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RESEARCH SUPPORT FOR THE
FORDWAH EASTERN SADIQIA (SOUTH)
IRRIGATION AND DRAINAGE PROJECT

# INFLOW-OUTFLOW CHANNEL LOSSES AND CANAL LINNING COST-EFFECTIVENESS IN THE FORDWAH EASTERN SADIQIA (SOUTH) IRRIGATION AND DRAINAGE PROJECT

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# FOREWORD

The large discrepancy in measured channel losses between the ponding method and the inflow-outflow method in the **FESS** project area has been the focus of considerable controversy. The result of field measurements by the International Waterlogging and Salinity Research Institute (IWASRI) in collaboration with the International Sedimentation Research Institute, Pakistan (ISRIP) reflected that ponding channel losses are equivalent to roughly one-third of inflow-outflow channel losses. Explaining this discrepancy has been a real dilemma that has challenged the minds of many professional engineers.

After much scrutiny and considerable analysis, Bodla et al (1998, 1999) have reported the water savings from the completed canal geomembrane lining as 15,215 acre-feet and 48,182 acre-feet for ponding tests and inflow-outflow tests, respectively. The IIMI inflow-outflow tests conducted by the Bahawalnagar Field Station staff showed similar results with that of IWASRI-ISRIP for the Hakra 3-R Khattan Distributary, but lower channel losses for all other cases. Also, IIMI conducted some additional "after lining" inflow-outflow tests during May-June 1999. The estimated reduction in channel losses for the completed canal lining as reported herein is 26,600 acre-feet.

This report offers a different approach for employing the inflow-outflow method for measuring channel losses. The inflow and outflow structures are field calibrated and discharge ratings are developed beforehand. The technology for developing accurate discharge ratings is also important. During the inflow-outflow test, only water levels, along with gate openings for gate structures are measured. This allows the test to be completed in only a few hours. During this time period, water levels are measured every 15-20 minutes at the inflow control structure. If an unsteady flow occurred, the results are discarded and the test repeated.

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## ACKNOWLEDGEMENTS

The authors would like to sincerely thank Dr. M. Abid Bodla for his cooperation in undertaking this study. He has willingly provided the field data on measured channel losses in the FESS project area collected under his supervision. On a number of occasions, the dilemma of the discrepancies between the ponding tests and the inflow-outflow tests have been thoroughly discussed. Most importantly, this has been a highly professional debate conducted in a manner of scientific inquiry. Finally, there is no conclusive evidence that would resolve this dilemma. But, out of these discussions has grown a tremendous respect for an extremely good engineer and scientist – a real researcher!

The authors extend thanks to Mr. Manzoor Hussain and Tabrez Ahmad of IWMI for providing excellent secretarial services and typing this report.

# 1 METHODOLOGY CONTROVERSY

Canal lining was an important component of Phase 1 of the Fordwah Eastern Sadiqia South (FESS) Irrigation and Drainage Project. The Punjab Department of Irrigation and Power, with Mott MacDonald as the canal lining consultants and China Beijing as the contractor, implemented the program. Prior to initiating the construction, the International Waterlogging and Salinity Research Institute (IWASRI[1]) and the International Sedimentation Research Institute of Pakistan (ISRIP) undertook both, ponding tests and inflow-outflow tests to evaluate the channel (seepage) losses among various reaches of secondary canals (distributaries and minors) scattered throughout the FESS project area. The area covered spans more than one lakh hectares (105,000 ha.) of culturable command (CCA).

For three years. from December 1994 to January 1998, 39 pre-lining and post-lining ponding tests and 14 pre-lining inflow-outflow tests were conducted on seven irrigation channels in FESS. The pre-lining ponding tests resulted in channel losses ranging from 1.40 – 3.31 cubic feet per second (cfs) per million square feet (msf) of channel wetted perimeter, with a mean seepage rate of 2.28 cfs/msf for the channels to be lined under FESS Phase 1. In contrast, the pre-lining inflow-outflow tests ranged from 3.7 – 7.3 cfs/msf with an average seepage rate of 6.20 cfs/msf for the channels to be lined. For various reaches. the inflow-outflow results exceeded the ponding test results, by 1.5 – 5 cfs/msf (Bodla et al 1999).

The large discrepancy between the ponding and inflow-outflow results proved to be a real dilemma. The analysis of this situation required as sound a scientific approach as possible, along with good professional .judgement. After rigorous analysis, along with consultations with many others knowledgeable on this subject, Bodla et al (1998) concluded that the ponding method was preferable to the inflow-outtlow method.

This report takes a different approach. A case is made that a meticulous procedure for the inflow-outtlow method will provide more reasonable estimates for channel losses (seepage plus leakage) than the ponding method.

[1] Both, IWASRI and ISRIP are research organizations under the Federal Water and Power Development Authority (WAPDA)

# 2 MEASUREMENT OF CHANNEL LOSSES[2]

The term "channel losses" is used to reflect that the measured losses may be a combination of "seepage" plus "leakage". This is particularly the case for the inflow-outflow method, but may also be true for the ponding method (e.g. rodent and snake holes).

## 2.1 INFLOW-OUTFLOW METHOD

In the majority of cases, the inflow-outflow method of measuring channel losses is highly preferred because the losses are being measured under the usual operating condition of the canal. The best procedure. but time consuming, is to sub-divide the canal network into reaches. Cross-regulators along a canal or branch canal would define the boundary between two reaches. Then, the gates at each cross-regulator would be field-calibrated in order to develop a discharge rating for each flow control structure. along with each distributary head regular off-taking in each reach. Then, during the inflow-outflow test. the flow is monitored at the head of the system to detect any changes in the water supply entering the canal; the water levels are monitored every 15-30 minutes to assure that steady-state flow conditions are occurring in the system. Then, the water levels are recorded at each structure in a relatively short time period of one or two hours. If steady-state flow conditions continued to exist during the duration of the test. then the results are accepted; if not, the test is repeated until this steady-state flow condition is satisfied

When the channel losses are low, such as being comparable with the accuracy of the current meter measurements used in field calibration of the flow control structures, then the ponding method must be used.

An accuracy of 2-3 percent can be achieved with a current meter, provided that: (1) the current meter velocity calibration is periodically checked using a towing tank or a V-notch weir at the head of a rectangular lined channel; and (2) excellent current metering procedures are used. When the second requirement is not met then the error in the calculated discharge rate will be 5-10 percent, which is frequently the case in Pakistan. When the first requirement is not satisfied, the error in velocity measurements with the current meter is commonly at least 10 percent, sometimes 20 percent, and occasionally as much as 30 percent. These statements are based on experiences in the **U.S.A.,** Pakistan, Thailand and the Philippines. In contrast, while calibrating a series of gate structures (two canal headworks and the river control gates) below a new dam constructed in Bolivia using an electro-magnetic current meter, an error in the calculated discharge rate of one-half of one percent could be detected. This amazed everyone: as a result, excellent discharge ratings were developed for each gate, which are more accurate than a single discharge measurement.

## 2.2 PONDING METHOD

The ponding method is used when the channel losses are relatively low. Contrary to some authors, the ponding method cannot be considered a standard for evaluating channel losses. The reason is because it violates one major condition; instead of having a sloping water surface gradient representative of the channel under usual operating conditions, a pond is a reservoir having a horizontal water surface. The only exception is in cases where the wind velocity results in one end of the pond having a higher water surface elevation than the other end of the pond. Also, it is well known that a pond filled with sediment-laden canal water will result in lower estimates of channel

[2] The contents of this section reflect the experiences and judgement of the senior author, much of which can also be considered as conjectural. The data presented in Sections *3.* 4 and **5** will provide some insights regarding the controversy between ponding tests and inflow-outflow tests.

losses because these sediments are filtered as the water seeps into the earthen embankment, thereby reducing the porosity of the soil at the wetted perimeter for a depth of only a few millimeters (mm), which is sufficient to significantly reduce the infiltration (seepage) into the bed and embankments.

The condition of having a water surface gradient corresponding with the usual operation conditions of the channel is related to the biological life in earthen embankments. An ideal environment for biological life is above the phreatic (saturation) line in embankments where unsaturated flow occurs, consisting of water from capillary rise, along with air. Besides rodents and snakes, there are worms, ants, etc. An interesting learning experience is to use a shovel (*kassi*) to carefully excavate the embankment, beginning just above the normal operating water surface to just above the phreatic line, through the entire width of the embankment. This enables discovering leakage holes, caverns, side passages and numerous small insect pathways.

A schematic of a typical seepage loss rate curve is shown in Figure 1. Note that the seepage rate increases rapidly as the water level in the channel is raised, particularly above the normal operating level. This is partly due to an increased hydraulic head, but is mostly related to the biological life in the embankments. When the water level is raised above the normal operating level, the rapid increase in channel losses is largely due to leakage and partly due to seepage.

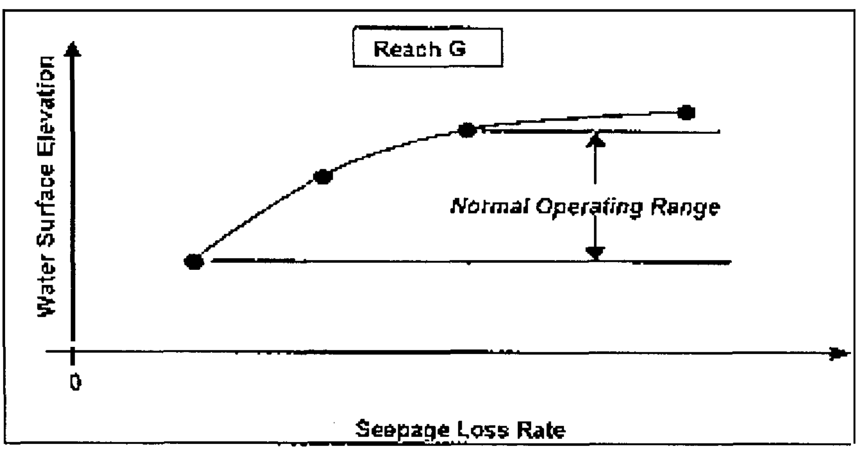


Figure 1. Example of a seepage loss rate curve for a canal reach.

As stated above, filling a pond with sediment-laden water will result in lower channel losses. Likewise, there is a concern when tubewell water is used to fill a pond. In the FESS project area, generally, the groundwater is fairly saline. The real concern with using groundwater is soil sodicity. In other words, filling a pond with tubewell water in the FESS area could result in the surface soils along the wetted perimeter becoming sodic. Although the embankments were constructed with coarse sandy loam soils, undoubtedly, the soils along the wetted perimeter contain finer soils resulting from filtering the canal water every time the channel has been closed. If these soils are only 2-5 mm in thickness, then became sodic, there would be a significant reduction in channel losses. Admittedly, this is a hypothesis that is purely conjecture. There is no field data to substantiate this hypothesis. Also, the process of water infiltrating into soils is the last major frontier of irrigation science that needs to be conquered. However, that infiltration rates are largely dictated by the soil physics and soil chemistry of just a few millimeters of thickness at the soil surface, is known.

# 3 CHANNEL LOSSES IN THE CHISHTIAN SUBDIVISION

## 3.1 DISTRIBUTARIES

The Fordwah Canal and the Eastern Sadiqia Canal obtain their water supply through the Suleimanki Headworks located along the Sutlej River. These waters come from the Chenab River during the summer *kharif* season and from the Mangla Reservoir during the winter ***rubi*** season. There are three subdivisions in the Fordwah Canal Division (Figure 2), with the Chishtian Subdivision being at the tail along the Fordwah Branch Canal. Fourteen distributaries (Figure 3) and eighteen direct outlets off-take from this branch canal in the Chishtian Subdivision. Some **of** the physical characteristics **of** these distributaries are listed in Table 1.

Some hydraulic calibration work was undertaken in 1993-94 on the field calibration of cross-regulators along the Fordwah Branch Canal and distributary head regulators. Then, in 1995, an earnest effort was undertaken to field-calibrate all of the outlet structures along each of the fourteen distributaries, which totaled approximately 500 outlets (*moghas*). After calibrating all of the outlets along a distributary or minor, an inflow-outflow test was conducted to measure the channel losses (seepage plus leakage) for various reaches in the distributary network. These inflow-outflow tests provided valuable insights regarding the accuracy of the hydraulic calibration of the outlet structures serving the tertiary watercourses. In other words, the inflow-outflow tests provided the sensitivity analysis regarding the accuracy of outlet field calibrations. This reflected a new approach in IIMI's fieldwork.

Table 1. Physical characteristics of distributaries in the Chishtian Subdivision.

| Distributary | Status | Design discharge (Cusecs) | Length (feet) | CCA (acres) | Numbers of outlets. |
|---|---|---|---|---|---|
| 3-L | NP | 18 | 23100 | 2970 | 6 |
| Mohar | NP | 38 | 20240 | 4447 | 12 |
| Hussainabad Minor | | 11 | 8840 | 738 | 3 |
| Daulat | NP | 209 | 115150 | 32690 | 72 |
| Biluka Minor | | 9 | 12700 | 1320 | 7 |
| Nakewah Minor | | 43 | 43800 | 6910 | 29 |
| Phogan | NP | 17.5 | 8750 | 2211 | 9 |
| 4-L | NP | 14 | 17350 | 2053 | 7 |
| Khemgarh | NP | 24 | 15500 | 5053 | 9 |
| Jagir | P | 28 | 13830 | 4704 | 9 |
| Shahar Farid | NP | 153 | 74880 | 24892 | 47 |
| Heenvah Minor | | 40 | 32180 | 6658 | 27 |
| Masood | P | 35 | 52300 | 8099 | 16 |
| Soda | NP | 77 | 43700 | 10113 | 33 |
| 5-L | P | 4 | 11300 | 884 | 3 |
| Fordwah | P | 158 | 139780 | 36679 | 87 |
| Jiwan Minor | | 27 | 34520 | 7089 | 22 |
| Mehmud | P | 8.25 | 11860 | 20066 | 7 |
| Azim | NP | 244 | 118000 | 30459 | 80 |
| Rathi Minor | | 10 | 10000 | 1395 | 10 |
| Feroze Minor | | 9 | 8000 | 1226 | 4 |
| Forest Minor | | 9 | 3300 | 730 | 4 |

NP: Non-perennial (summer (*kharif*) season)
P: Perennial (year-round canal water supply)

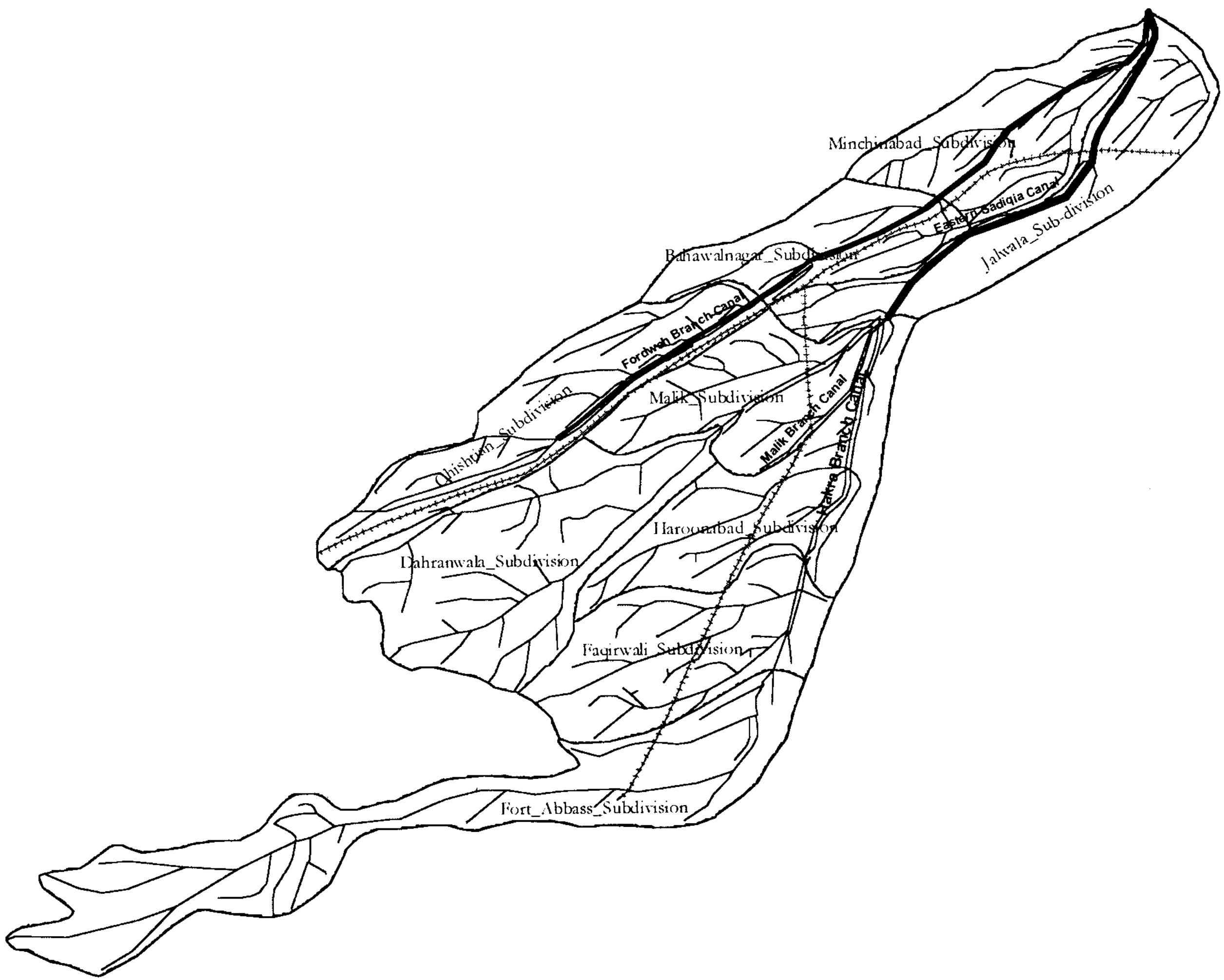


Figure 2. Administrative subdivisions in the Fordwah Eastern Sadiqia Irrigation System in the Sutlej Valley.

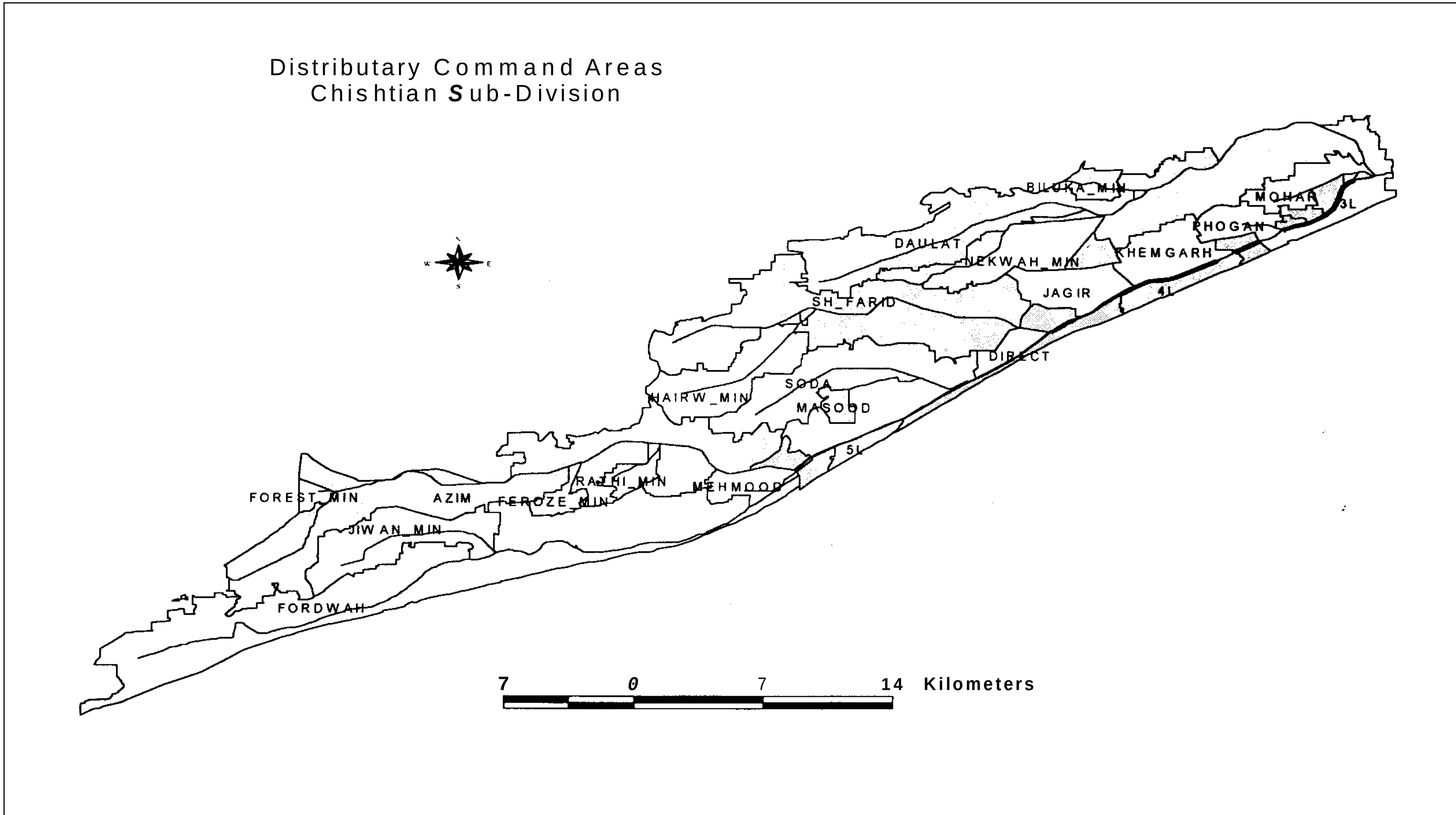


Figure 3. Distributaries and their command areas in the Chishtian Subdivision.

The inflow-outflow tests were mostly conducted from June 1995 to May 1996. The results by Tareen et al (1996) are summarized in Table **2.**

Table 2. Channel **loss** rates measured by the inflow-outflow method for the fourteen distributaries in the Chishtian Subdivision (Tareen et al 1996).

| Channel Name | Inflow (cfs) | Total ***Q*** of outlets (cfs) | Outflow (cfs) | Channel losses (cfs) | Wetted perimeter (msf) | Channel loss rate (cfs/msf) |
|---|---|---|---|---|---|---|
| 3-L | 20.12 | 15.50 | 4.10 | 0.52 | 0.18 | 2.9 |
| Daulat | 153.83 | 143.33 | 3.35 | 7.15 | 2.73 | 2.6 |
| Mohar | 33.71 | 30.33 | 2.56 | 0.82 | 0.29 | 2.8 |
| Phogan | 28.50 | 14.37 | 13.34 | 0.79 | 0.09 | 8.8 |
| 4-L | 16.99 | 14.21 | 3.04 | -0.26 | 0.137 | -1.9 |
| Khemgarh | 42.70 | 36.70 | 2.99 | 3.01 | 0.143 | 21.0 |
| Jaqir | 26.53 | 24.16 | 2.14 | 0.23 | 0.1 19 | 1.9 |
| Shahar Farid | 134.30 | 120.15 | 0.10 | 14.05 | 1.41 | 10.0 |
| Masood | 23.10 | 21.80 | 1.90 | -0.60 | 0.49 | -1.2 |
| Soda | 77.76 | 72.49 | 0.00 | 5.27 | 0.73 | 7.2 |
| 5-L | 3.88 | 2.32 | 0.98 | 0.58 | 0.05 | 11.6 |
| Fordwah | 167.30 | 157.96 | 2.36 | 6.98 | 3.32 | 2.1 |
| Azim | 194.81 | | | | | |
| Mahmood | 18.80 | 8.60 | 10.09 | 0.1 1 | 0.172 | 0.6 |

Six distributaries (3-L, Mohar, 4-L, Khemgarh, Jagir and Masood) parallel the Fordwah Branch Canal in their head reaches, so they intercept seepage from the Fordwah Branch. Distributaries 4-L and Masood gained water (negative loss rate) because of intercepting this seepage water. Three distributaries (3-L, Mohar and Jaqir) had low loss rates ranging from 1.9 – 2.9 cfs/msf because they intercepted seepage in the head reaches, then higher channel losses were measured in the lower reaches, thereby resulting in this low range of channel losses. Khemgarh Distributary was an exception, where heavy losses occurred in the head reach because contractors had excavated significant portions of the embankment and there was considerable ponded water alongside the distributary as a result of both, seepage and heavy leakage at that time.

The other eight distributaries varied from 0.6 cfs/msf (Mahmood at the tail of Fordwah Branch) to 11.6 cfs/msf (5-L). Daulat and Fordwah Distributaries had measured channel loss rates of 2.6 cfs/msf and 2.1 cfs/msf, respectively. In contrast, the measured channel loss rates were 10.0 cfs/msf for the Shahar Farid Distributary, 8.8 cfs/msf for the Phogan Distributary and 7.2 cfs/msf for the Soda Distributary.

In general, the results from the inflow-outflow tests made good physical sense. The argument is not that this technique gives the correct results, but rather, that the inflow-outflow method provides reasonably good estimates of the actual channel losses.

### 3.2 FORDWAH BRANCH CANAL

**A** major inflow-outflow test was conducted on 6 June 1995 on the Fordwah Branch Canal, from RD 199 to RD 371 (tail). Prior to this test, this canal was operated under steady-state flow conditions, which required a few days to achieve. This allowed the model "Simulation of Irrigation Canals" (SIC) to be calibrated, which facilitated the analysis. However, during this test, the water levels did rise somewhat during the day, which would affect the results by yielding lower channel losses than would occur if steady-state flow conditions had existed.

The results are shown in Table 3. The inflow at the RD 199 cross-regulator was measured as 885.2 cusecs, while the total outflows were 766.3 cusecs, indicating channel losses of 118.9 cusecs. This amounts to 13.4 percent of the inflow. The total area of wetted perimeter was 12.4 million square feet (msf), so the channel loss rate is 9.6 cfs/msf.

Table 3. Results of the inflow-outflow test for the Fordwah Branch from RD 199-371.

| Structure[1] | $h_u$[2] feet | $h_d$ feet | $G_O$ feet | Inflow cusecs | Outflow cusecs |
|---|---|---|---|---|---|
| RD 199 | 5.14 | 0.82 | 2.22 | 885.2 | |
| Daulat | 4.28 | | | | Closed[3] |
| Mohar | 4.885 | | | | 30.1 |
| | 3.285 | 3.200 | | | 13.9 |
| DO 260115-R | | | | | Closed |
| DO 263186-R | | | | | 2.7 |
| Phogan | 2.40 | 0.96 | | | 25.9 |
| DO 272600-R | | | | | 2.5 |
| DO 273200-L | | | | | 2.4 |
| Khemgarh | 2.745 | 1.745 | 0.55 | | 36.7 |
| 4-L | 3.895 | 3.805 | | | 10.3 |
| DO 296500-R | | | | | 6.0 |
| Jagir | 6.27 | 5.28 | 1.29 | | 38.0 |
| DO 303000-L | | | | | 1.2 |
| DO 305500-L | | | | | 1.9 |
| DO 308855-L | | | | | 2.1 |
| DO 311620-R | | | | | 3.2 |
| DO 313384-L | | | | | 2.6 |
| DO 314050-R | | | | | Closed |
| DO 316250-L | | | | | 3.1 |
| Shahr Farid | 5.37 | | 1.41 | | 141.8 |
| Masood | 5.27 | 5.00 | 1.72 | | 23.0 |
| Soda | 1.42[4] | | | | 63.7 |
| DO 333500-L | | | | | 2.4 |
| DO 342275-L | | | | | 2.3 |
| 5-L | 3.155 | 2.805 | | | 11.5 |
| DO 352700-R | | | | | 3.2 |
| DO 363500-L | | | | | Closed |
| DO 368000-R | | | | | 6.9 |
| DO 370742-L | | | | | 1.7 |
| Fordwah | 4.72 | 2.38 | 0.67 | | 84.9 |
| Azim | 4.69 | 1.26 | 2.12 | | 204.9 |
| Mehmood | 3.12 | 2.69 | 0.99 | | 27.4 |
| Total | | | | 885.2 | 766.3 |

[1]DO means direct outlet
[2]$h_u$ is the upstream water depth over the crest, $h_d$ is the downstream water depth over the crest and $G_o$ is the gate opening
[3]Some leakage and overflow occurred. A value of 10 cusecs is assumed.
[4]Representative of the water depth over the karees.

## 4 CHANNELS LOSSES IN THE MALIK SUBDIVISION

The Malik Subdivision (Figure 4) consists of the Malik Branch Canal (design discharge **of** 1,538 cusecs) and the Sirajwah Distributary. Both distributaries off-take at the tail (RD 245) of the Eastern Sadiqia Canal. The Dahranwala Subdivision starts at the tail of the Malik Branch Canal, and consists of the Murad and Fateh Distributaries off-taking from the tail of the Malik Branch Canal.

### 4.1 GUJJIANI DISTRIBUTARY

The Gujjiani Distributary off-takes from the right side of the Malik Branch Canal at RD 38+900, which is the major perennial distributary in the Malik Subdivision. The Gujjiani Distributary has a design discharge of 319 cusecs and a length of almost 140,000 feet (28 canal miles). Six minors off-take from the Gujjiani Distributary, plus 102 direct outlets.

During the last week of August and the first week of September 1996, a training course was conducted with the Punjab Irrigation and Power Department on the field calibration of irrigation structures, and also to conduct a quality inflow-outflow test. In the training, discharges had been measured downstream of the Gujjiani Distributary cross regulators and downstream of the off-taking minors. As these discharges were to be almost similar *to* the discharges expected on the day of the inflow-outflow test, and the concerned structures had been calibrated, the upstream and downstream water level readings would be sufficient to determine the discharges at these **points.**

IIMI staff had already calibrated all of the direct outlets along the Gujjiani Distributary. If the flow condition of the concerned outlet does not change, then the measurement of the upstream and downstream water levels are sufficient to know the discharge through the outlet. In case the flow condition of **an** outlet is not the same as when the outlet was calibrated, and there **has** not been a second calibration of the outlet for the differing flow condition, the outlet has to be re-calibrated at the time of the inflow-outflow test. The wetted area was estimated by taking the actual wetted perimeter at different locations along the distributary and multiplying by the length between two different sections.

Considerable work had to be done during a single day and in **as** short a time span as possible. This was necessary in order to minimize the risk of any fluctuations that might enter the distributary that would affect the results of the test. For this reason, the participants were divided into groups. Each group took a different section of the total distributary length and tried to finish the work as quickly **as** possible without allowing the accuracy to suffer. The results of the inflow-outflow test are depicted in Table 4.

Table 4. Results of the inflow-outflow test for the Gujjiani Distributary.

| Reach | Inflow Gujjiani (Cfs) | Outflow Gujjiani (cfs) | Total Q of O/L & minors (cfs) | Seepage (cfs) | Wetted area (msft) | Seepage rate (cfs/msf) |
|---|---|---|---|---|---|---|
| Gujjiani head to Rd 53200 | 427.72 | 202.19 | 220.19 | 5.34 | 2.974 | 1.80 |
| Gujjiani RD 53200 to 98700 | 202.19 | 63.32 | 135.85 | 3.02 | 1.568 | 1.93 |
| Gujjiani RD 98700 to tail at RD 139905 | 63.32 | 2.86 | 58.64 | 1.82 | 0.507 | 3.59 |
| Total Gujjiani Distributary | 427.72 | 2.86 | 414.68 | 10.18 | 5.048 | 2.02 |

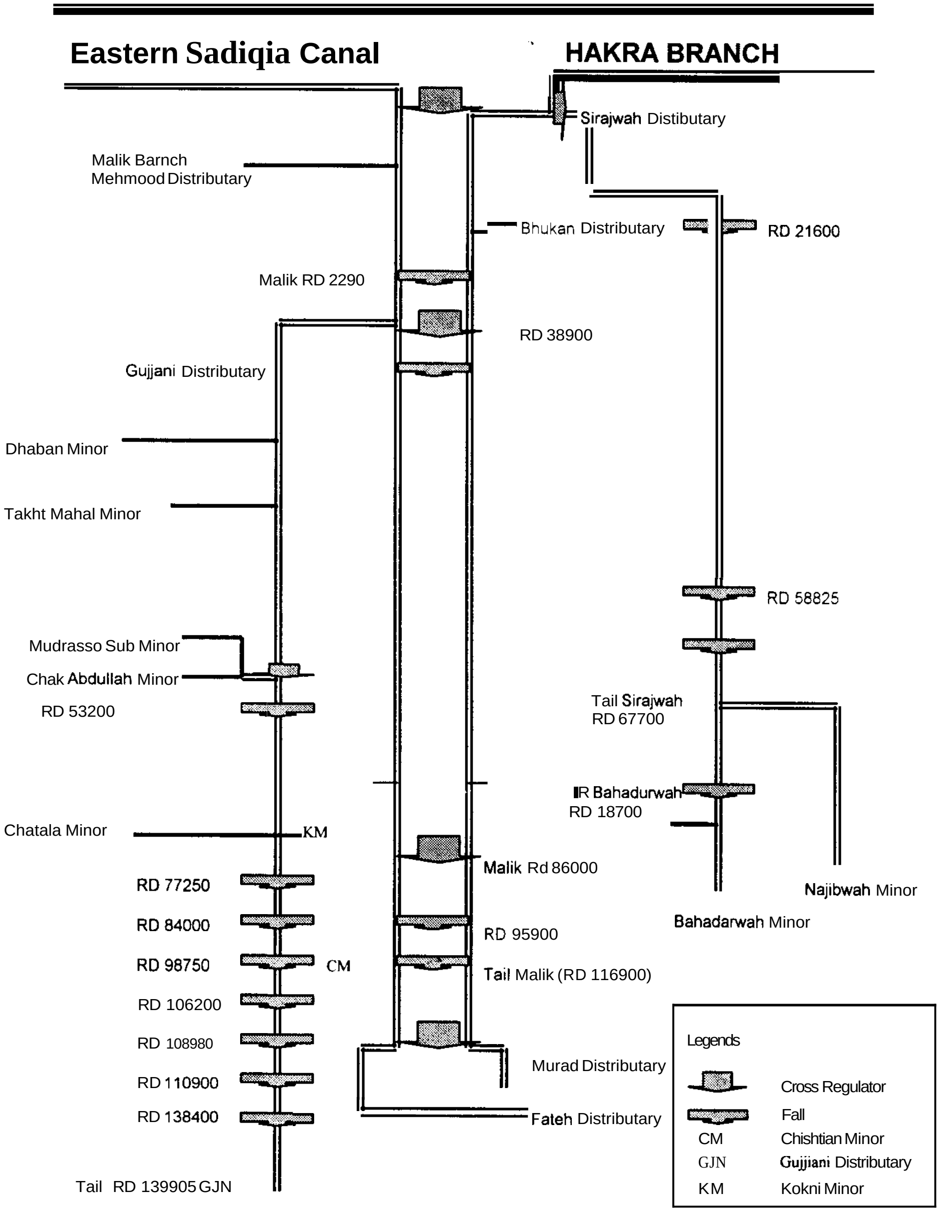


Figure 4. Schematic layout of the Malik Subdivision.

According to the results of the inflow-outflow test, the seepage in the Gujjiani Distributary is very low. Seepage over the whole length of the distributary is around 2 cubic feet per second per million square feet (cfs/msf) of wetted area. In the first two reaches of the distributary, the seepage is a little less than 2 cfs/msf, while the seepage increases to 3.59 cfs/msf for the third (tail) reach.

In the inflow-outflow test, the accuracy of the measurements is of prime importance. If there is any negligence in calibrating outlets or structures, this will influence the end results of the test to a significant degree, as illustrated by Table 5. The percentage of the seepage is calculated in relation to the inflow of each reach.

Table 5. Percentage of seepage related to the inflow of Gujjiani Distributary.

| Reach | Inflow Gujjiani (cfs) | Seepage (cfs) | Seepage (percentage) |
|---|---|---|---|
| Gujjiani head to RD 53200 | 427.72 | 5.34 | 1.25 |
| Gujjiani RD 53200 to 98700 | 202.19 | 3.02 | 1.49 |
| Gujjiani RD 98700 to tail at RD 139905 | 63.32 | 1.82 | 2.87 |
| Total Gujjiani Distributary | 427.72 | 10.18 | 2.38 |

The amount of seepage is a very low percentage of the inflow. According to the conducted inflow-outflow test. the seepage for the Gujjiani Distributary is 2.4 percent of the inflow. This means that the calibration of the structures and outlets should be done in such a manner that the observed total discharges are accurate to well below one percent. By dividing the Gujjiani Distributary into different sections and having separate resulting seepage percentages, the range of values provides a good indication for the accuracy of the test.

A few months later, on 31 October 1996, IIMI field staff conducted an inflow-outflow test on the Takhat Mahal Minor, which off-takes from the Gujjiani Distributary (Figure 4). The measured inflow was 40.66 cusecs, while the sum of all outflows was 38.75 cusecs, which results in 1.91 cusecs of channel losses. The measured wetted perimeter was 440,000 square feet (0.44 rnsf). Thus, the measured channel loss rate is 4.3 cfs/msf (1.91 cfs ÷ 0.44 msf = 4.34 cfs/msf).

## 4.2 BHUKAN DISTRIBUTARY

On 25 May 1995, the Watercourse Monitoring and Evaluation Directorate (WMED) of WAPDA, assisted by the IIMI Director, conducted an inflow-outflow test on the Bhukan Distributary. The measured discharge at the head regulator was 15.94 cfs, while the total discharge from eight outlets was 14.88 cfs, resulting in channel losses of 1.06 cfs (6.6 percent of the inflow). The wetted perimeter was measured every 100 meters and the total wetted perimeter was 151,175 square feet. Thus, the measured channel loss rate was 7.0 cfs/msf (1.06 cfs ÷ 0.151175 rnsf).

On 20 June 1999, the IIMI Bahawalnagar Field Station staff conducted an inflow-outflow test on the Bhukan Distributary to evaluate the geo-membrane canal lining. The measured inflow was 20.89 cfs, while the sum of outflows was 20.36 cfs, which results in a channel loss of 0.53 cfs. The area of measured wetted perimeter was 118,720 square feet. Thus, the channel losses rate is 4.46 cfs/msf (0.53 cfs ÷ 0.11872 rnsf).

## 4.3 SIRAJWAH DISTRIBUTARY

The Sirajwah Distributary is a perennial distributary having a design discharge of 197 cusecs. The tail is at RD 67+700, where the Bahadanvah and Najibwah Minors off-take (Figure 4).

For the inflow-outflow test conducted in early November 1995, the full length (67,700 feet) was treated as one reach. The inflow at the Sirajwah Distributary head regulator was 194.7 cusecs. The total outflows to 36 outlets (three were closed) was 65.7 cusecs, while the total outflows to the two minors off-taking from the tail was 120.4 cusecs, giving a total outflow of 186.1 cusecs (65.7+120.4). Thus, the channel losses are 8.6 cusecs (194.7-186.1). The total measured wetted perimeter was 2.6 msf. The channel loss rate is 3.3 cusecs/msf (8.6 cusecs÷ 2.6 msf).

IIMI conducted an inflow-outflow test on the lined Najibwah Minor on 13 March 1999. The inflow was 43.17 cfs and the channel losses were 2.70 cfs (6.25 percent of the inflow). The measured wetted perimeter was 619,015 square feet. Thus, the channel loss rate is 4.36 cfs/msf (2.70 cfs ÷ 0.619 msf).

## 4.4 MALIK BRANCH CANAL

IWASRI and ISRIP conducted two ponding tests in January 1998 during the canal closure (Bodla et al 1999). One pond was located in the head reach from RD 15+980 to RD 16+930 and another in the middle reach from RD 67+050 to RD 67+845 (the tail of Malik Branch is at RD 116+900, as shown in Figure 4). The measured seepage rate was 1.04 cfs/msf in the upper reach and 1.5 cfs/msf in the middle reach. Later, the investigators excavated some test pits during the canal closure period that disclosed an extensive larger of clay soil at a shallow depth beneath the canal bed. Bodla et al (1999) state that this clay layer not only explains the low values **of** measured seepage loss rates, but also the large amounts of ponded water alongside the Malik Branch Canal.

Such low values for seepage loss rates (1.04 cfs/msf and 1.50 cfs/msf) are extremely surprising. For example, ponding tests on a month-old machine concrete lining with no cracks resulted in uniform loss rates of 0.8 cfs/msf for canals having a discharge capacity of 100 cfs, or less, in the western U.S.A. If the Malik Branch Canal had near-perfect concrete lining, then the expected channel loss rate would be **1.0-1.5** cfs/msf. Since this is an earthen canal, this casts much suspicion about the accuracy of the ponding method. There is no doubt about the field methodology used in the ponding tests, but rather the issues discussed in Section 2.2.

The IIMI Bahawalnagar Field Station staff has conducted two inflow-outflow tests on the Malik Branch Canal, from RD 0-116.9 (tail) on 27 March 1997 and 11 May 1999, respectively. The 1997 test had an inflow of 1,773 cusecs and channel losses of 95.2 cusecs, which resulted in a channel loss rate of 9.1 cfs/msf. The 1999 test had a slightly higher inflow of 1,833 cusecs and channel losses of 108.7 cusecs, resulting in a loss rate of 10.4 cfs/msf, which would be expected when based on Figure 1.

# 5 CHANNEL LOSSES IN THE HAROONABAD SUBDIVISION

## 5.1 DISTRIBUTARIES AND MINORS

As mentioned in Section 1, IWASRI and ISRIP have evaluated channel losses in the **FESS** area using both, the ponding method (Table 6) and inflow-outflow method (Table 7). Since 1995, the IIMl Bahawalnagar Field Station staff is engaged in evaluating channel losses using the inflow-outflow method. Some comparisons can be drawn from these sets of data.

In addition, WMED conducted an inflow-outflow test on the Hakra 2-R Dunga Distributary on 26 May 1995, assisted by the Director of IIMI-Pakistan. The measured inflow at the distributary head regulator was 29.03 cfs. The total outflow from the 13 outlets was 27.04 cfs. Therefore, the channel losses are 1.99 cfs, which is 6.8 percent of the inflow. The total length of this distributary is 33,720 feet. The wetted perimeter was measured every 100 m, with the average being 9.31 feet, so that the total area of wetted perimeter is 313,933 square feet. Thus, the channel loss rate is 6.34 cfs/msf (1.99 cfs ÷ 0.313933 msf).

The inflow-outflow tests conducted by the IIMI Bahawalnagar Field Station staff are listed in Table **8.** An interesting comparison can be made for the Hakra **3-R** Khattan Distributary. The measured seepage loss rate is 7.77 cfs/msf in Table **8** for the reach RD 33-73. In Table 7, the reach RD 24-55 has a channel loss rate of 6.25 cfs/msf, while the reach Rd 55-71.8 has a channel loss rate of 10.42 cfs/msf. The weighted value for RD 33-71.8 being:

$$\text{Weighted Channel Loss Rate (RD 33-73)} = \frac{6.25\ (22\ \text{RDs}) + 10.42\ (16.8\ \text{RDs})}{38.8\ \text{RDs}} = 8.06\ \text{cfs/msf}$$

Thus, the difference between inflow-outflow tests listed in Tables 7 and **8** for the Hakra **3-R** Khattan Distributary is less than 4 percent.

## 5.2 HAKRA BRANCH CANAL

On 18 May 1999, IIMl conducted an inflow-outflow test on the Hakra Branch Canal from RD 0+000 to RD 89+750. The inflow was 2,594 cusecs and the total outflows were 2,502 cusecs, with the resulting channel losses being 92 cusecs. The measured wetted perimeter was 13.47 msf. Thus, the channel loss rate is ***6.8*** cfs/msf (92 cfs ÷ 13.47 msf).

Because of the military situation during June 1999, IIMl was unable to conduct additional inflow-outflow tests from RD 0-89.75. **Also,** as a consequence of the military situation, there are no inflow-outflow tests that have been conducted from RD 89+750 to RD 165+000 on the Hakra Branch Canal.

Table **6.** Summary of ponding seepage loss rates in the FESS area (Taken from Bodla et al **1998).**

| Canal Under Test | Reach RD's | Lining Type(*) | Year | Discharge (c fs) | Canal Geometry | | Soil Type R/B-B-L/B | Depth to Water Table | Average Seepage Losses | | Average Seepage Losses |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | FSD (ft) | BW (ft) | | (ft) | (ft/day) | (cfs/mst) | cfs/msf (ft/day) |
| Najibwah Minor | 0+000 - 1+000 | PL | 1995 | 43.0 | 2.5 | 14.0 | -S.L-S-S.L | 4.0 | 0.11 | 1.25 | |
| | 4+626 - 5+626 | PL | 1995 | 43.0 | 2.5 | 13.0 | Si.L-S-S.L | 4.13 | 0.12 | 1.38 | |
| | 8+545 - 9+555 | PL | 1996 | 39.0 | 2.5 | 10.5 | Si.L-S.L-Si.L | 4 | 0.12 | --T-- | 1.40 (0.12) |
| | | | | | | | | | | .35 | |
| | 15+000 - 16+007 | PL | 1996 | 33.0 | 2.4 | 9.5 | Si.L-S.L-Si.L | 4 | 0.14 | 1.62 | |
| IR Bahadurwah Minor | 0+075 - 1+110 | EL (1c) | 1996 | 4.0 | **1.1** | 3 | Si.L-Si.L-Si.L | 6 | 0.23 | 2.65 | 2.65 (0.23) |
| 3R Khatan Disty | 2+200 - 3+200 | EL (Option **2a)** | 1996 | 307.0 | 4.4 | 35 | S.L-S-S.L | 5 | 0.10 | 1.19 | |
| | 130+250 - 131+250 | PL | I996 | 60.0 | 2.4 | 17 | Si.L-S.L-S.L | 7 | 0.38 | 4.39 | |
| | 14+700 - 15+750 | EL (Option **la)** | 1997 | 300.0 | 4.4 | 35 | | 3.5 | 0.08 | 0.96 | 1.88 (0.16) |
| | 25+000 - 26+000 | EL (Option 2b) | 1997 | 276.0 | 4.3 | 35 | | 4 | 0.12 | 1.35 | |
| | 29+000 - 29+960 | EL (Option I b) | I997 | 276.0 | 4.3 | 35 | | 2.5 | 0.14 | 1.57 | |
| | 37+750 - 38+780 | None | 1997 | 276.0 | 4.3 | 32 | | 2.5 | 0.16 | | |
| IR/3R Qaziwala Minor | 0+000 - 1+000 | EL (2 **&** 1**)** | 1995 | 79.0 | 3.0 | 20.0 | Si.L-S-Si.L | 5.0 | 0.13 | 1.51 | |
| | 16+030 - 17+035 | EL (5c) | I996 | 66.0 | 2.7 | 19.0 | Si.L-S.L-Si.L | 4.5 | 0.18 | 2.04 | |
| | 27+800 - 28+800 | EL (6) | 1996 | 40.0 | 2.4 | 12.0 | Si.L-S.L-Si.L | 6 | 0.20 | 2.28 | |
| | 10+650 - 11+650 | EL (I b) | 1997 | 66.80 | 3.6 | 20.0 | | 4 | 0.22 | 2.60 | 2.04 (0.18) |
| | 20+250 - 21+200 | EL (5c) | 1997 | 40.66 | 3.6 | 18.0 | | 4 | 0.26 | 2.96 | |
| | 35+600 - 36+600 | EL (Ic) | 1997 | 40.0 | 3.0 | 12.0 | | 7 | 0.12 | | |
| | 43+000 - 43+950 | EL (Ic) | 1997 | 17.0 | 2.0 | 9.0 | | 5 | 0.13 | | |
| IL/3R Jourkanwala | 0+500 - 1+500 | PL | I995 | 34.0 | 2.10 | **10** | Si.L-S.L-S.L | 10.20 | 0.37 | 4.28 | |
| Minor | **16+100** - 17+108 | PL | 1996 | 13.0 | 1.7 | 7 | Si.L-L.S-S.L | 8.5 | 0.20 | 2.35 | 3.31 (0.29) |
| **4R** Haroonabad Disty | 76+000 - 76+842 | PL | 1995 | 51.0 | 3.3 | 18 | Si.L-Si.L-L | 2.0 | 0.16 | 1.86 | |
| | 62+200 - 63+200 | PL | 1996 | 240.0 | 2.37 | 27.0 | S.L.-S.-S.L. | 4 | 0.22 | **.55** | 2.41 (0.21) |
| | 88+750 - 89+765 | PL | 1996 | 46.0 | 2.2 | **15** | Si.L.-S.L.-L. | 3.5 | 0.24 | 2.83 | |
| Malik Branch | 15+980 - 16+930 | | 1998 | 1538.0 | 6.5 | 90 | | | 0.09 | 1.04 | |
| | 67+050 - 67+845 | ***R** | 1998 | 1 154.0 | 6.0 | 75 | | | 0.13 | | 1.27 (0.11) |
| | be lined) | | 2.28 (0.20) | | | | | | | | |

(*): Lining types are described in Tables 1.2(b) and **1.3** of Bodla et al (1998).
PL = Production Lining, EL = Experimental Lining, BW = Bed Width, R/B = Right Bank, B = Bed, L/B = Left Bank
**Si** = Silty, **S** = Sandy, L - Loam

Table **7.** Summary of inflow-outflow seepage loss rates in the **FESS** area (Taken from Bodla et al **1998)**

| Sr. No. | Canal Under Test | Reach RD's | Year | Discharge (c fs) | Canal Geometry | | Soil Type WB-B-L/B | Depth to Water table | Average Seepage Losses | | Average Seepage Losses |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | FSD (ft) | BW (ft) | | | (ft/day) | (cfs/msf) | cfs/msf (ft/day) |
| I | Najibwah Minor | 0 + 225 - 17 + 560 | 1995 | 48.0 | 2.5 | 10.0 | Si.L-S.L-Si.L | 3-5 | 0.58 | 6.67 | 6.67(0.58) |
| 2 | l 3R Khattan Disty | 0+900 - 24 +000 | 1995 | 385 -445 | 4.4 | 35-19 | Si.L-S-Si.S.L | 5-10 | 0.56 | 6.52 | |
| | | 24+000 - 55+000 | 1995 | 385 - | 4.4 | 35-19 | Si.L-S.L-Si.S.I, | 5-10 | 0.54 | 6.25 | 7.73(0.67) |
| | | 55+000 - 71 + 800 | 1995 | 385 -445 | 4.4 | 35-19 | Si.L-S.L-Si.S.L | 5-10- | 0.90 | 10.42 | |
| 3 | IR/3R Qaziwala Minor | 0+260 - 14+490 | 1995 | 85.0 | 3.5 | 17.0 | Si.L-S.L-Si.L | 3-5 | 0.45 | 5.26 | |
| | | 14+490 - 29+800 | 1995 | 85.0 | 3.5 | 17.0 | Si.L-S.L-Si.L | 3-5 | 0.18 | 2.12 | 3.69(0.32) |
| 4 | IL/3R Jourkanwala Minor | 0+250- 14+000 | 1995 | 33.0 | 2.0 | 10-5 | S.L-S.L-S.L | 5-10 | 0.63 | 7.32 | |
| | | 14+000 - 27+000 | 1995 | 33.0 | 2.0 | 10-5 | Si.L-S.L-S.L | 5-10 | 0.34 | 3.90 | 5.61(0.48) |
| 5 | 4R Haroonabad Disty | 58+500 - 64+ 150 | .1995 | 139.0 | 2.4 | 27.0 | Si.L.-S.L.- Si.L. | 3-5 | 0.67 | 7.70 | |
| | | 64+250 - 72+500 (Lined Section) | 1995 | 92 - 108 | 2.2 | 33.0 | Lined | 3-5 | 0.18 | 0.50 | |
| | | 72+500 - 89+200 | 1995 | 60.0 | 2.2 | 18.0 | Si.L.-S.L.-Si.L. | 3-5 | 0.38 | 4.36 | |
| | | 1+ 100 - 25 +600 | 1995 | 247- 300 | 2.8 | 39-26 | S.L.-S.-S.L. | 3-5 | 0.55 | 6.25 | 6.56(0.58) |
| | | 25+600 - 46+850 | 1995 | 247 - 300 | 2.8 | 39-26 | Si.-S-S.L. | 3-5 | 0.63 | 6.82 | |
| | | 46 + 850 - 64 + 150 | 1995 | 247 - 3 | | | S.L.-S.-S.L. | 3-5 | 0.68 | 7.68 | |

Average seepage loss rate by inflow-outflow tests (unlined channels)

BW = Bed Width, R/B = Right Bank, B = Bed, L/B **Left** Bank
**Si** = Silty, **S** = Sandy, L Loam

**Table 8. Inflow-outflow tests conducted by IIMI on distributaries and minors in the Haroonabad Subdivision.**

| Channel | Date | Inflow (cfs) | Outflow (cfs) | Channel losses (cfs) | Wetted area (sqft) | Seepage Loss Rate (cfs/mst) |
|---|---|---|---|---|---|---|
| Hakra 3-R Distributary RD 33-73 | 09.05.99 | 373.13 | 359.36 | 13.77 | 1,772,100 | 7.77 |
| 1RA Minor (lined), Hakra 4-R Distributary RD 0-22 | 07.04.99 | 35.62 | 35.56 | 0.06 | 233,640 | 0.26 |
| Najibwah Minor (lined), Sirajwah Distributary RD 0-56.32 | 13.03.99 | 43.17 | 40.47 | 2.70 | 619.015 | 4.36 |
| Hakra 2-R Disty (lined) RD 0-33.72 | 22.06.99 | 26.08 | 25.77 | 0.31 | 207,446 | 1.44 |

# 6 WATER SAVINGS FROM LINED CANALS

The data presented in Section 5 can be used for two purposes: to estimate the water savings resulting from the completed canal lining, and preparation of cost-effectiveness relations for those channels that have not been lined, which includes distributaries and branch canals that will be presented in Section 7.

In order to estimate the water savings from completed lining, some additional information must be presented. First of all, Table 9 presents the pre- and post-lining ponding tests reported by Bodla et al (1998). Secondly, a map prepared by Mott MacDonald, the international canal lining consultants, showing the reaches of completed canal lining is presented in Figure 5, while the cost for each reach of completed canal lining is listed in Table 10.

Bodla et al (1998) prepared estimates of annual water savings resulting fi-om the completed canal lining. Using the pre- and post-lining ponding tests, the annual water savings would be 15,2 15 acre-feet (1870 ha-m) by assuming 295 operational days per year. Using the IWASRI-ISRIP inflow-outflow tests, the annual water savings would be 48,182 acre-feet (5,923 ha-m),

Assuming that the inflow-outflow tests are the best estimates of the channel loss rates, Table 11 has been prepared using both, the IWASRI-ISRIP and IIMI data for estimating the annual water savings resulting from the completed canal lining. The channel **loss** rates listed in parenthesis are estimated values, which can be expected to have considerable margins for error. The most notable example would be the Hakra 1-L Distributary because there are no data on losses in this channel.

Table 11 shows that the estimated water savings resulting fi-om the completed canal lining is 45.5 cusecs, of which 13.1 cfs of water savings occurs on the left side of the Hakra Branch Canal. The remainder of 32.4 cfs occurs on the right side (including the Bhukan Distributary and Shadab Subminor that receive water from the Malik Branch Canal). Thus, water savings on the right side of the Hakra Branch Canal amounts to 2,315 ha-m (18,9596 acre-feet), while the left side amounts to 943 ha-m (7,665 acre-feet). The crude estimate of water savings for the Hakra 1-L Distributary amounts to 27 percent of the total estimated water savings for the FESS project area, but 93 percent of the water savings on the left side of the Hakra Branch Canal.

The total. estimated annual water savings of 26,621 acre-feet (3,528 ha-m) in Table 11, using inflow-outflow measurements, is only 55 percent (26,621 divided by 48,182) of the inflow-outflow estimates of water savings reported by Bodla et al (1998). This lower estimate of annual water savings can be attributed to two factors: (1) there are more inflow-outflow measurements listed in Table 11 when compared to Table 9; but more importantly. (2) an improved inflow-outflow methodology.

The key to obtaining reasonably reliable estimates of channel losses lies with the methodology for conducting inflow-outflow tests. The first step is to field calibrate all inflow and outflow structures prior to conducting any inflow-outflow test. These discharge ratings have to be done very meticulously using an appropriate discharge measuring instrument (current meter, pygmy current meter or cutthroat flume) that has recently been carefully calibrated to measure discharges within one or two percent. Secondly, during an inflow-outflow test, the water levels at the inflow control structure must be monitored every 15-30 minutes to assure steady flow conditions. This is more likely to occur if the test can be completed in only one or two hours because only water levels and gate opening have to be measured.

Table 9. Comparison of seepage results for pre- and post- lining ponding (Taken from Bodla et al 1998).

(1/cfs/msf=0.0864 ft/day)

| Canal | Reach RD's | Discharge (cfs) | Average Seepage Loss | | | | Lining Type |
|---|---|---|---|---|---|---|---|
| | | | Pre Lining | | Post Lining | | |
| | | | (ft/day) | (cfs/msf) | (ft/day) | (cfs/msf) | |
| I-R Bahadanvah Minor | 2+750 - 4+292 | 4.00 | 0.2270 | 2.63 | 0.0355 | 0.411 | 4: (Precast parabolic section with joint sealant) |
| 3-R Hakra Disty | 2 +000 - 3 +000 | 307.00 | 0.1000 | 1.16 | 0.0511 | 0.591 | lb: (Geomembrane only on canal bed with 1.5' soil cover) |
| lR/3R Qaziwala Minor | 15+353 - 17+046 | 66.00 | 0.1760 | 2.04 | 0.0045 | 0.052 | 5c: (Geomembrane with Geotextile underlying 3" in-situ concrete) |
| | 26 +000 - 27 + 167 | 40.00 | 0.1970 | 2.28 | 0.0053 | 0.061 | 6: (Geomembrane underlying bricks in mortar layer) mortar layer) |
| | 35+000 - 36+562 | 40.00 | 0.1180 | 1.37 | 0.0611 | 0.893 | Ic: (Geomembrane underlying tognued & grooved precast slabs **without joint sealant)** |

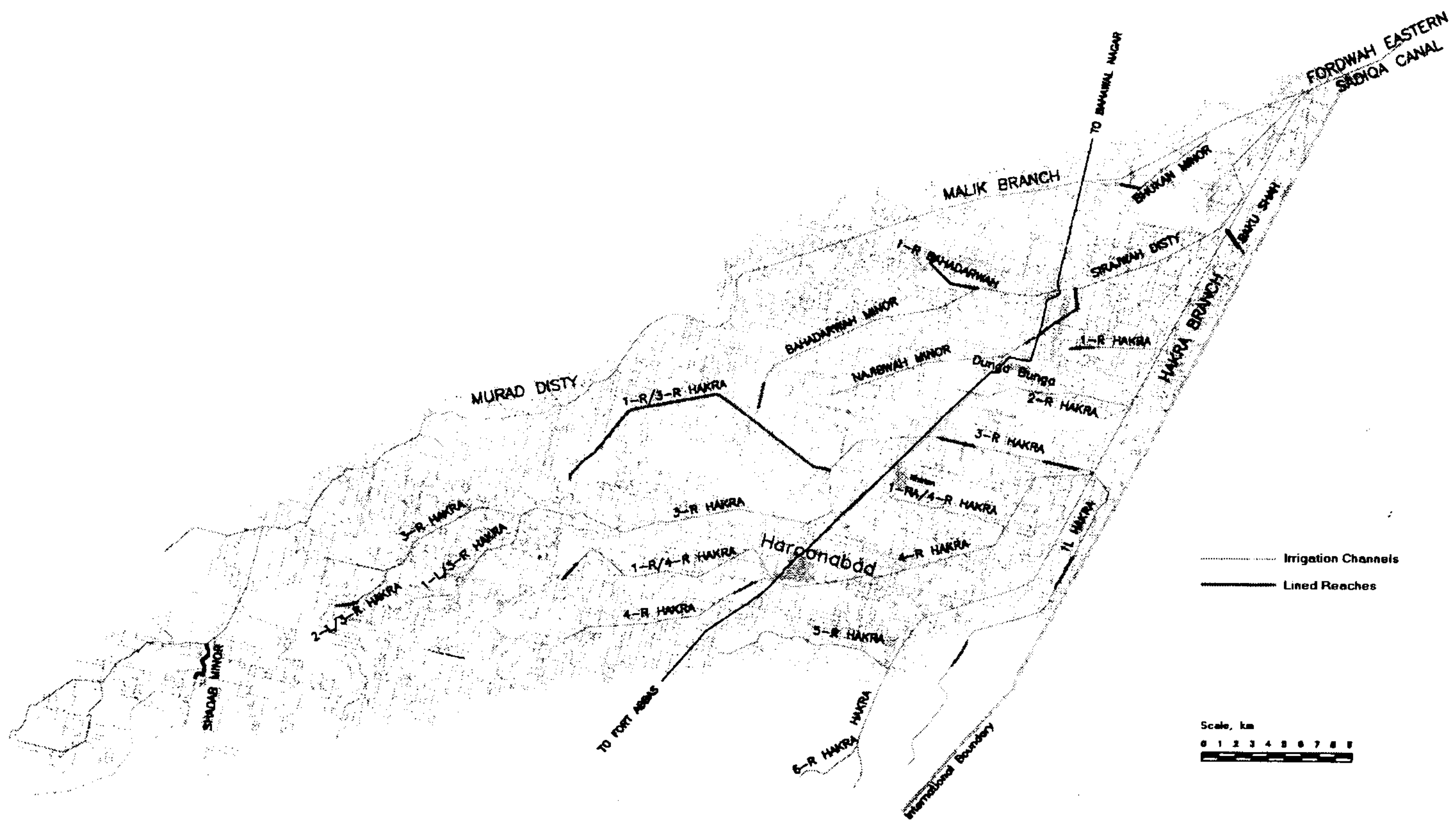


Figure 5. Completed canal lining in the FESS project area.

Table 10. Costs **of** completed lining in the **FESS** project area (obtained from Mott MacDonald, 1999).

| Channel | Lined Reach (RDs) | Length Lined (ft) | Reach Q (cfs) | Unit Cost* (Rs/ft) | Total Cost (MRs)** |
|---|---|---|---|---|---|
| EASTERN SADIQIA CANAL | | | | | |
| Girdariwala Distributary | 0+000-5+500 | 5500 | 13 | 608 | 3.34 |
| | 5+500-11+310 | 5810 | 10 | 608 | 3.53 |
| | 11+310-15+660 | 4350 | 10 | 608 | 2.64 |
| MALIK BRANCH CANAL | | | | | |
| Bhukan Distributary | 0+000-17+000 | 17000 | 13 | 608 | 10.34 |
| | 17+000-17+738 | 738 | 13 | 608 | 0.45 |
| Shadab Subminor | 0+000-5+300 | 5300 | 3.53 | 608 | 3.22 |
| SIRAJWAH DISTRIBUTARY | | | | | |
| Najibwah Minor | 0+000-18+151 | 18151 | 33.0 | 1173 | 21.29 |
| | 18+151-56+032 | 37881 | 28.0 | 1173 | 44.43 |
| Bahadarwah Minor | 0+000-56+000 | 56000 | 81.94 | 1794 | 100.46 |
| | 56+000-58+416 | 2416 | 81.94 | 1794 | 4.33 |
| | 58+416-60+785 | 2369 | 78.00 | 1794 | 4.25 |
| Subminor IR | 0+000-2+000 | 2000 | 4 | 608 | 1.22 |
| Bahadanvah Minor | 2+000-5+500 | 3500 | 4 | 608 | 2.13 |
| HAKRA BRANCH CANAL | 11+310-15+660 | 4350 | 10 | 608 | 2.64 |
| Bhaku Shah Distributary | 0+000-2+740 | 2740 | 6 | 608 | 1.67 |
| Hakra 1-R Distributary | 0+000-10+100 | 10100 | 19 | 608 | 6.14 |
| | 10+100-12+150 | 2050 | 19 | 608 | 1.25 |
| Hakra 2-R Distributary | 0+000-21+700 | 21700 | 20 | 608 | 13.19 |
| | 21+700-27+340 | 5640 | 17 | 608 | 3.43 |
| Hakra 3-R Distributary | 0+000-4+890 | 4890 | 307 | 3725 | 18.22 |
| | 4+890-8+660 | 3770 | 300 | 3725 | 14.04 |
| | 8+660-10+360 | 1700 | 300 | 3725 | 6.33 |
| | 10+360-11+360 | 1000 | 300 | 3725 | 3.73 |
| | 11+360-23+780 | 12420 | 300 | 3725 | 46.26 |
| | 23+780-25+300 | 1520 | 276 | 3725 | 5.66 |
| | 25+300-27+000 | 1700 | 276 | 3725 | 6.33 |
| | 27+000-28+400 | 1400 | 276 | 3725 | 5.22 |
| | 28+400-29+500 | 1100 | 276 | 3725 | 4.10 |
| | 29+500-30+670 | 1170 | 276 | 3725 | 4.36 |
| | 30+670-33+700 | 3030 | 276 | 3725 | 11.29 |
| | 126+370-159+730 | 33360 | 60 | 1794 | 59.85 |
| | 159+730-162+300 | 2570 | 60 | 1794 | 4.61 |
| Minor 1-R of Hakra 3-R Distributary | 0+000-0+048 | 48 | 79 | 1794 | 0.086 |
| | 0+048-0+096 | 48 | 79 | 1794 | 0.086 |
| | 0+096-0+192 | 96 | 79 | 1794 | 0.172 |
| | 0+192-0+300 | 108 | 79 | 1794 | 0.194 |
| | 0+300-0+400 | 100 | 79 | 1794 | 0.179 |
| | 0+400-1+200 | 800 | 79 | 1794 | 1.435 |
| | 1+200-2+200 | 1000 | 79 | 1794 | 1.794 |

| Channel | Lined Reach (RDs) | Length Lined (ft) | Reach Q (cfs) | Unit Cost* (Rs/ft) | Total Cost (MRs)** |
|---|---|---|---|---|---|
| | 2+200-2+700 | 500 | 79 | 1794 | 0.897 |
| | 2+700-3+200 | 500 | 79 | 1794 | 0.897 |
| | 3+200-7+200 | 4000 | 79 | 1794 | 7.176 |
| | 7+200-7+970 | 770 | 79 | 1794 | 1.381 |
| | 7+970-10+000 | 2030 | 79 | 1794 | 3.642 |
| | 10+000-11+741 | 1741 | 66 | 1794 | 3.122 |
| | 11+741-11+791 | 50 | 66 | 1794 | 0.090 |
| | 11+791-12+120 | 329 | 66 | 1794 | 0.590 |
| | 12+120-13+600 | 1480 | 66 | 1794 | 2.655 |
| | 13+600-22+000 | 8400 | 40 | 1794 | 15.070 |
| | 22+000-28+000 | 6000 | 40 | 1794 | 10.764 |
| | 28+000-34+000 | 6000 | 40 | 1794 | 10.764 |
| | 34+000-34+408 | 408 | 40 | 1794 | 0.732 |
| | 34+408-34+504 | 96 | 40 | 1794 | 0.172 |
| | 34+504-34+552 | 48 | 40 | 1794 | 0.086 |
| | 34+552-34+600 | 48 | 40 | 1794 | 0.086 |
| | 34+600-40+585 | 5985 | 40 | 1794 | 10.737 |
| | 40+585-41+502 | 917 | 40 | 1794 | 1.645 |
| | 41+502-42+500 | 998 | 17 | 1173 | 1.17 |
| | 42+500-44+500 | 2000 | 17 | 1173 | 2.35 |
| | 44+500-46+000 | 1500 | 17 | 1173 | 1.76 |
| | 46+000-46+200 | 200 | 17 | 1173 | 0.23 |
| | 46+200-48+000 | 1800 | 17 | 1173 | 2.11 |
| | 48+000-54+970 | 6970 | 17 | 1173 | 8.18 |
| 1L/3R Hakra | 0+000-26+700 | 26700 | 34 | 1173 | 31.32 |
| Minor 2L | 0+000-6+000 | 6000 | 7 | 608 | 3.65 |
| Hakra 3-R Distributary | 6+000-6+400 | 400 | 7 | 608 | 0.24 |
| Hakra 4-K Distributary | 72+000-89+178 | 17178 | 51 | 1794 | 30.82 |
| | 89+178-112+050 | 22871 | 46 | 1794 | 41.03 |
| Minor 1-RA/Hakra 4-R Distributary | 0+000-22+000 | 22000 | 33 | 1173 | 25.81 |
| Minor 1-R of Hakra 4-R Distriburtary | 0+000-43+650 | 43650 | 40 | 1794 | 78.31 |
| | 43+650-47+500 | 3850 | 35 | 1173 | 4.52 |
| | 47+500-50+812 | 3312 | 30 | 1173 | 3.88 |
| Hakra 1-L Distributary | 0+000-76+650 | 76650 | 67 | 1794 | 137.51 |
| | 76+650-78+000 | 1350 | 60 | 1794 | 2.42 |

* Cost (in rupees) per foot of canal at January 1999 prices (exchange rate, Rs./US$, official in January 1999=46.2300).

** Million rupees

Table 11. Estimated water savings resulting from completed canal lining using inflow-outflow tests.

| Irrigation Channel Designation | Length of Lining RDs | Channel Loss Rate Before cfs/msf | Channel Loss Rate After cfs/msf | Wetted Perimeter Msf | cfs | Water Savings acre-feet | Water Savings ha-m |
|---|---|---|---|---|---|---|---|
| EASTERN SADIQIA CANAL | | | | | | | |
| Girdariwala Distributary | 15.66 | (8)* | (2)* | 0.14 | 0.8 | 468 | 58 |
| MALIK BRANCH CANAL | | | | | | | |
| Bhukan Distributary | 17.78 | 7.0 | 4.4 | 0.151 | 0.4 | 234+ | 29 |
| Murad Distributary | | | | | | | |
| Shadab Sub-minor | 5.25 | (6)* | (1)* | 0.035 | 0.2 | 117 | 14 |
| SIRAJWAH DISTRIBUTARY | | | | | | | |
| Bahadarwah Minor | 60.79 | (7)* | (1)* | 1.24 | 7.4 | 4,329 | 532 |
| 1-R Sub-minor, Bahadanvah Minor | 5.60 | (7)* | (1)* | 0.03 | 0.2 | 117 | 14 |
| Najibwah Minor | 56.03 | 6.7 | 4.3 | 0.81 | 1.9 | 1,112 | 134 |
| HAKRA BRANCH CANAL | | | | | | | |
| Bakhu Shah Distributary | 2.74 | (8)* | (2)* | 0.018 | 0.1 | 59 | 7 |
| Hakra 1-R Distributary | 12.15 | (7)* | (1)* | 0.115 | 0.7 | 410 | 50 |
| Hakra 2-R Distributary | 27.34 | 6.3 | 1.5 | 0.314 | 1.5 | 878 | 108 |
| Hakra 3-R Distributary (upper) | 33.7 | 6.3 | 0.5 | 0.325 | 1.9 | 1,112 | 134 |
| Hakra 3-R Distributary (tail) | 35.97 | 8 | 0.5 | 0.799 | 6.0 | 3,506 | 431 |
| 1-R Minor | 54.97 | 3.7 | 0.2 | 1.021 | 3.6 | 2,106 | 259 |
| 1-L Minor | 26.70 | 5.6 | (0.2)* | 0.459 | 2.5 | 1,463 | 180 |
| 2-L Minor | 6.42 | (5.2)* | (0.2)* | 0.06 | 0.3 | 175 | 22 |
| Hakra 4-R Distributary | 40.08 | 4.3 | (0.2)* | 0.66 | 2.7 | 1,583 | 195 |
| 1-RA Minor | 22.00 | (4)* | 0.26 | 0.27 | 1.0 | 585 | 72 |
| 1-R Minor | 50.88 | (4)* | (0.3)* | 0.58 | 2.1 | 1,229 | 151 |
| Hakra 1-L Distributary | 78.01 | (8)* | (1)* | 1.686 | 12.2 | 7,138 | 878 |
| | | | | Totals | 45.5 | 26,621 | 3,258 |

* The channel loss rates listed in parenthesis are the best estimates, but certainly crude.

\+ Assumes distributary operations of 295 days per year.

# 7 COST-EFFECTIVENESS OF CANAL LINING

## 7.1 COMPLETED CANAL LINING

The costs for the various reaches of completed canal lining are listed in Table 10, while the water savings have been estimated in Table 11. This data is compiled in Table 12 so that the cost-effectiveness of each reach can be calculated. The last column in Table 12 ranks the cost-efl'ectiveness, where the most cost-effective reach (lowest cost per hectare-meter of water saving per year) is ranked 1. Then, Table 13 was prepared where each reach of completed canal lining is listed by ranking from I to 18. In this manner, the lining costs can be accumulated, as well as the water savings, for use in preparing the cost-effectiveness function.

For the I8 reaches of completed canal lining. the cost-effectiveness relationships are shown in Figure 6. The most cost-effective lined reaches are (I)Hakra I-R Distributary; (2) tail reach of the Hakra 3-R Distributary: and (3) Hakra 2-R Distributary. The Hakra I-L Distributary is ranked tourth. but unfortunately, there are no channel loss measurements either before or after lining. The least cost-effective lining is the head reach of the Hakra 3-R Distributary, but this includes a variety of experimental linings, which is necessarily expensive. The lining of two minors and the tail reach of the Hakra 4-R Distributary were not very cost-effective, which is also the case for the Najibwah Minor and the Bhukan Distributary.

Table 12. Cost-effectiveness for various reaches of completed canal lining.

| Irrigation Channel Designation | Lining cost MRs. | Water Savings ha-m/yr | Cost-effectiveness MRs/ha-m/yr | Ranking by most cost-effectiveness |
|---|---|---|---|---|
| EASTERN SADIQIA CANAL | | | | |
| Girdariwala Distributary | 9.5 | 58 | 0.164 | 5 |
| MALIK BRANCH CANAL | | | | |
| Bhukan Distributary | 10.8 | 29 | 0.372 | 15 |
| Murad Distributary | | | | |
| Shadab Subminor | 3.2 | 14 | 0.229 | 9 |
| SIRAJWAH DISTRIBUTARY | | | | |
| Bahadarwah Minor | 109 | 532 | 0.205 | 8 |
| I-R Sub-minor | 3.4 | 14 | 0.243 | 10 |
| Najibwah Minor | 65.7 | 134 | 0.490 | 16 |
| HAKRA BRANCH CANAL | | | | |
| Bakhu Shah Distributary | 1.7 | 7 | 0.243 | 11 |
| Hakra 1-R Distributary | 7.4 | 50 | 0.148 | 1 |
| Hakra 2-R Distributary | 16.6 | 108 | 0.154 | 3 |
| Hakra 3-R Distributary | | | | |
| Upper Reach | 125.5 | 134 | 0.937 | 18 |
| Tail Reach | 64.5 | 431 | 0.I50 | 2 |
| I-R Minor | 89.4 | 259 | 0.345 | 12 |
| I-L Minor | 31.2 | I80 | 0.173 | 6 |
| 2-L Minor | 3.9 | 22 | 0.I77 | 7 |
| Hakra 4-R Distributary | 71.9 | 195 | 0.369 | 14 |
| I-RA Minor | 25.8 | 72 | 0.358 | 13 |
| I-R Minor | 86.7 | 151 | 0.574 | 17 |
| Hakra 1-L Distributary | 139.9 | 878 | 0.159 | 4 |

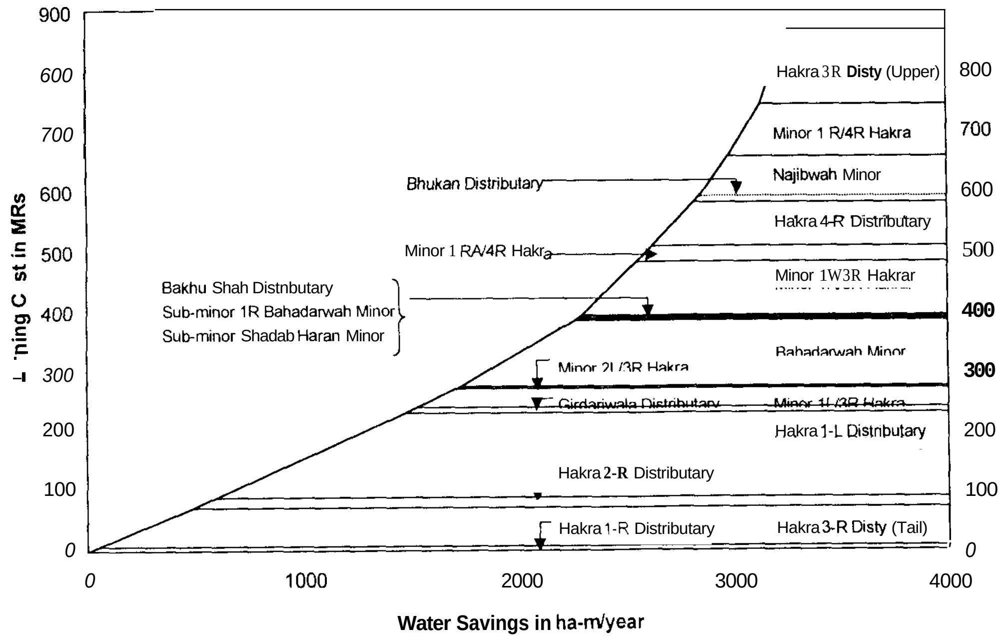


Figure 6. Cost-effectiveness function for completed canal lining.

Table 13. Lining costs and water savings for reaches of completed canal lining in accordance with cost-effectiveness ranking.

| Ranking | Lining Costs (MRs) | | Water Savings (ha-m/yr) | |
|---|---|---|---|---|
| | Reach RDs | Accumulated | Reach | Accumulated |
| 1 | 7.4 | 7.4 | 50 | 50 |
| 2 | 64.5 | 71.9 | 431 | 481 |
| 3 | 16 6 | 88.5 | 108 | 589 |
| 4 | 139.9 | 228.4 | 879 | 1467 |
| 5 | 9.5 | 237.9 | 58 | 1525 |
| 6 | 31.2 | 269.1 | 180 | 1705 |
| 7 | 3.9 | 273 | 22 | 1727 |
| 8 | 109 | 382 | 532 | 2259 |
| 9 | 3.2 | 385.2 | 14 | 2273 |
| 10 | 3.4 | 388.6 | 14 | 2287 |
| 11 | 1.7 | 390.3 | 7 | 2294 |
| 12 | 89.4 | 479.7 | 259 | 2553 |
| 13 | 25.8 | 505.5 | 72 | 2625 |
| 14 | 71.9 | 577.4 | 195 | 2820 |
| 15 | 10.8 | 588.2 | 29 | 2849 |
| 16 | 65.7 | 653.9 | 134 | 2983 |
| 17 | 86.7 | 740.60 | 151 | 3134 |
| 18 | 125.5 | 866 I | 134 | 3268 |

## 7.2 PROPOSED CANAL LINING

The remaining canal lining among the distributaries consists of (1) the Sirajwah Distributary from RD 0 - 67+700 (tail); (2) the unlined portion of the Hakra 3-R Distributary having a total length of 92,770 feet (RDs 92.77); and (3) the Hakra 4-R Distributary from RD 0 - 72+150. In addition, the Malik Branch Canal could be lined from the head to the tail (RD 0 - 116+900), as well as the Hakra Branch Canal in two reaches from RD 0 - 90 and RD 90 - 165. Cost estimates and water savings for each channel of proposed canal lining are listed in Table 14. These channels are again listed in Table 15 according to a ranking based on the most cost-effective channel lining being ranked 1. The cost-effectiveness function for this proposed canal lining is shown in Figure **7.**

Figure 6 displays that the Malik Branch Canal has a cost-effectiveness (million rupees of lining cost per hectare-meter of water saving per year) better than any reach of completed canal lining. The Hakra Branch Canal (RD 0-90) is comparable to the Bahadarwah Minor that off-takes from the Sirajwah Distributary, while the Sirajwah Distributary (Figure 7) has cost-effectiveness comparable with the Najibwah Minor (Figure 6).

The most important consideration when comparing Figures 6 and 7 is the tremendous difference in water savings. The completed canal lining has an estimated water savings of 45 cusecs (Table 11), which amounts to 3,258 ha-m per year assuming that the distributaries are operated 295 days per year. The branch canals are operated on 330 days per year, so that the total water savings for the proposed canal lining, excluding the Sirajwah Distributary, is 296 cusecs, which amounts to 23,415 ha-m per year. The proposed canal lining would have a significant impact in lowering groundwater levels.

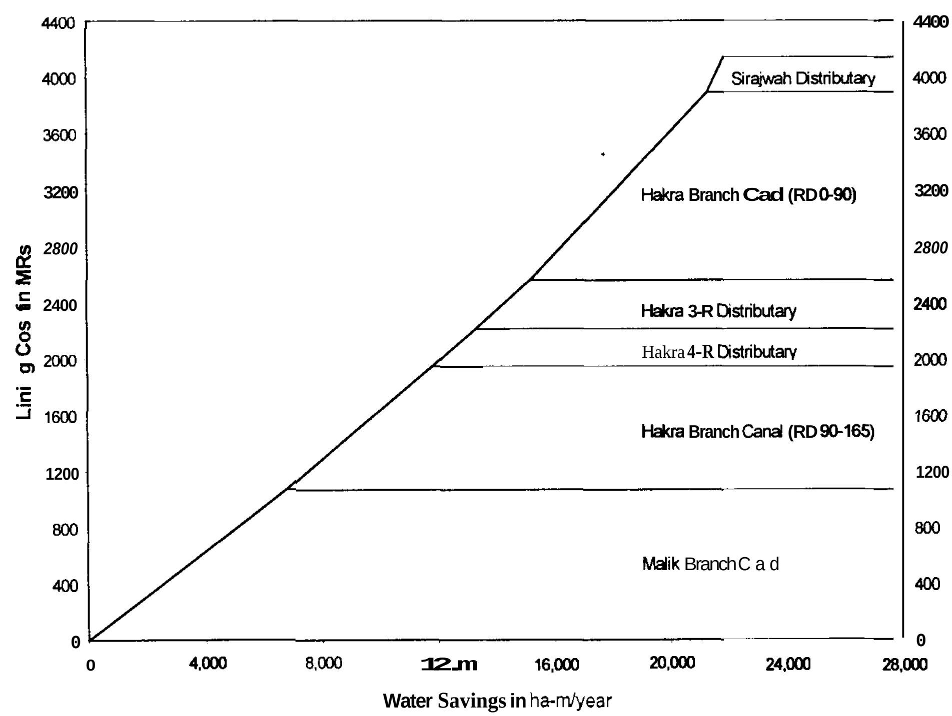


Figure 7. Cost-effectiveness function for the proposed canal lining.

Table 14. Cost-effectiveness for various reaches of proposed canal lining.

| Irrigation Channel Designation | Lining Cost MRs. | Water Savings cfs | Water Savings ha-m/yr | cost-effectiveness MRs/ha-m/yr | Ranking by Most Cost-effectiveness |
|---|---|---|---|---|---|
| Malik Branch Canal | 1070 | 94 | 7564 | 0.1415 | 1 |
| Hakra Branch Canal | | | | | |
| RDO-90 | 1330 | 85 | 6839 | 0.1945 | 5 |
| RD 90 - 165 | 875 | 70 | 5632 | 0.1545 | 2 |
| Sirajwah Distributary | 249 | 8 | 575 | 0.433 | 6 |
| Hakra 3-R Distributary | 345 | 26 | 1870 | 0.1845 | 4 |
| Hakra 4-R Distributary | 269 | 21 | 1510 | 0.1781 | 3 |

Table 15. Lining costs and water savings for reaches of proposed canal lining in accordance with cost-effectiveness ranking.

| Ranking | Channel | Lining Costs (MRs) Reach | Lining Costs (MRs) Accumulated | Water Savings (ha-m/yr) Reach | Water Savings (ha-m/yr) Accumulated |
|---|---|---|---|---|---|
| 1. | Malik Branch Canal | 1070 | 1070 | 7564 | 7564 |
| 2. | Hakra Branch RD 90-165 | 875 | 1945 | 5632 | 13196 |
| 3. | Hakra 4-R Distributary | 269 | 2214 | 1510 | 14706 |
| 4. | Hakra 3-R Distributary | 345 | 2559 | 1870 | 16576 |
| 5. | Hakra Br. RD 0-90 | 1330 | 3889 | 6839 | 23415 |
| 6 | Sirajwah Distributary | 249 | 4138 | 575 | 23990 |

If the centerlines of the Malik and Hakra Branches are used as imaginary boundaries for a water budget analysis, the completed canal lining had water savings of 32.4 cusecs inside these boundaries amounting to 2,331 ha-m. This would be a reduced water depth of 19-mm spread over the gross command area (GCA) of 121,000 ha. For a mean specific yield of 14.6 percent (Ejaz and Ahmad, 1999), the groundwater levels will be lowered by an average of 130 mm, say 0.13 meter. For the proposed canal lining, the water savings inside the imaginary boundaries would be 147 cusecs (294÷2) amounting to 11,700 ha-m (23, 415÷2), which amounts to 97 mm of water spread over the GCA, or groundwater levels would be reduced by 664 mm (97mm divided by 0.146). Since the water savings would be used as an additional irrigation water supply, there would be watercourse conveyance losses and deep percolation resulting from irrigating croplands, so that the groundwater levels would be lowered less than two-thirds of a meter, say 0.50 meter. The combination of completed canal lining and proposed canal lining should result in lowering the groundwater levels by 0.6 meter over the entire GCA.

# 8 SUMMARY AND CONCLUSIONS

In summary, flow measurement is a rather simple technology, but good procedures and meticulous care of the equipment is required in order to obtain accurate discharge rates. This is particularly the case for conducting inflow-outflow tests to measure irrigation channel losses. The best procedure requires that all inflow and outlet structures must be calibrated in the field for developing appropriate discharge ratings. Then, when conducting the inflow-outflow test, only the gate openings and water levels need to be measured and recorded, which can later be converted into the discharge rate for each structure using the appropriate rating. This allows an inflow-outflow test to be completed in only a few hours, which is very important given the high degree of discharge variability occurring in the canals of Pakistan.

IWASRI and ISRIP conducted both, ponding and inflow-outflow tests during 1995 in the FESS project area. Bodla et al (1998) provided the test results, which yielded an average seepage loss rate of 2.3 cfs/msf for ponding tests and 6.2 cfs/msf for inflow-outflow tests. To explain this large disparity is a real dilemma. Certainly, Bodla et al (1998 and 1999) have taken a highly professional approach in trying to explain this discrepancy. In the end, they used the ponding method as the standard for measuring seepage losses.

This report has taken a different approach. The ponding method would only be used as a last resort when the channel losses are so small that they cannot be accurately measured using the inflow-outflow method. The primary advantage of the inflow-outflow method is that the channel losses are being measured under usual canal operating conditions. This is not the case for the ponding method, where the pond serves as a reservoir having a horizontal (rather than sloping) water surface.

The single most important clue to the deficiency in using the ponding method for the **FESS** area is related to results for the Malik Branch Canal. Ponding tests were conducted during January 1998 at two locations along the Malik Branch. The measured seepage loss rates were 1.04 cfs/msf and 1.50 cfs/msf. These low values were explained by the presence of a shallow clay layer beneath the canal bed. However, these low values would be expected for such a large canal if there existed a near-perfect concrete lining without open joints and having very few hairline cracks.

Given the situation in the FESS project area, the conclusion is that the inflow-outflow method, with all inflow and outflow structures being field-calibrated prior to the test, provides better estimates of the channel loss rates than the ponding method.

The inflow-outflow tests by IIMI and IWASRI/ISRIP have been used to estimate the water savings resulting from the completed canal lining. The estimated water saving is 45 cfs. Considering 295 canal operational days per year (canal closure plus days with zero flows in a distributary), the annual volume of water savings would be 26,600 acre-feet, which corresponds to 3,250 ha-m/yr. This water saving could potentially lower the water table over the FESS area by 0.13 m, which would likely be **0.1** m when taking into account watercourse conveyance losses.

For the completed canal lining, a cost-effectiveness function has been developed. In addition, another function was developed for the proposed lining (using geo-membrane, geo-textile plus concrete) of (1) the Malik Branch Canal RD 0 - 116+900 (tail); (2) the Hakra Branch Canal, RD 0 - 90; (3) the Hakra Branch Canal, RD 90 - 165; (4) the Sirajwah Distributary, RD 0 - 67+700 (tail); (5) the Hakra **3-R** Distributary, all unlined reaches; and (6) the Hakra 4-R Distributary, RD 0 - 72+156. **A** comparison of the two cost-effectiveness functions discloses that lining the Malik Branch Canal would be more cost-effective than any of the reaches under the completed canal lining.

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