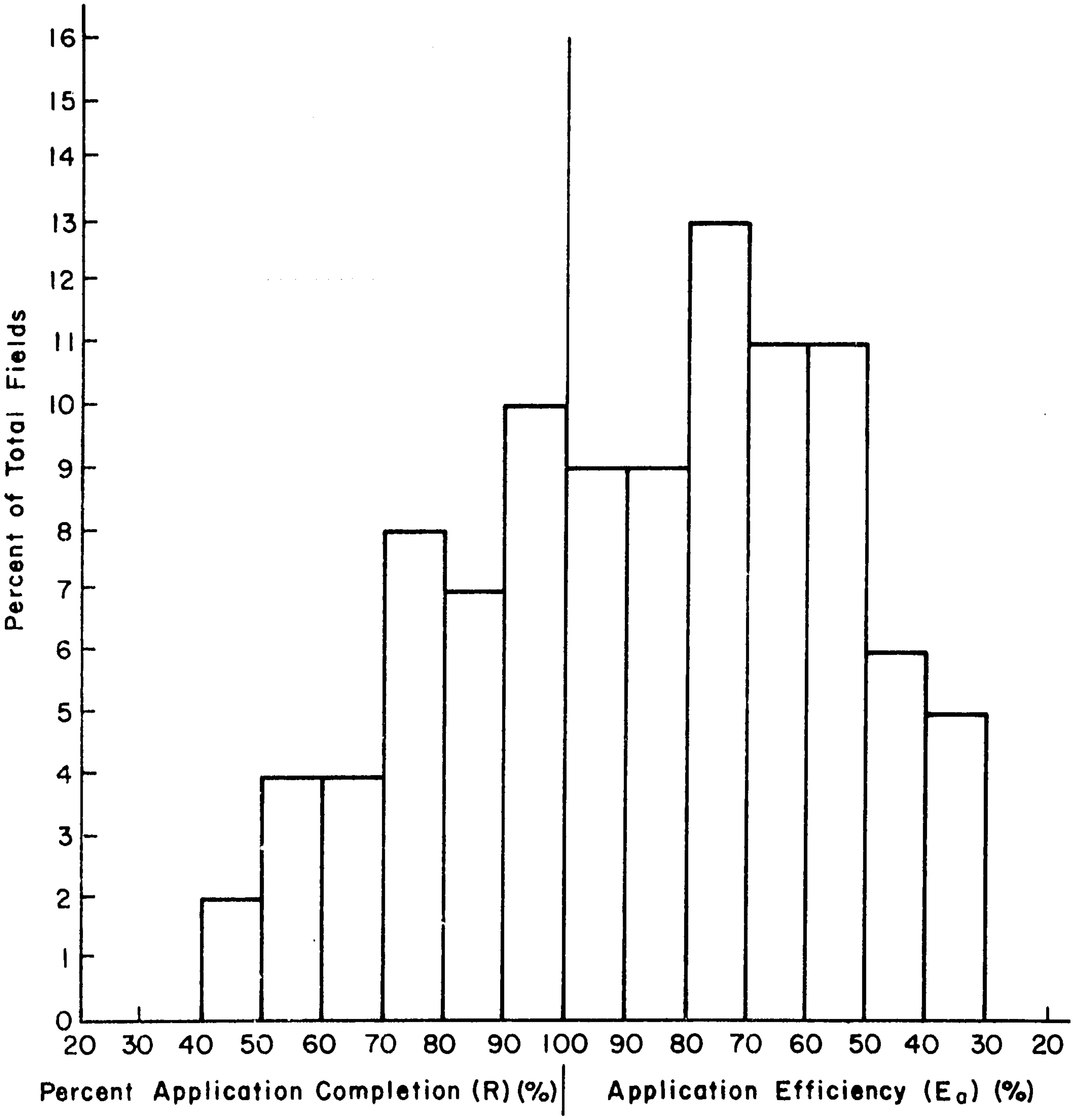


Figure 13. Percentage of the total irrigated fields on MP 35 watercourse which were irrigated within given ranges of Application Efficiency (E_a) or Application Completion (R).

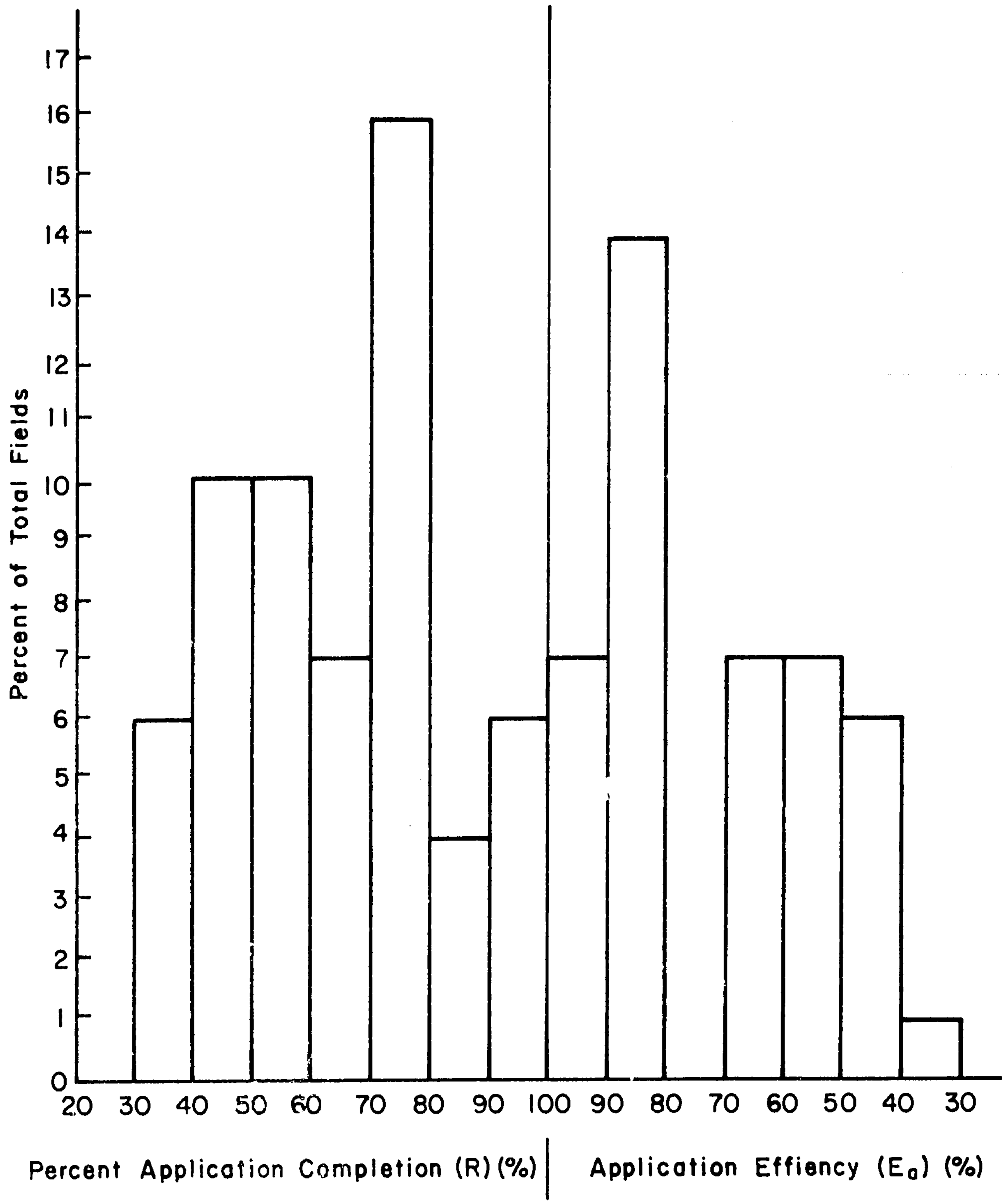


Figure 14. Percentage of the total irrigated fields on MP 52 watercourse which were irrigated within given ranges of Application Efficiency (E_a) or Application Completion (R).

In order to better understand the farmers' application of water relative to their water supply, linear regressions were run between water application parameters and water supply parameters. Since water flow rates generally decrease with distance from the mogha, but warabundi time allocations per holding size are constant, distance from the mogha is an indicator of water availability. Table 15 lists derived regression equations relating water depth applied, irrigation time per hectare, and percent of total holdings irrigated per week, with distance from the mogha. Depth applied varied inconsistently with distance, but farmers whose fields lie farther from the mogha did tend to take more time to irrigate their fields, and to irrigate fewer of their fields per turn. Thus, one would expect to find lower cropping intensities, but not necessarily lower yields, near the tail of the watercourses. Farmer questioning on TW 81-R and Tik #1 watercourses did indicate that cropping intensities decrease with distance from the mogha. Cropping intensities also correlated positively with measured conveyance efficiencies, but neither relationship was significant at the 95% level. No relationship could be established between yields and distance or conveyance efficiency.

Application efficiencies and irrigation depths applied were also regressed with various factors such as field size, distance of the field from the mogha, soil moisture deficiencies, and flow rate at the field on MP 6, MP 35 and MP 52 watercourses. There were no consistently significant

Table 15. Regression relationships between depth irrigated (d_i), time utilized to irrigate one hectare (T_i), and percent of total holding irrigated (% Irr); and distance of the fields from the mogha (D)(100m) for the five studied watercourses.

Watercourse	d_i (cm)	Ti (hr/ha)	% Irr (%)
TW 81-R	d_i=11.1-0.17D r^2=.05*	T_i=6.3+0.09D r^2=.02	I_p=17-0.14D r^2=.02
Tik #1	d_i=6.1-0.03D r^2=.001	T_i=2.4+0.33D r^2=.01	I_p=20+0.16 r^2=.01
MP #6	d_i=8.7+0.10D r^2=.01*	T_i=4.6+0.26D r^2=.39**	L_p=30-0.98D r^2=.31**
MP #35	d_i=6.4+0.07D r^2=.01*	T_i=6.1+0.28D r^2=.41**	I_p=24-0.43D r^2=.36**
MP #52	d_i=9.7-0.13D r^2=.05	T_i=10.7+0.10D r^2=.11*	I_p=31-0.03D r^2=.00

*Significant at the 95% level.
**Significant at the 99% level.

correlations for any factor, but the data indicated that application efficiencies tended to increase with soil moisture deficiency and with flow rate at the field, both probably a result of the tendency to overirrigate; and depth of water applied increased with flow rate and decreased as field size increased. Depth applied was not correlated with soil moisture deficiency. Farmers do not appear to vary applications with the soil moisture requirements.

Measured conveyance and application efficiencies were divided between those occurring at night (6:00 PM to 6:00 AM) and during the day. The results, presented in Table 16, indicate that any differences between daytime and nighttime irrigation efficiencies are small.

The flow diagrams shown in Figures 15 through 19 summarize the findings on each studied watercourse by depicting the flow of water through and out of each of the conveyance systems.

Table 16. Daytime and nighttime irrigation efficiencies on the five operationally studied watercourses.

Watercourse	Conveyance Eff. Day	Conveyance Eff. Night	Application Eff. Day	Application Eff. Night	Irrigation Eff. Day	Irrigation Eff. Night
TW 81-R	47%	42%	nm*	nm*		
Tik # 1	63%	63%	nm*	nm*		
MP 6	61%	60%	30%	29%	18%	17%
MP 35	60%	62%	76%	74%	46%	46%
MP 52	48%	49%	87%	82%	42%	40%
Average	56%	55%	64%	62%	36%	35%

*not measured

TW 81-R WATERCOURSE

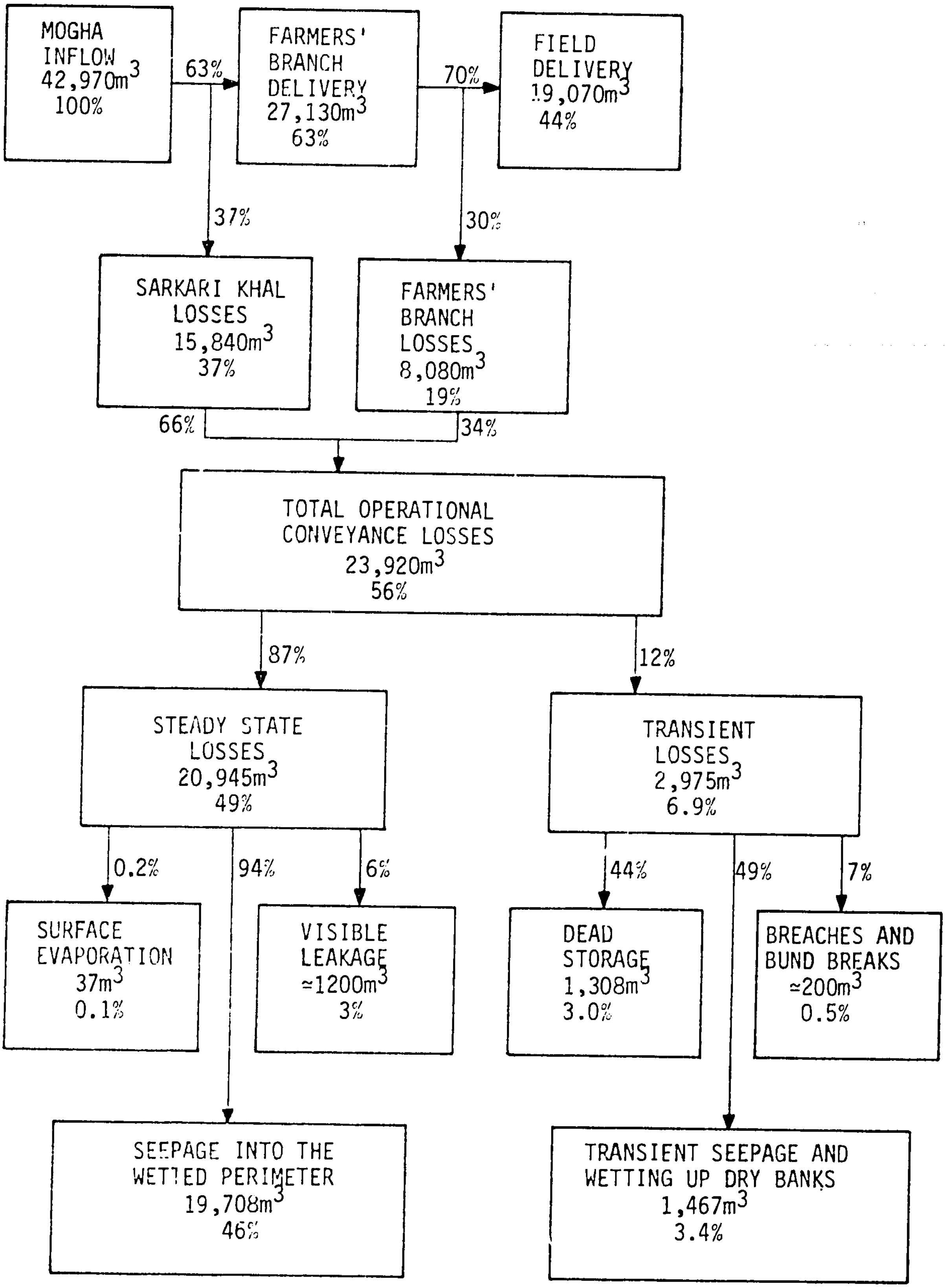


Figure 15. Flow diagram depicting the flow of water through and out of TW81-R watercourse during the studied week.

Tik #1 WATERCOURSE

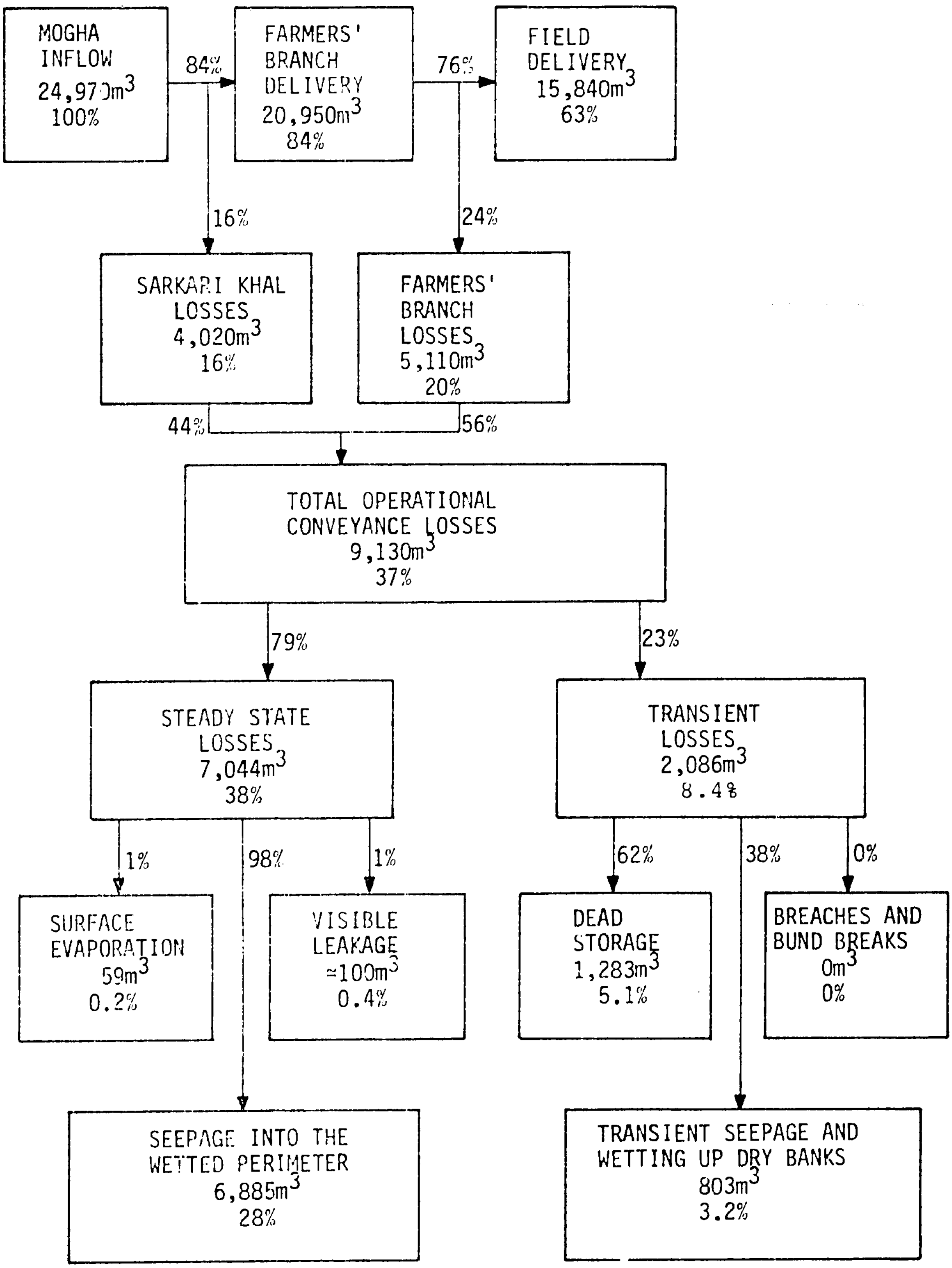


Figure 16. Flow diagram depicting the flow of water through and out of Tik #1 watercourse during the studied week.

MP 6 WATERCOURSE

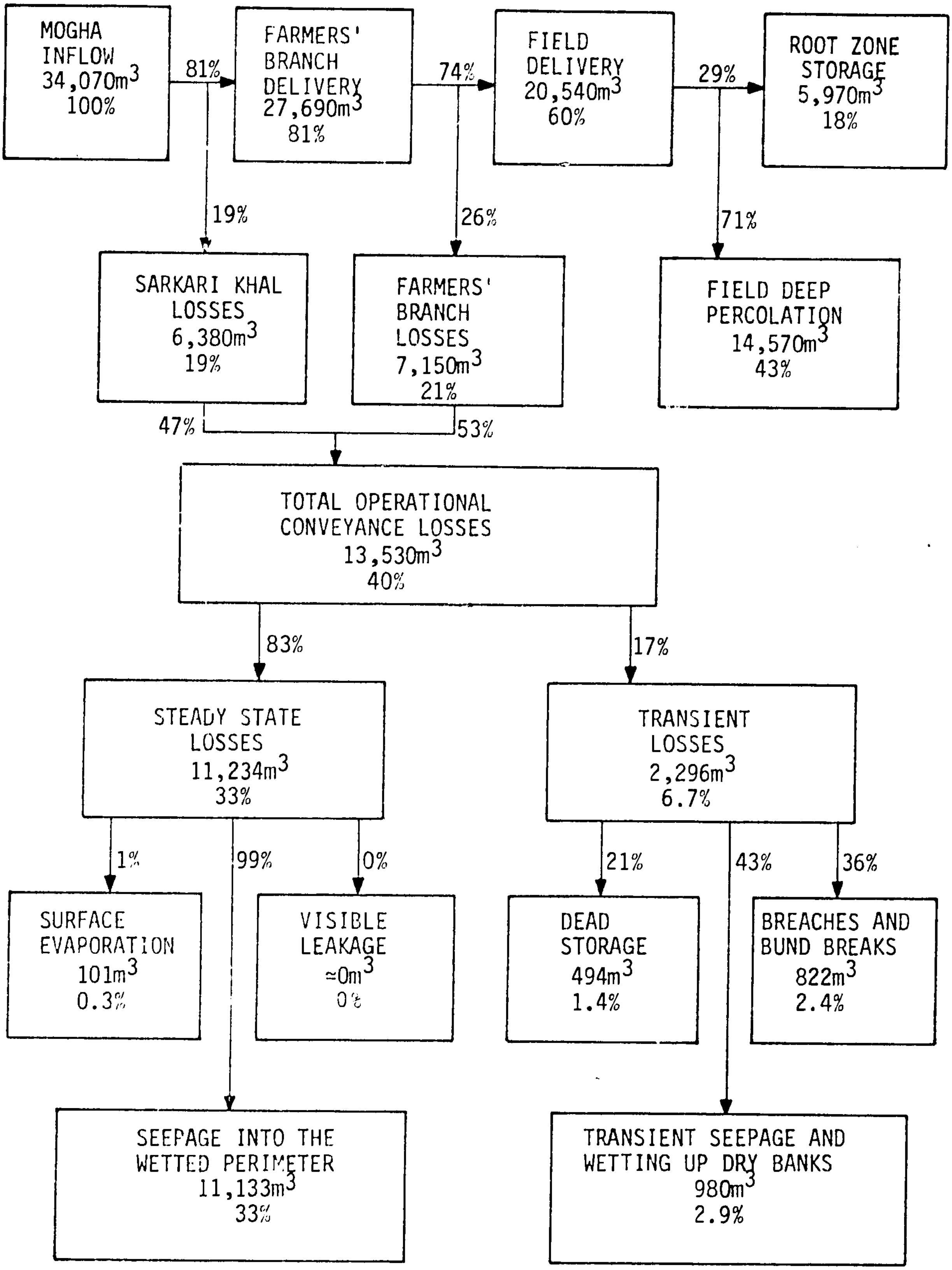


Figure 17. Flow diagram depicting the flow of water through and out of MP 6 watercourse during the studied week.

MP 35 WATERCOURSE

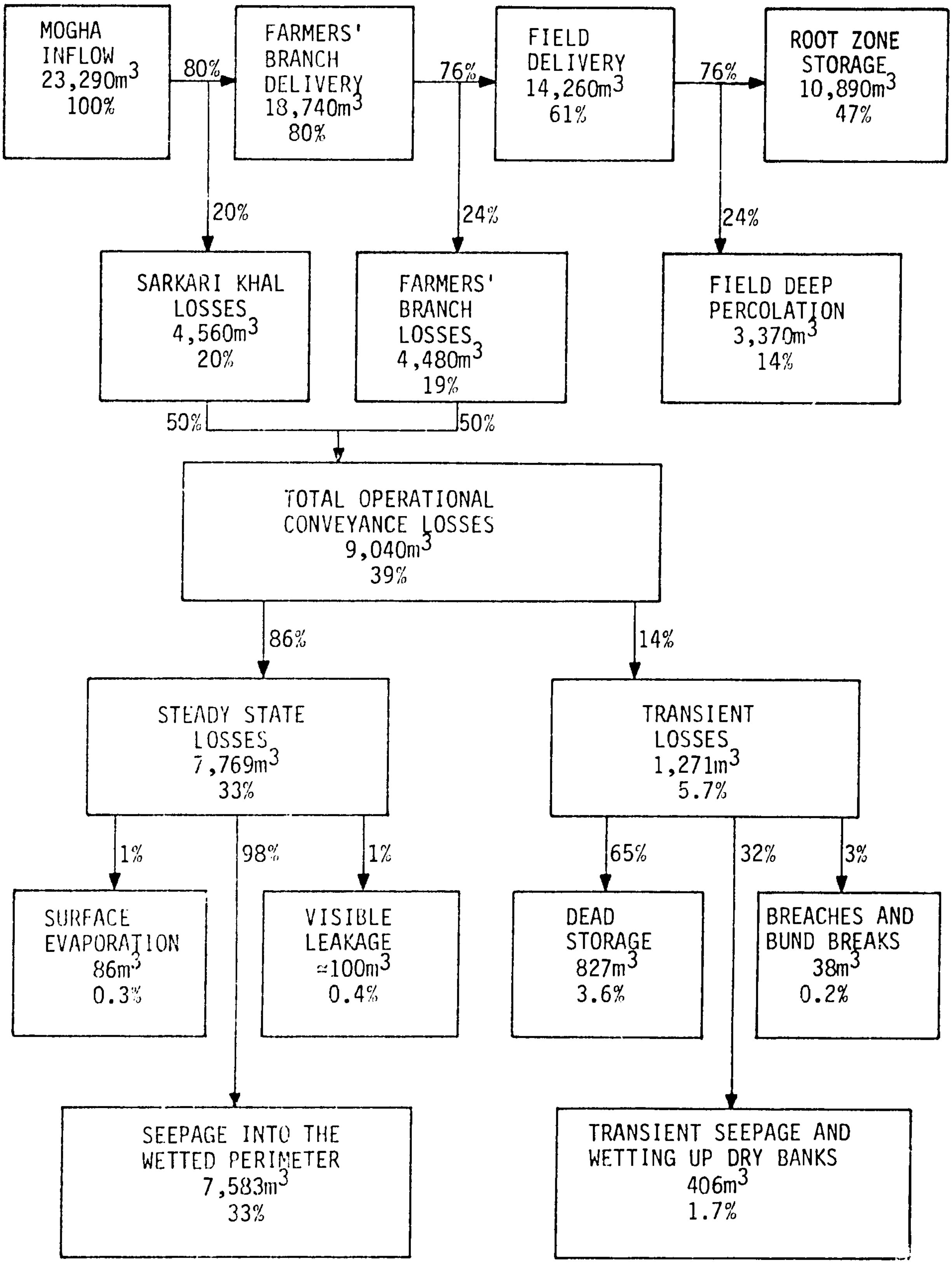


Figure 18. Flow diagram depicting the flow of water through and out of MP 35 watercourse during the studied week.

MP 52 WATERCOURSE

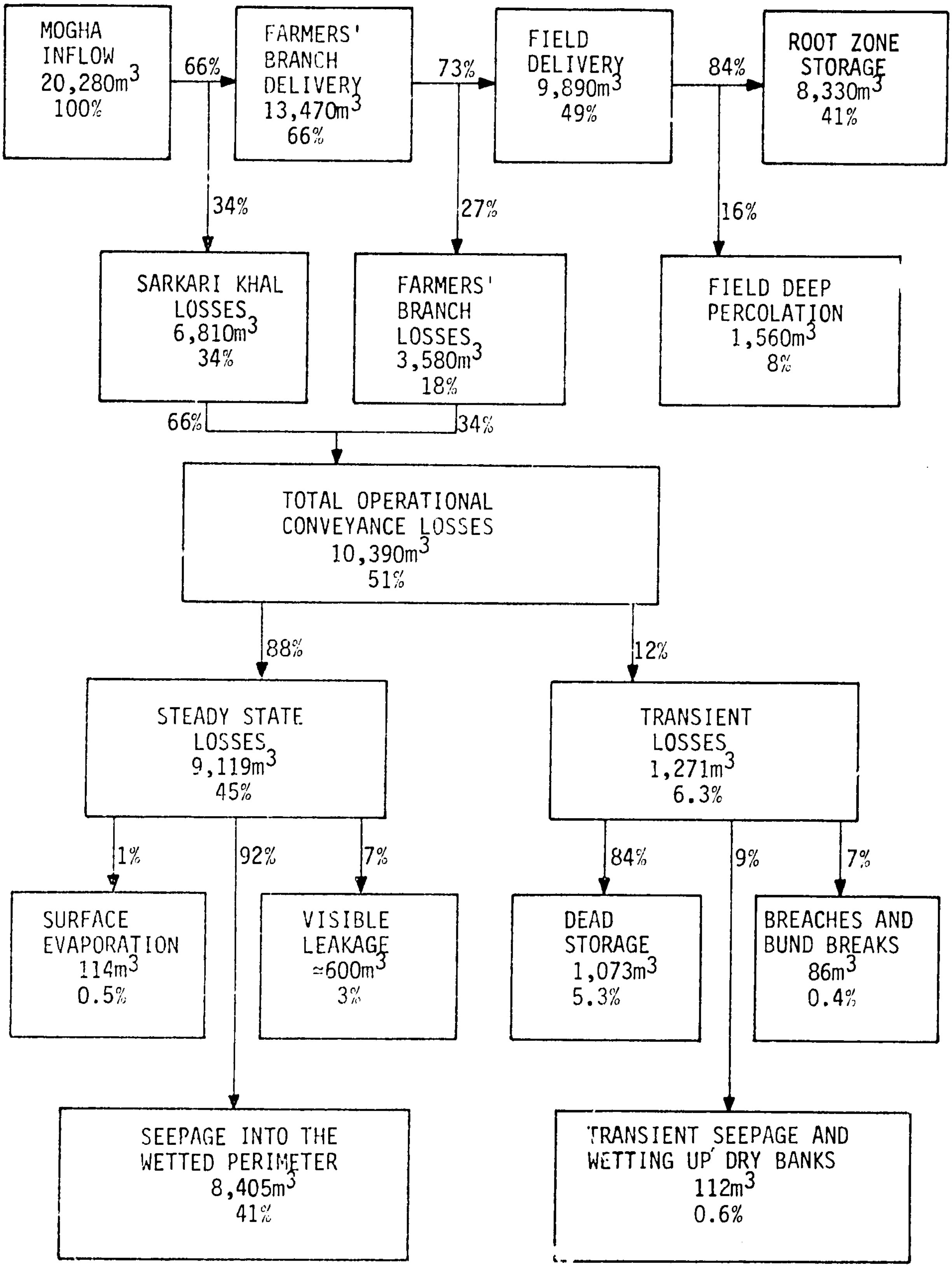


Figure 19. Flow diagram depicting the flow of water through and out of MP 52 watercourse during the studied week.

SECTION 5

DISCUSSION OF THE FINDINGS

Between 38% and 56% of the water delivered to the five studied watercourses was lost from the conveyance system before reaching the fields during the studied weeks. This range and the average losses (45%) is somewhat higher than earlier steady-state inflow-outflow loss measurements. The difference is roughly equivalent to the 6 to 8% of the inflow which was lost to transient condition losses on each watercourse. These results consequently compare closely with previous measurements, and past steady-state measurements should be adjusted upward by 6 to 8 percentage points (percent of the inflow) to reflect true operational conditions.

Analysis of flume effects on inflow-outflow loss measurements indicated that flume induced water losses will cause an overestimation of the water loss in a normally flowing channel. Application of the flume effect adjustment factor (Eq. 1) to each set of the collected data indicates that measured steady-state losses were probably higher than normal losses by 6 to 8 percentage points on each watercourse. Consequently, measured steady-state losses should be adjusted downward by 6 to 8 percentage points to correct for flume effects. This implies that, because the two adjustments (transient losses and flume effects) essentially cancel each other out, past steady-state measurements should be representative of true operational conveyance losses, and the conclusion still stands that 30 to 50% of the water which enters

Pakistan's watercourses is lost during conveyance to the fields.

Such high losses indicate a large potential for delivering more water to the often water-shortage constrained Pakistani farmers. Reducing watercourse conveyance losses by 5 percentage points would provide the same amount of additional water to the field as the construction of an 11 billion cubic meter storage reservoir (approximately the size of Tarbela reservoir).

This study has indicated some potential methods of reducing conveyance losses. Percent loss rates increased rapid. with increasing inflow rates. This implies that inflows to a watercourse should be maintained fairly constant. If it is desirable to increase the inflow rate, perhaps via canal enlargement or the installation of a public tubewell, the watercourse must be redesigned and enlarged for the increased flow. Otherwise, little of the additional flow will reach the field.

Over 80% of the conveyance losses were the result of steady-state seepage and leakage into the bed and banks of water channels. These seepage rates were much higher than the normal intake rates of the heavier soils, even though silt deposition and microbial activity (Allison, 1947) in the often wet channels would be expected to reduce channel seepage rates much below the normal soil intake rates. Ponding loss studies reported in Trout (1979) indicate that earthen watercourse beds are relatively impermeable, while the seepage rates into the upper banks are 20 to 100 times greater than normal soil intake rates.

The high seepage rates indicate that potential exists to reduce water losses in earthen channels without installing lining materials. Techniques suggested by past studies to reduce seepage rates into earthen banks include:

1. destroying and rebuilding watercourse banks to eliminate "macropores" (insect and rodent holes) which increase the effective wetted perimeter and may lead to more permeable strata;
2. compaction of watercourse banks to reduce permeability and destroy macropores;
3. design of channels to encourage silt deposition; and
4. design of channel layout and operation to maximize the percent of time main sections are full, in order to promote microbiological sealing of the wetted perimeter, as well as inhibit rodent and insect activity in the banks.

If any of these techniques can reduce seepage rates by only 25%, conveyance losses would be reduced by about 10 percentage points. Watercourse earthen renovation has been shown to reduce steady-state losses by as much as 50% on some watercourses (Cheema, et al., 1976, Bowers, et al., 1976). The relatively low loss rates compared to soil intake rates on some sections of MP 6 watercourse show that, even in sandy soils, conveyance losses from earthen channels do not have to be high.

Visible leakage, although a small proportion of the total losses on most watercourses, is the most obvious form of water wastage to the farmer, and perhaps the easiest to control. All farmers are aware of such leakage and the damage it often causes to nearby crops, but because individual leaks are small, and irrigation turn times are relatively short, they are often ignored.

A farmer with 4 ha on a watercourse where visible leakage amounts to 3% of the inflow, should be able to increase his cropped area by about 0.1 ha by plugging the visible leaks. As an individual, to plug the leaks on the 1,300 m of channels leading to his fields might require a couple hours during his six hour irrigation turn each week, and he might not consider it worthwhile. However, if each farmer plugged the leaks to his fields, then the present irrigator would need to monitor only the additional 300 m or so of channel he fills, which would require much less time and would certainly be worth the additional land he could cultivate. Farmers on watercourses where visible leakage is high must be informed about the total volume of water which is being wasted through all the small visible leaks, so that they will be motivated to stop this obvious loss.

Evaporation losses from the surface of the flowing water is such a small percentage of the total losses, that eliminating them via closed conveyance systems should be considered only after all other loss reducing alternatives have been applied.

Lining channels with an impermeable material can (but not necessarily will) reduce seepage and leakage rates to nearly zero. But the cost of channel lining is high and must be evaluated in the light of the amount of water saved and its value. The amount of water saved will depend both on the reduction in the loss rate and the amount of time water flows in the channel. This study has indicated that lost rates vary widely from watercourse to watercourse, and within one watercourse between sarkari khal sections and farmers' branches.

The data also indicated that the average farmer's branch section is used only 2% of the time; consequently, it will only be economical to apply very low cost earthen improvements to farmers' branch channels even though 45% of the total losses occur in these branches. Usage of sarkari khal sections will vary with location in the network. Figures 16, 17, 18 and 19 show the percentage of total length of sarkari khal sections which were full a given percent of the time on four of the studied watercourses. Potential water saving through lining will obviously vary from watercourse to watercourse and within each watercourse.

When loss rates, channel usage, lining (or other improvement) costs, and the value of water is known, various seepage reducing techniques can be optimally applied to a given watercourse network. (See Reuss(1979) for an example of such an optimization technique.) A sequence of improvement techniques, from high to low cost, will probably lead to the highest benefit/cost ratio.

Transient losses for an individual farmer depends primarily on the length of channel he fills and drains in the process of irrigating his fields. If a farmer can organize his fields and manage his irrigations such that he irrigates only neighboring or nearby fields during one turn, he can save a significant amount of his water. For example, assume a farmer whose fields lie on three branches, each extending about 200 m from the sarkari khal, has a turn time of 8 hours. If he splits his time between fields on two branches, instead of irrigating from only one branch, his losses will increase by 3 percentage points. If he irrigates from all three branches, his losses would be 6 percentage points higher. While irrigating a single field on a branch for only an hour, nearly 20 percent of the hour's water would be lost to filling 200 m of previously empty channels.

Reshaping fields into long narrow borders would assist the farmer in reducing branch channel usage since more land is accessible from each branch. Field reorganization and, in some cases, additional outlets from the sarkari khal, could reduce the length of branch channels to some fields and would reduce losses if leak-free outlets (nuccas) are available. Land consolidation also would allow farmers longer turn times on compact blocks of land and would result in reduced transient losses.

The warabundi turn rotation system has been designed to minimize the amount of channel filled and drained, and thus minimize the transient losses. Deviations from the warabundi will increase transient losses. A demand system where water is moved randomly around the watercourse system could result in 10 to 40 percent of the inflow being lost to transient conditions alone, unless the channels were lined.

Transient losses resulting from dead storage account for 3 to 5% of the total inflow. Raising watercourse levels, when the head is available at the canal, could eliminate dead storage losses. But this saving must be evaluated in the light of the value of land taken out of production in the process of constructing the higher channels, and the finding presented in Trout (1979) that steady-state loss rates are higher in channels which flow higher with respect to the surrounding field surface. The referenced study found, in fact, that total losses will often be reduced by lowering, rather than raising, channel levels.

On MP 6 watercourse, 2.4 percent of the inflow was lost to bank and nucca washouts. On MP 52 watercourse, the closed nuccas often leaked because of shrinkage and cracking of the fine textured soils. For both situations, installation of concrete outlet structures could have saved a significant portion of the water supply, in addition to saving farmer labor and allowing more precise control of the water.

Application efficiencies were estimated on 3 of the studied watercourses. Average values varied from 29% on the sandy MP 6 watercourse to 84% on MP 52 watercourse. These results assume a uniform water application across each field when, in fact, application uniformities, even with the best irrigation methods, are always less than 100%. Consequently, the efficiencies given are upper limits, and true water wastage must be greater than reported.

To illustrate this point, Figure 20 depicts the soil moisture deficiency before irrigation and the water application on a hypothetical basin. Because of the time it takes water to flow across a field, and due to unlevelness of the

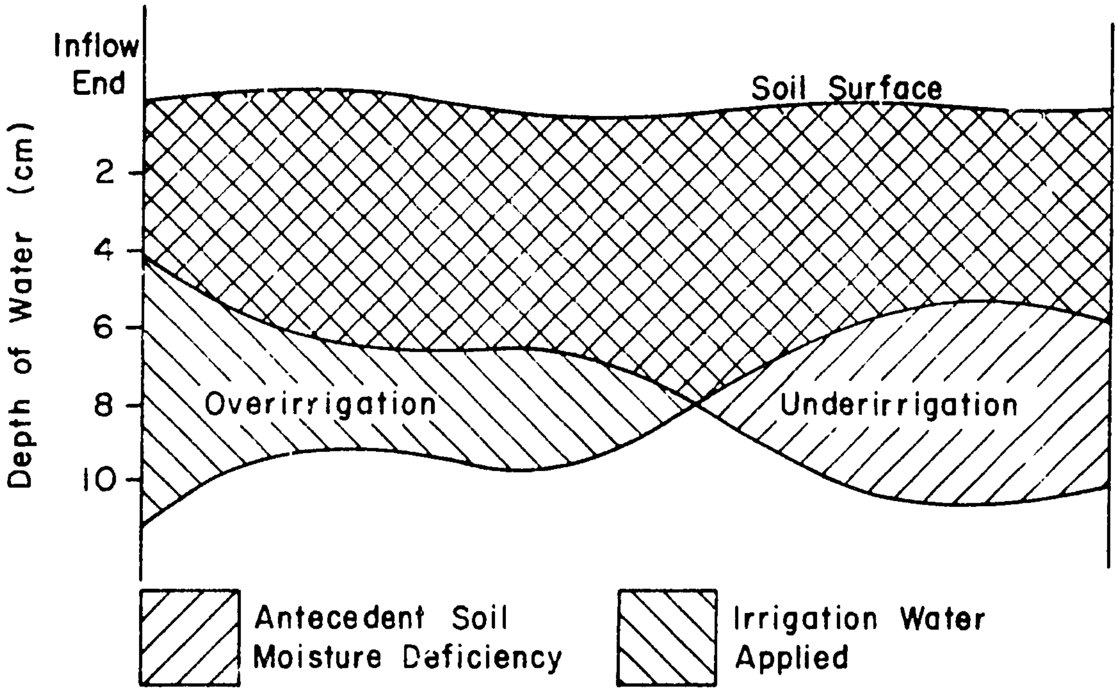


Figure 20. Example of irrigation application uniformity depicting the distribution of antecedent soil moisture deficiency and water application on a field.

surface, different amounts of water are applied to different parts of the field. This effect is compounded since that portion of the field which received the most water previously, and has the least need for water (lowest soil moisture deficiency (SMD)) will again receive the most water. The field depicted has an average SMD of 8 cm, and an 8 cm irrigation was applied. This would result in a "uniform" application efficiency of 100%, although the true efficiency as depicted is only 77%, and the true irrigation completion is also 77%.

To estimate an average "uniformity coefficient" for Pakistan's fields would be difficult. It would be possible to achieve 90% uniformity in a precision leveled basin with low intake rates, while small irrigations on uneven or sandy fields could seldom exceed a uniformity of 50%.

A final factor to consider when discussing overapplication is whether the excess water is truly wasted, or if it serves a useful purpose as a leaching fraction or groundwater storage. The concept of leaching fraction was developed in irrigated regions where the rainfall was minimal and essentially the only water applied was through irrigation. Regular leaching is required in such areas to keep salts washed below the root zone, especially if the quality of irrigation water is not good.

The situation over most of the Indus Basin is much different from this. Annual monsoon rains will often exceed the soil moisture deficiency and flush the root zone. The surface water supply is of very high quality, and except where poor quality tubewell water is applied, or the water table is near the surface and there is upward movement of water and salts, only periodic leaching (maybe once a season) is required. Also, the canal water is not applied only when required, but must be applied to the fields constantly throughout the year. This creates periods of moisture stress and under-irrigation, but also results in periods of excess water availability when overirrigation and leaching occurs. For these three reasons, the application of a regular leaching fraction is usually not required and need not be considered when calculating crop-water requirements during peak demand periods, or estimating application efficiencies for much of the Indus Basin.

Much of the water lost from fields and watercourses deep percolates to the groundwater. In an irrigation system where inflows are fairly constant while demand fluctuates greatly with season and crop growth, the potential benefits of pumping supplemental water from the groundwater is high. However, an analysis presented in Trout and Reuss (1978), clearly demonstrates that present deep percolation losses far exceed the peak demand supplemental water requirements, and losses could be reduced by over 50% without limiting groundwater usage. It is doubtful that such a reduction could be achieved unless most channels are lined. Present quantitites of seepage and deep percolation losses have in fact led to rising water tables and serious waterlogging and salinity problems, which have a cost not only in water wastage but also land degradation. Of course, in saline groundwater areas, which cover over 30% of the Basin, seepage and deep percolation losses have no reuse value. It must consequently be concluded that at the present and foreseeable levels of irrigation efficiencies, no benefit can be ascribed to water losses for the purpose of groundwater recharge.

Although siltation can reduce seepage rates and conveyance losses in channels built in sandy soils, it is difficult to achieve high application efficiencies with level basin irrigation in soils with high intake rates and low moisture holding capacities. The best way to reduce losses is to spread the water across the field surface as quickly as possible. The farmers on MP 6 watercourse had subdivided their fields to less than half the size of any of the other study areas and always irrigated down any slope, but still had low application efficiencies. A technique which could speed up the water advance and thus reduce deep percolation losses, would be to shape the field surface into beds or ridges and furrows. The reduction of water storage on the soil surface, channelization of the advancing water, and reduction of wetted area, would all lead to reduced advance times and evener distribution of water across the field.

A common factor on all three watercourses, where irrigation applications were monitored, is that the irrigators did not seem to apply water to their crops according to the dryness of the soil, or the soil moisture deficiency. Consequently, fields were almost randomly over and underirrigated. Nearly half of the fields were irrigated more than 40% above or below the required amount! A farmer needs only a basic understanding of root zones and soil moisture to estimate his water needs closer than that. Thus, there exists a potential through extension education to provide guidelines for farmers that would reduce irrigation application losses. The argument can be made that such applications are not totally the result of farmer ignorance, but are also the result of a rigid water turn rotation system. But a farmer who understands crop rooting depths, soil water holding capacities, and crop water usage can better utilize the flexibility of the soil water storage capacity and still irrigate relatively efficiently.

SECTION 6

SUMMARY

1. Watercourse operational conveyance losses are in the range of 30 to 50%.

2. About 20% of the losses, or 6 to 8% of the inflow, is lost to transient conditions.

3. About half of the transient losses, or 3 to 5% of the inflow, is lost to dead storage.

4. Transient losses depend primarily on the length of channel filled and drained and secondarily on the size of the channels (as indicated by inflow rate).

5. Watercourse seepage rates are often higher than the intake rates of the surrounding fields.

6. Surface evaporation is less than 1% of total conveyance losses.

7. Visible leakage is a small proportion of total losses on most watercourses, but can be significant in some cases.

8. Loss rates in farmers' branches are usually much higher than loss rates in sarkari khal channels, with about 45% of the total losses occurring in these branches, which entail only 20% of the total conveyance distance.

9. Steady-state conveyance losses increase rapidly as watercourse inflows increase.

10. Application efficiencies varied widely, but averaged 63% on 3 measured watercourses.

11. Farmers did not apply irrigation water in response to soil moisture deficiencies.

Figure 21 summarizes these findings in the form of a watercourse water flow diagram.

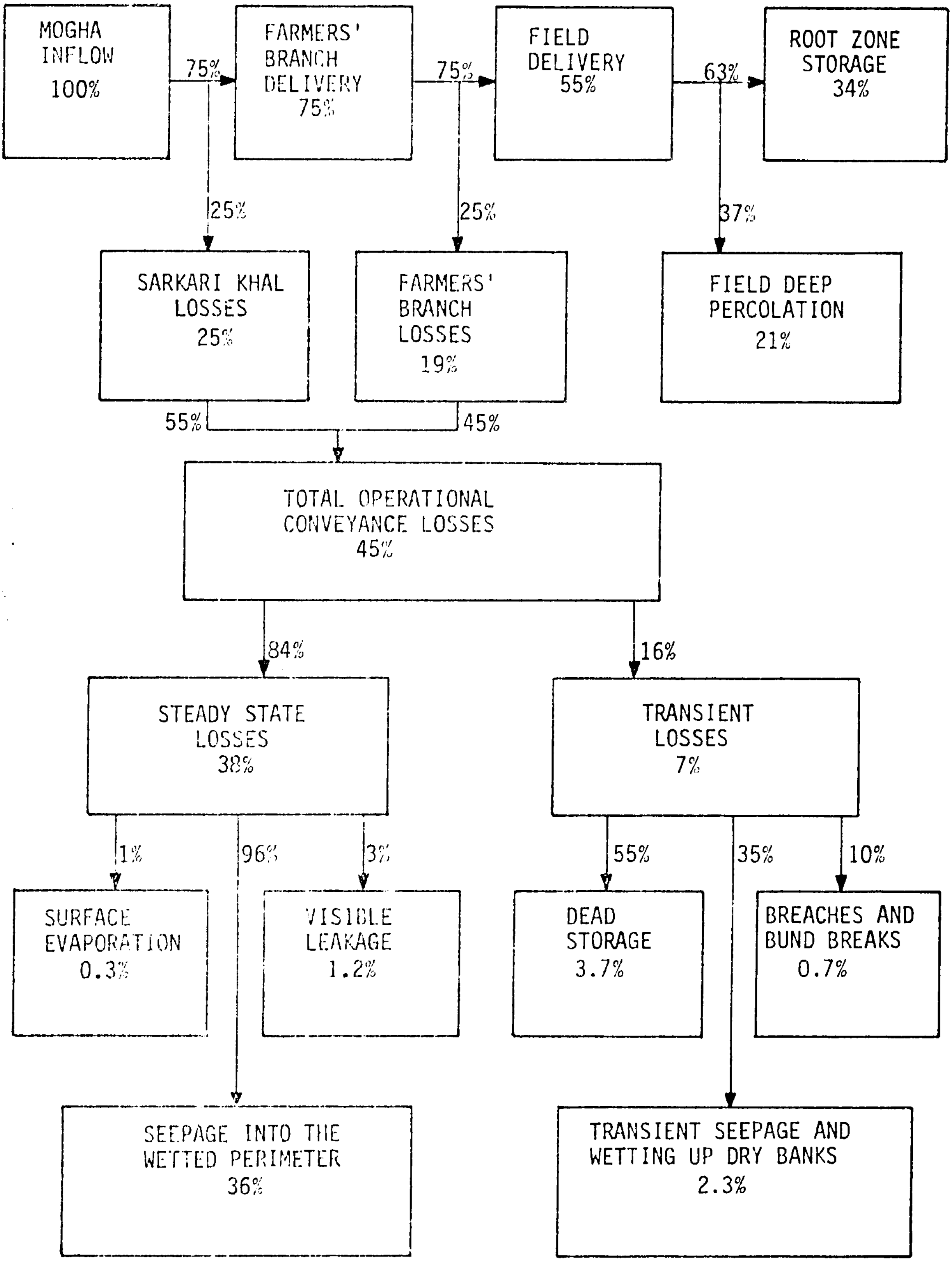


Figure 21. Flow diagram depicting the flow of water through and out of a watercourse conveyance system. Values are averages of the five measured watercourses.

SECTION 7

CONCLUSIONS

1. High watercourse and field application losses indicate a large potential for increasing water supply to crops and thus crop production in Pakistan through improved on-farm water management practices.
2. Watercourse losses can be greatly reduced through earthen watercourse improvements.
3. Optimum watercourse loss reduction strategies will involve the application of several improvement techniques of varying costs depending on channel loss rates and usage.
4. Deviations from the present warabundi turn rotation system will lead to increased transient conveyance losses.
5. Farmer education regarding soil-water-plant relationships should lead to improved irrigation application efficiencies.

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APPENDIX

Table A-1 Conveyance efficiency data for watercourse MP 6

	WEEK 1			WEEK 2			WEEK 3			AVERAGE		
	Sarkari Khal	Farmers Branch	Total to Fields	Sarkari Khal	Farmers Branch	Total to Fields	Sarkari Khal	Farmers Branch	Total to Fields	Sarkari Khal	Farmers Branch	Total to Fields
Volume of Inflow (m^3)	31690	24710	17950	32490	26280	20530	38020	32070	23160	34070	27690	20540
Conveyance Efficiency (%)	78%	73%	57%	81%	78%	63%	84%	72%	61%	81%	74%	60%
Volume Loss (m^3)	6970	6760	13740	6210	5750	11960	5950	8910	14860	6380	7150	13530
Distribution of Losses (%)	51%	49%		52%	48%		40%	60%		47%	53%	
Total Length of Channel Utilized (m)	3260	8480	11740	3260	9240	12500	3260	7420	10670	3260	8390	11650
Weighted Average Channel Length Utilized (m)	1395	225	1620	1392	182	1575	1232	179	1411	1340	196	1535
Distribution of Usage (%)	86%	14%		88%	12%		87%	13%		87%	13%	

Table A-2 Conveyance efficiency data for watercourse MP 35

	WEEK 1			WEEK 2			WEEK 3			AVERAGE		
	Sarkari Khal	Farmers Branch	Total to Fields	Sarkari Khal	Farmers Branch	Total to Fields	Sarkari Khal	Farmers Branch	Total to Fields	Sarkari Khal	Farmers Branch	Total to Fields
Volume of Inflow (m^3)	29650	20490	14960	22030	18410	13760	18180	17320	14050	23290	18740	14260
Conveyance Efficiency (%)	69%	73%	50%	84%	74%	62%	95%	81%	77%	80%	76%	61%
Volume Loss (m^3)	9160	5530	14690	3630	4640	8270	860	3270	4140	4560	4480	9040
Distribution of Losses (%)	62%	38%		44%	56%		21%	79%		50%	50%	
Total Length of Channel Utilized (m)	980	8170	9150	980	9700	10670	980	7560	8540	980	8480	9450
Weighted Average Channel Length Utilized (m)	449	424	873	425	468	892	443	416	859	436	445	875
Distribution of Usage (%)	51%	49%		48%	52%		52%	48%		50%	50%	

Table A-3 Conveyance efficiency data for watercourse MP 52

	WEEK 1			WEEK 2			WEEK 3			AVERAGE		
	Sarkari Khal	Farmers Branch	Total to Fields	Sarkari Khal	Farmers Branch	Total to Fields	Sarkari Khal	Farmers Branch	Total to Fields	Sarkari Khal	Farmers Branch	Total to Fields
Volume of Inflow (m^3)	21640	13860	8810	20340	13100	10360	18860	13440	10490	20280	13470	9890
Conveyance Efficiency (%)	64%	64%	41%	64%	79%	51%	71%	78%	56%	66%	78%	49%
Volume Loss (m^3)	7780	5050	12830	7250	2740	9990	5420	2950	8370	6810	3580	10390
Distribution of Losses (%)	61%	39%		73%	27%		65%	35%		66%	34%	
Total Length of Channel Utilized (m)	3960	3050	7010	3960	3660	7620	3050	3050	6100	3660	3350	7010
Weighted Average Channel Length Utilized (m)	1609	452	2061	1235	215	1450	817	232	1050	1220	300	1520
Distribution of Usage (%)	78%	22%		85%	15%		78%	22%		80%	20%	

Table A-4 Steady state and transient loss data for watercourse MP 6

	WEEK 1	WEEK 2	WEEK 3	AVERAGE
Weighted average inflow rate (lps)	49.8	60.6	58.9	56.3
Weighted average intermediate flow rate (lps)	38.8	49.0	49.5	45.8
Weighted average field flume flow rate (lps)	33.7	43.9	40.8	39.3
Weighted average steady state sarkari khal loss rate				
(lps/100m)	0.79	0.83	0.75	0.79
(% of inflow/100m)	1.6	1.3	1.3	1.3
Weighted average steady state farmers' branch loss rate				
(lps/100m)	3.97	5.40	6.08	4.85
(% of inflow/100m)	10.2	9.2	12.1	10.5
Weighted average steady state total loss rate				
(lps/100m)	1.06	1.11	1.31	1.16
(% of inflow/100m)	2.0	2.0	2.3	2.0
Total steady state losses to intermediate flume (%)	22%	19%	16%	19%
Total steady state losses to Field Flume (%)	32%	37%	31%	33%
Transient losses (m^3)	2295	2061	2530	2295
(% of inflow)	7.3%	6.3%	6.7%	6.8%
(% of losses)	16.7%	17.2%	17.1%	17.0%
Dead storage (m^3)	617	370	370	494
(% of inflow)	2.1%	1.1%	0.9%	1.4%
(% of losses)	4.8%	3.0%	2.2%	3.3%
(% of transient losses)	29.0%	17.2%	12.9%	19.7%
Average unit dead storage (m^3/m drained)	.057	.031	.033	.040
Total length of channel filled and drained (m)	11860	12470	10610	11650

Table A-5 Steady state and transient loss data for watercourse MP 35

	WEEK 1	WEEK 2	WEEK 3	AVERAGE
Weighted average inflow rate (lps)	49.0	36.2	30.0	38.5
Weighted average intermediate flow rate (lps)	34.0	30.6	28.6	31.1
Weighted average field flume flow rate (lps)	27.7	26.0	25.5	26.3
Weighted average steady state sarkari khal loss rate				
(lps/100m)	3.34	1.39	0.33	1.69
(% of inflow/100m)	6.9	3.3	1.0	3.9
Weighted average steady state farmers' branch loss rate				
(lps/100m)	1.67	0.78	0.85	1.10
(% of inflow/100m)	4.9	2.6	2.9	3.6
Weighted average steady state total loss rate				
(lps/100m)	2.59	1.05	0.57	1.40
(% of inflow/100m)	5.2	2.9	2.0	3.6
Total steady state losses to intermediate flume (%)	31%	16%	5%	17%
Total steady state losses to Field Flume (%)	43%	29%	15%	29%
Transient losses (m^3)	1148	1641	1024	1271
(% of inflow)	4.0%	7.4%	5.7%	5.7%
(% of losses)	7.9%	19.8%	24.6%	17.4%
Dead storage (m^3)	864	975	629	827
(% of inflow)	2.9%	4.4%	3.4%	3.6%
(% of losses)	5.9%	11.7%	15.1%	10.9%
(% of transient losses)	75%	59%	61%	65%
Average unit dead storage (m^3/m drained)	0.096	0.086	0.077	0.086
Total length of channel filled and drained (m)	9120	10820	8870	9600

Table A-6 Steady state and transient loss data for watercourse MP 52

	WEEK 1	WEEK 2	WEEK 3	AVERAGE
Weighted average inflow rate (lps)	40.5	35.4	35.7	37.1
Weighted average intermediate flow rate (lps)	26.0	22.9	25.5	24.[illegible]
Weighted average field flume flow rate (lps)	19.2	21.2	22.9	21.2
Weighted average steady state sarkari khal loss rate (lps/100m)	0.91	1.02	1.26	1.07
(% of inflow/100m)	2.3	2.9	3.5	2.8
Weighted average steady state farmers' branch loss rate (lps/100m)	1.71	1.04	1.34	1.36
(% of inflow/100m)	6.6	4.6	5.2	5.5
Weighted average steady state total loss rate (lps/100m)	1.07	1.02	1.27	1.12
(% of inflow/100m)	2.7	2.9	3.6	3.0
Total steady state losses to intermediate flume (%)	36%	36%	29%	34%
Total steady state losses to Field Flume (%)	52%	40%	36%	43%
Transient losses (m^3)	1148	1407	1246	1271
(% of inflow)	5.3%	6.9%	6.6%	6.3%
(% of losses)	8.9%	14.0%	14.9%	12.6%
Dead storage (m^3)	1851	961	469	1074
(% of inflow)	8.6%	4.4%	2.5%	5.3%
(% of losses)	14.5%	8.9%	5.6%	9.8%
(% of transient losses)	163.0%	64.0%	37.3%	88.1%
Average unit dead storage (m^3/m drained)	.153	.063	.088	.101
Total length of channel filled and drained (m)	10580	13020	6490	10030

Table A-7 Irrigation application data for watercourses MP 6, MP 35 and MP 52

	Watercourse MP 6				Watercourse MP 35				Watercourse MP 52			
	Week 1	Week 2	Week 3	Average	Week 1	Week 2	Week 3	Average	Week 1	Week 2	Week 3	Average
Total acres irrigated (ha)	19.4	19.0	23.5	20.6	21.4	20.6	21.4	21.2	16.2	14.6	13.3	14.8
Number of bunded units irrigated	361	368	477	402	203	205	195	201	126	113	109	116
Average size of bunded units (ha)	.05	.05	.05	.05	.11	.10	.11	.11	.13	.13	.12	.13
Total volume applied (m^3)	17940	20520	23150	20540	14960	13760	14040	14260	8810	10350	10490	9890
Average depth applied (cm)	9.2	10.8	9.9	10.0	7.0	6.6	6.6	6.8	5.4	7.0	7.9	6.8
Total volume of over-irrigation (m^3)	12140	15240	16310	14570	2990	3710	3420	3370	1430	1520	1700	1560
Total volume of under-irrigation (m^3)	260	70	90	140	1510	1460	1810	1590	3480	3820	2970	3430
Total application efficiency (%)	32.0	25.8	29.5	29.1	80.0	73.0	75.6	76.2	83.8	85.4	84.0	84.4
Average application efficiency of over-irrigated fields (%)	39.4	35.0	36.2	36.9	68.5	66.1	67.5	67.4	58.1	68.5	68.6	65.1
Average application completion of under-irrigated fields (%)	65.9	74.0	73.8	71.3	77.7	72.7	70.7	73.7	66.7	54.1	65.6	62.2

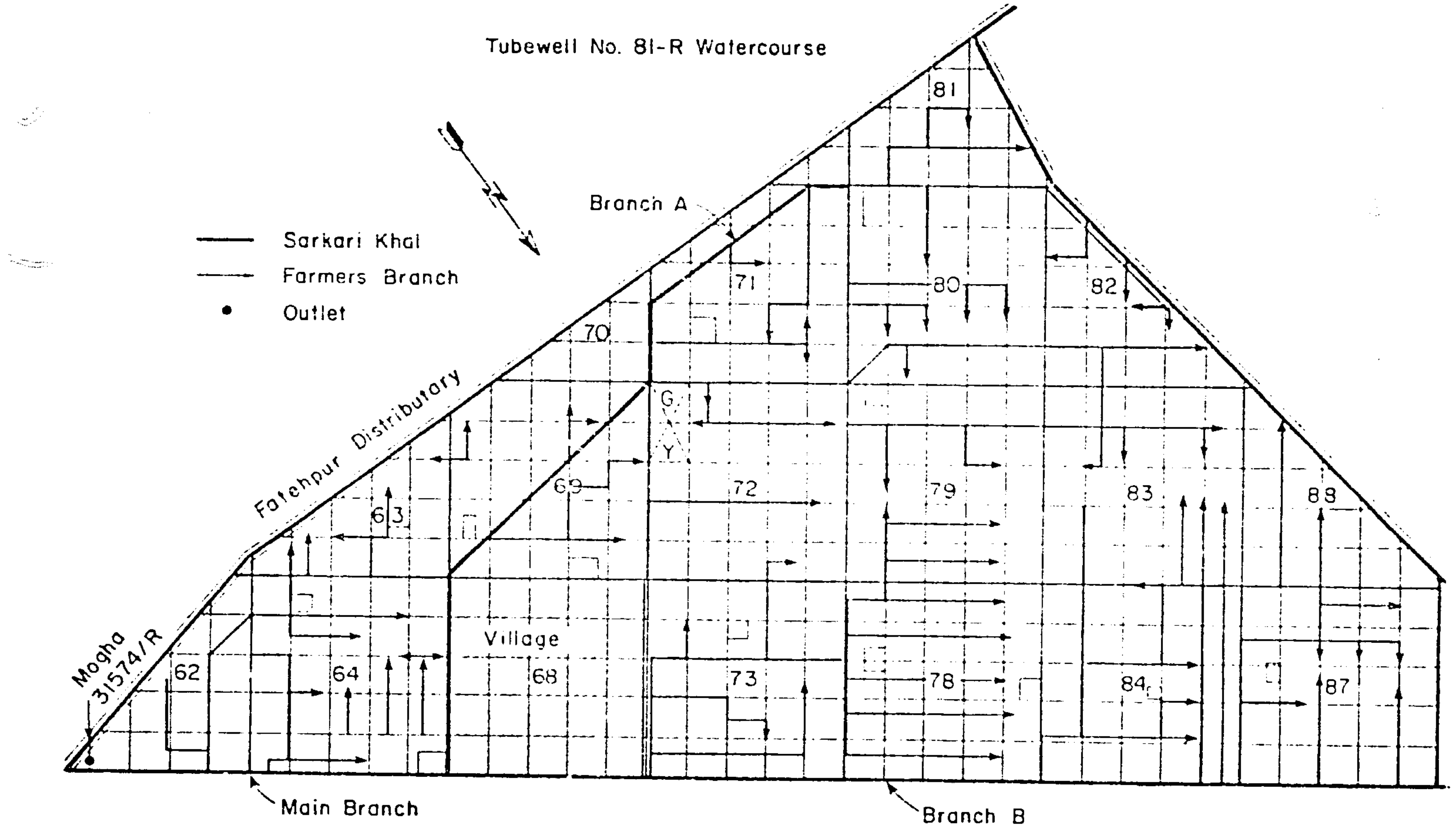

Figure A-1. Layout of watercourse TW 81-R.

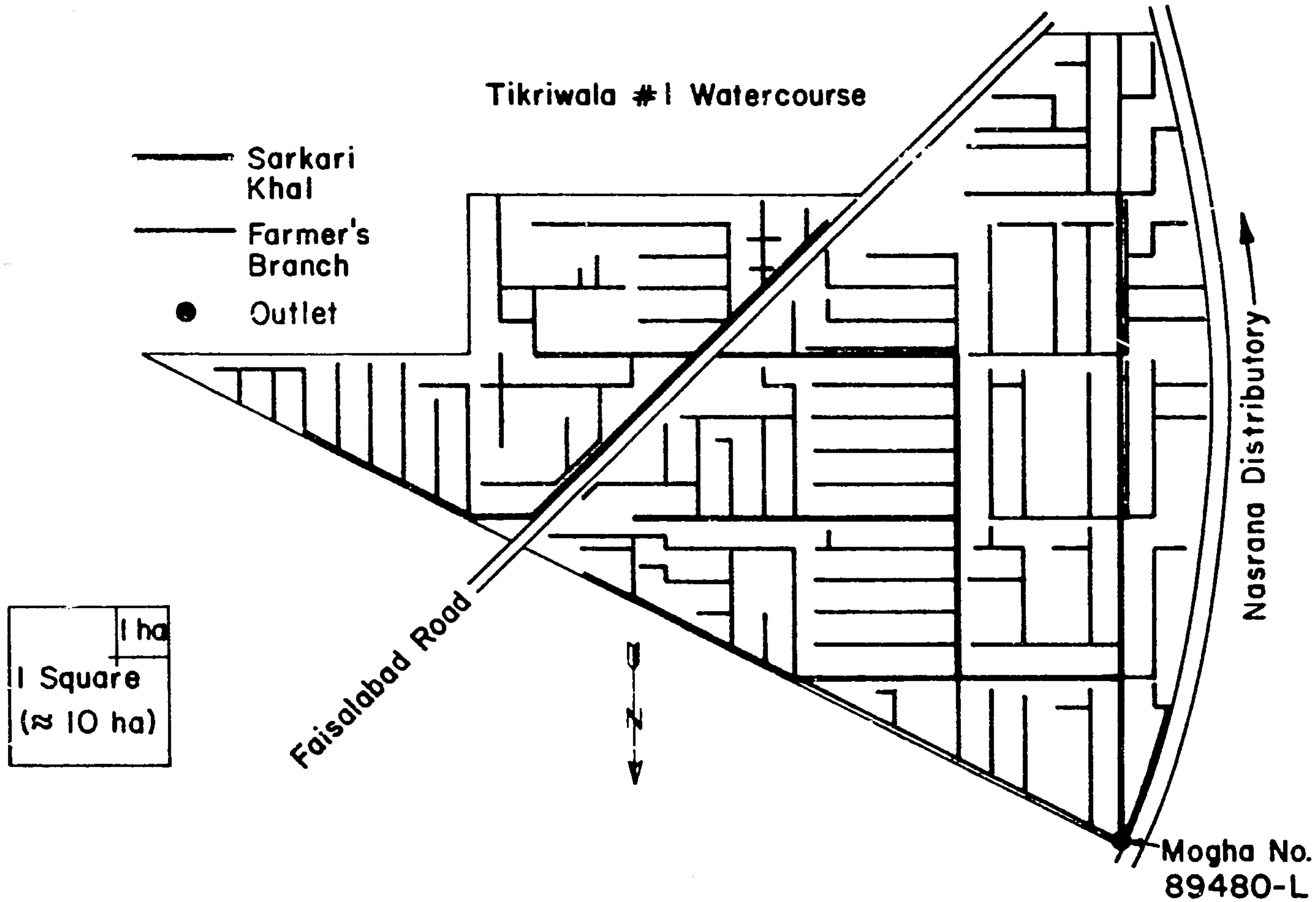

Figure A-2. Layout of Tikriwala #1 watercourse.

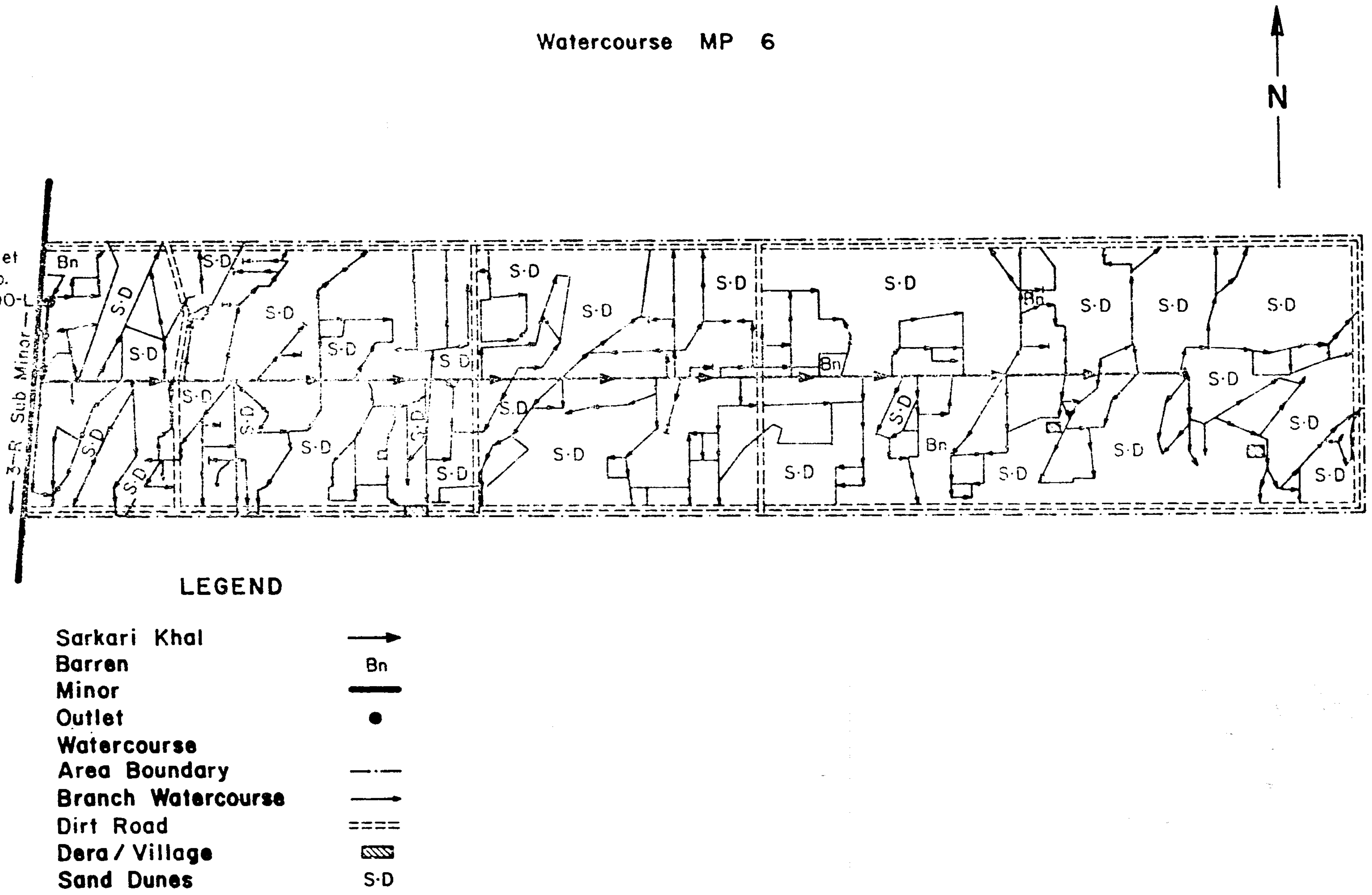

Figure A-3. Layout of MP 6 watercourse.

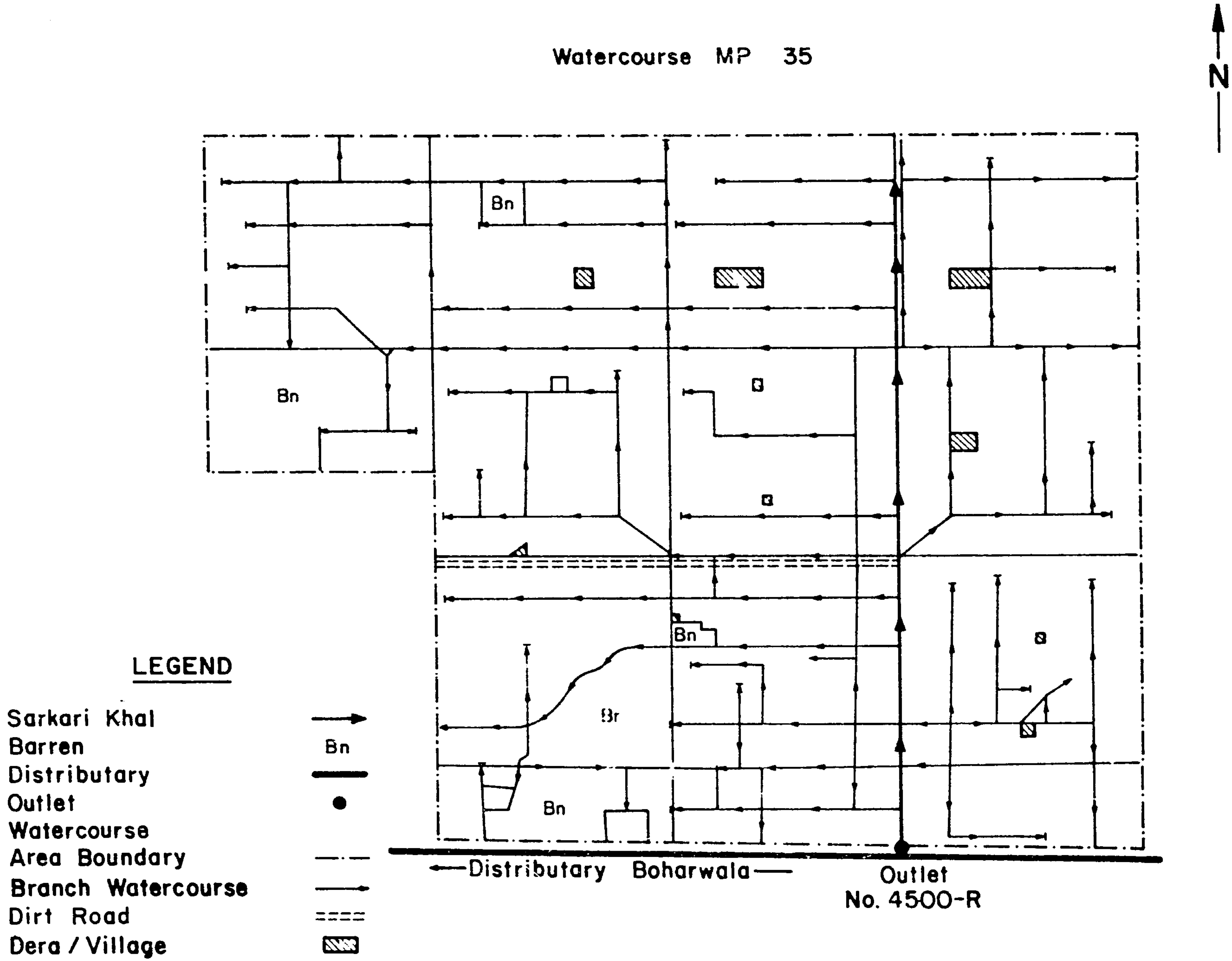

Figure A-4. Layout of MP 35 watercourse.

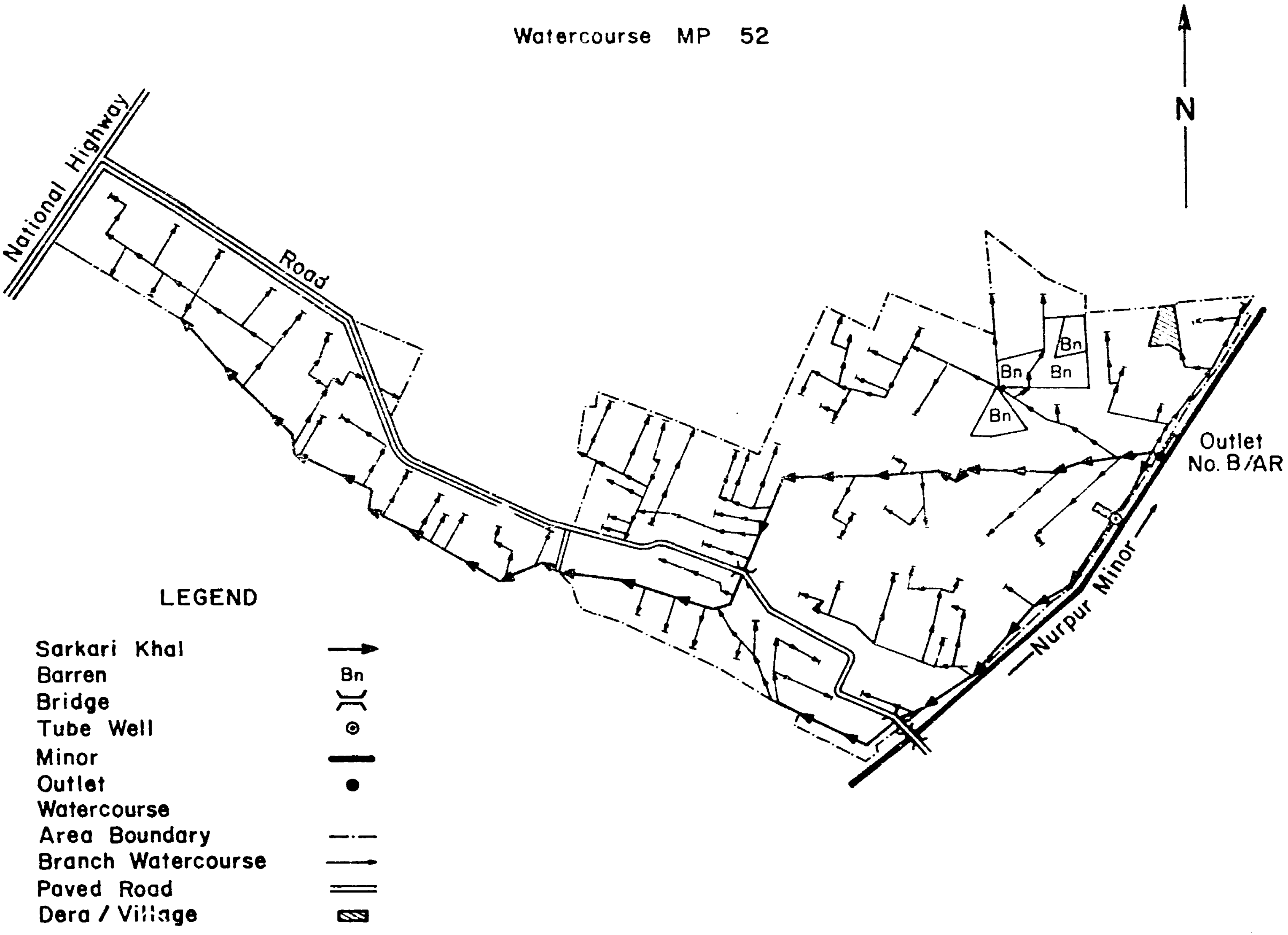

Figure A-5. Layout of MP 52 watercourse.