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WATERCOURSE IMPROVEMENT IN PAKISTAN*

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ABSTRACT

Extensive conveyance loss measurements in watercourses in the Pakistan Indus Basin indicated water loss in the range of 30 to 50 per cent of the inflow. This high loss motivated the development and testing of several system improvements which could be grouped in the categories of improved maintenance, redesign and earthen reconstruction, and channel lining. Evaluation of the costs and water savings of these techniques allowed the formulation of an optimal watercourse improvement strategy. This improvement strategy, which increases water deliveries to the field by 30 per cent, is presently being applied on a large scale by the Pakistan On-Farm Water Management Project. Total farmer provision of labor is evidence of their support for the program and recognition of its benefits.

RESUME ET CONCLUSIONS

Par suite du besoin d'augmentation de production agricole, l'eau étant insuffisante dans le bassin de l'Indus, une recherche sur l'utilisation de l'eau a été faite durant onze années pour identifier les différents problèmes, et trouver des solutions.

Il a été constaté que le système de transmission de cours d'eau que l'on trouve dans une ferme, perd 30 à 50 pour cent de son eau avant d' atteindre les champs. On a approfondi les recherches à propos sur les quantités d'eau perdues avec l'intention de convaincre les fonctionnaires du gouverne-

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ment sur l'importance du problème. Les vraies causes ont été trouvées; des solutions ont été proposées. Des solutions pratiques ont été rassemblées.

1. Amélioration dans le nettoyage et l'entretien,

2. Reconstruction des cours d'eau faits en terre elle-même et construction de divisions durables,

3. Des cours d'eau faits en ciment.

Les trois techniques ont été rassemblées dans le but d'avoir les meilleurs cours d'eau, comprenant 15 pour cent des principaux cours faits en ciment. Les autres principaux cours d'eau sont reconstruits en terre. Les cours d'eau secondaires ont connu des améliorations dans le nettoyage et dans l'entretien. Avec ces améliorations, on peut récupérer 50 pour cent des eaux que l'on perdait habituellement.

Après avoir mis ce système en pratique durant cinq ans dans le cadre d'un programme qui a assuré des formations et des institutions administratives, le processus est maintenant utilisé partout dans le pays. Ces constatations ont été faites:

1. Les cours d'eau que l'on trouve dans une ferme perdent environ 40 pour cent de son eau.

2. Les terriers et autres genre d'écoulements causent un très grand pourcentage de fuite dans le cours d'eau.

3. L'amélioration du nettoyage de l'entretien et la reconstruction des cours d'eau en terre peuvent sauver une grande partie des causes perdues et sont souvent plus économiques que les cours d'eau en ciment.

4. Les fermiers ne consentent à faire de gros investissements pour améliorer leur système d'irrigation que si les avantages sont évidents.

5. L'amélioration des cours d'eau doit être maintenue pour atteindre une durée raisonnable d'utilisation, et les fermiers doivent être organisés et avoir la possibilité d'exercer leur autorité pour assurer l'entretien de l'ensemble des cours d'eau.

BACKGROUND

One hundred twenty-five billion cubic meters of water is diverted from the Indus River system each year to irrigate the Indus Basin in Pakistan. The supply is insufficient to adequately irrigate the 13 million hectares of canal commanded land. Earlier studies, including limited measurements indicating that loss from the village and farm level watercourse system is only 10 per cent (Hunting Technical Services, Ltd., 1965, and Irrigation Research Institute of Punjab, 1972), indicated that the conveyance system was relatively efficient in delivering water to the land. Thus, water resource development was pursued as the most economical means of supplying more water to the farmers' fields. Large investments were made in storage works and ground-water pumping including Tarbela and Mangla Reservoirs and the SCARP ground-water pumping program.

Beginning in 1973, Colorado State University engineers and cooperators from several Pakistan agencies again measured watercourse conveyance losses. Their extensive inflow-outflow and ponding loss measurements on over 200 channel systems showed that, in fact, watercourse losses were high—in the range of 30 to 50 per cent (Clyma et al., 1975, Ashraf et al., 1978, and Trout, 1979). The large measurement effort was necessary to convince governmant officials that the previously accepted efficiency value, which time had legitimized and institutionalized, was wrong. This finding required a reevaluation of Pakistan's water resource investment strategy. If even half of the watercourse loss could be eliminated, more extra water would be delivered to the fields than from five Tarbela reservoirs.

Initial efforts to reduce the watercourse water loss involved the traditional engineering solution of channel lining. As expected, the studies showed that good quality, well maintained lining will eliminate nearly all conveyance loss in the lined sections. However, at the cost of U S $15 per meter, lining all of the watercourse channels in Pakistan would cost over 27 billion dollars. Such a program would have competed with other development projects for cement and skilled labor as well as limited funds. The initial tests also showed that insuring good quality government contracted construction would be difficult, and that farmers would be reluctant to maintain government provided linings.

Based on these initial tests, less expensive means were sought to save a portion of the high watercourse water loss. This required a better understanding of the way the watercourse system worked, or didn't work, by diagnosing the problems and determining their causes. Based on this understanding, economic water saving improvements could be proposed, tested, and implemented.

The diagnosis and improvement process required understanding both the socio-economic and physical factors involved. This paper describes the physical aspects. Other aspects have been reported elsewhere (Johnson, et al., 1977; Johnson, et al., 1978; Lowdermilk, et al., 1979; Reuss, et al., 1979; Skogerboe, et. al., 1980).

PAKISTAN WATERCOURSE CONVEYANCE SYSTEMS

The 13 million hectares of land irrigated from canals in the Indus Basin in Pakistan receive water from about 89,000 individual watercourse systems. Each system generally serves between 80 and 350 ha of land divided into 0.1 to 0.4 ha level basins and farmed by an average of 40 cultivators. The average system is composed of 140 m of channel per hactare of irrigated land, of which about one-fifth is government constructed and cooperatively used and maintained main channel ("*sarkari khal*") and four-fifths is individually or jointly owned farmers' branches (Figure 1). Channel slopes in the flat basin vary between 0.0002 and 0.0010 m/m.

The watercourse system receives from its gateless canal turnout ("*mogha*") a supply of approximately 1 L/s for each 5 ha of irrigated land. The constantly flowing water is distributed to farmers on a weekly "*warabundi*" turn rotation in which the turn proceeds progressively down each channel and branch and turn time is based on the area cultivated.

PROBLEM DIAGNOSIS

In order to economically reduce watercourse conveyance losses, the system had to be studied to understand the causes of the loss. This required not only observing its layout and operation, but also making measurements to determine where, when, and why the loss occurred.

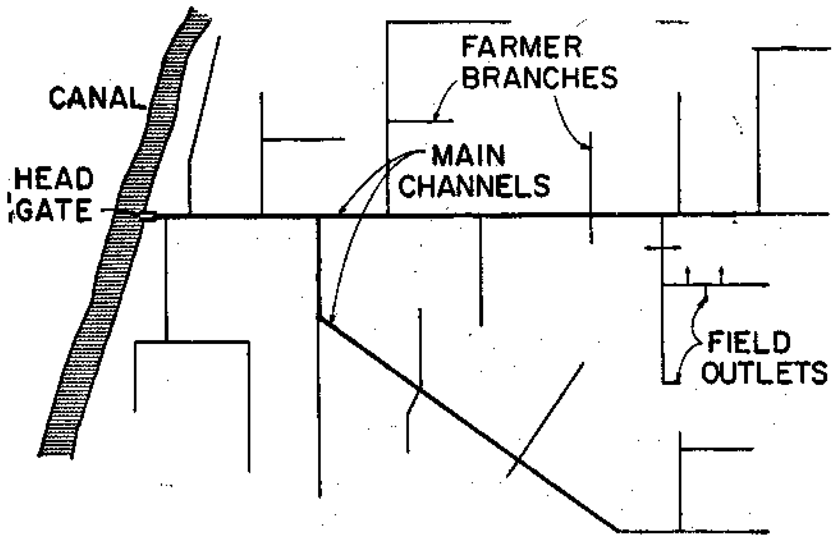

FIGURE 1 : Typical Watercourse layout

Intensive volumetric inflow-outflow loss measurements were conducted on five representative watercourse systems (Trout and Bowers, 1981). These allowed the measurement of short term "transient" losses which are not measured in steady state measurements, and the quantitative division of the total loss into the categories shown in the flow chart in Figure 2. From these categorized data, the major problem areas were identified and the amount of water which could be saved by solving specific problems was estimated.

This volumetric study showed that 7 per cent of the inflow is lost to transient condition losses such as high initial infiltration into dry channel banks, bank washouts, and dead storage water which will not drain into the fields. The high transient loss is primarily due to the large number of branch channels filled and drained during each rotation period. Because of the small field and holding sizes, 500 m of channel was filled for each hectare of land irrigated. Analysis of transient loss data indicated that about 0.14 m^3 of water was lost for each meter of channel filled and later drained.

The seepage loss shown on the flow chart is much larger than would be expected in the medium to fine textured soils. Since the seepage rate was about 3 times the measured infiltration rate into the same soils on adjoining fields, three-fourths of the loss is considered "excess seepage".

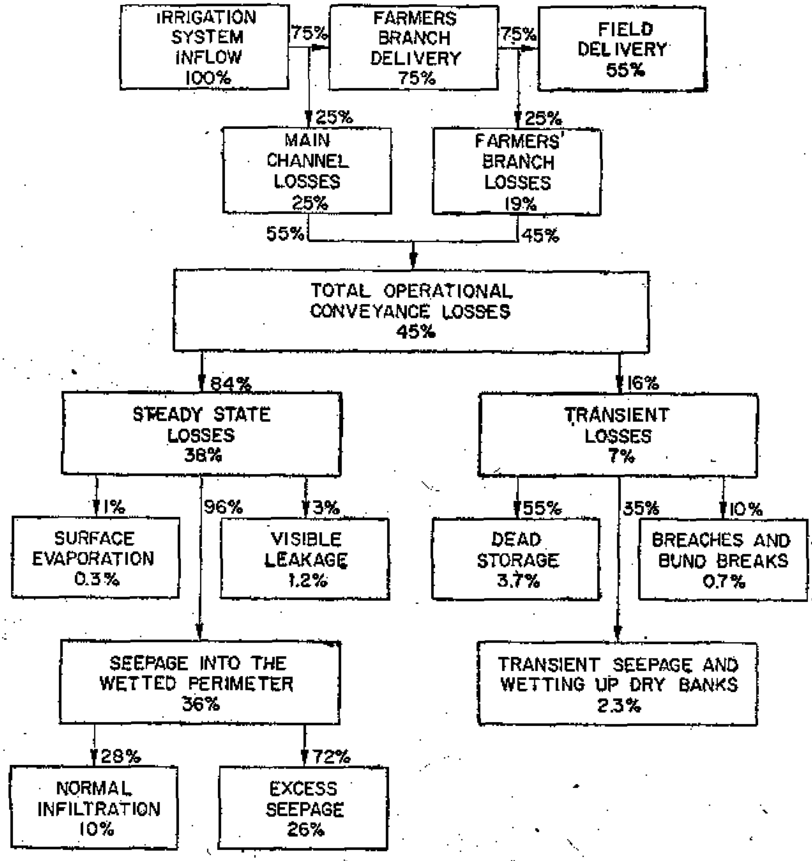

FIGURE 2 : Flow chart showing where water goes which enters five watercourse systems. Valves in boxes are per cent of total inflow while those with arrows are per cent of the previous loss or volume (from Trout and Bowers, 1981).

Ponding measurements consistently showed a strong positive exponential relationship between the loss rate and water depth (Figure 3). Loss rates in typical channels doubled with a 50 mm increase in flow depth. When these data are converted to seepage rates (Figure 4) they show that, although the channel beds are fairly impermeable, the seepage rate into the upper banks is extremely high.

Excavation of watercourse banks unearthed an extensive array of worm holes, rodent burrows, decayed root channels and other macroscopic flow paths (Figures 5 and 6). This "macroporosity" is concentrated primarily in the upper banks with occasional holes leading down below the channels and out under the fields. Although these potential flow paths only occasionally lead completely through the banks and allow visible leakage, the extensive network apparently fills with water and increases the

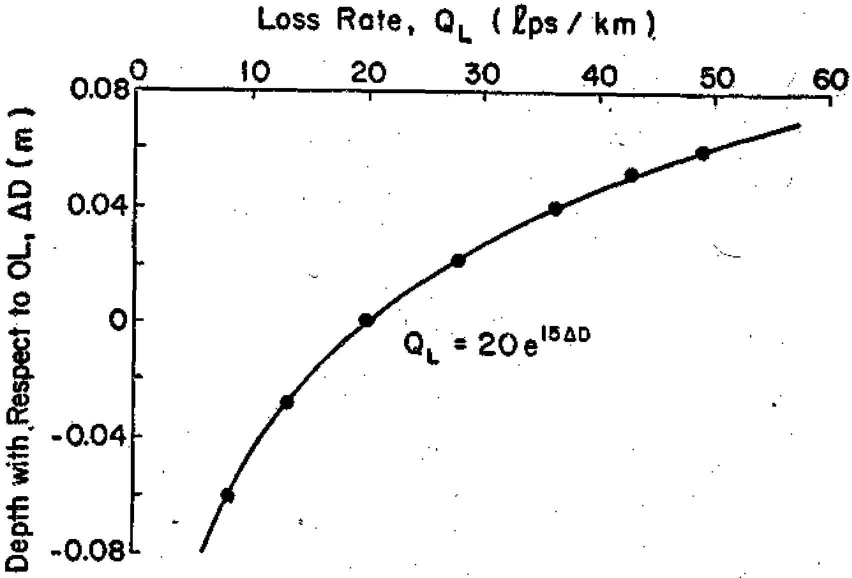

FIGURE 3 : Loss rate vs. flow depth relative to the normal operational level, OL

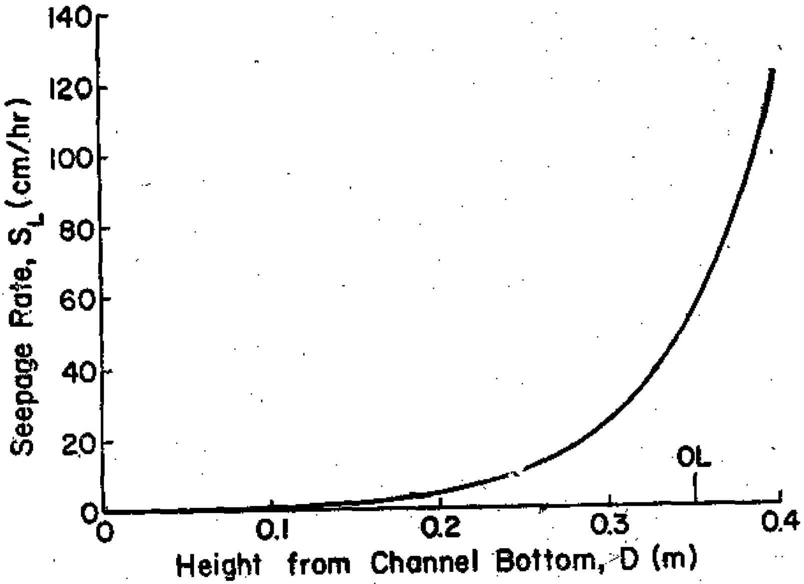

FIGURE 4 : Seepage rate into the channel wetted perimeter vs. height from the bottom

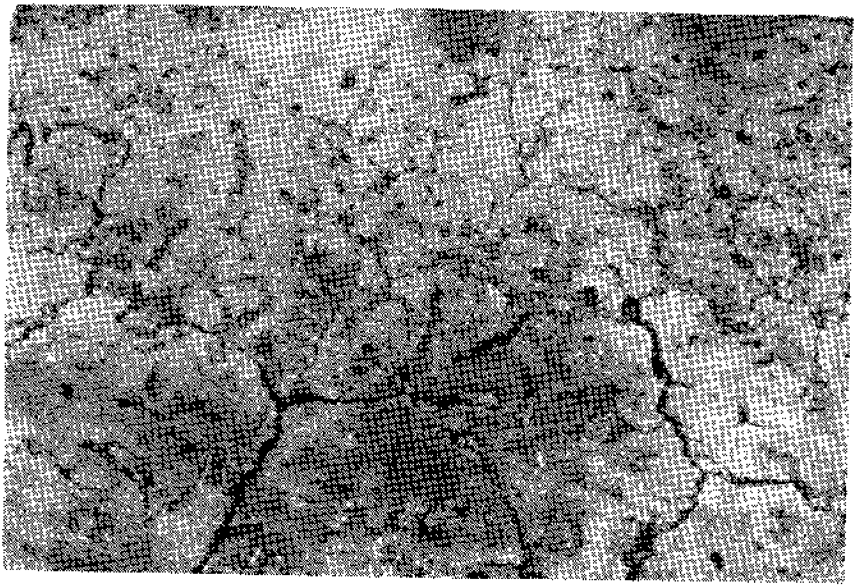

FIGURE 5 : Worm holes visible on the inside surface of a recently cleaned channel bank

FIGURE 6 : Rat burrows visible in a partially excavated channel bank

"effective" wetted perimeter of the channel so seepage rates are several times higher than normal infiltration rates into the same soils. The excess seepage occurs primarily into the upper banks because the digging and burrowing pests prefer to be near the water surface level and deposited sediment tends to plug flow paths in the channel bottom.

Much of the visible leakage and short-term breaches on many systems occur in junction areas and through old outlet cuts in the earthen banks. In junctions, the channel banks become thin and low and cross sections widen into ponds due to the borrowing of earth to construct check dams. Part of this borrowed soil is washed downstream when the check is opened.

As the flow chart shows, 55 per cent of the total loss occurred in main channels. However, 80 per cent of the channel used to convey water to the average field is main channel. This implies that the loss per unit channel length from farmers branches is 3 times higher than the unit loss in main channels, a fact supported by steady state measurements.

SOLUTIONS FOR THE MAJOR PROBLEMS

The transient loss is related to the large number of channels filled and drained each rotation period due to the channel and field layout and operational procedures. Figure 7 shows a typical layout in which there are 130 m of field channels per hectare of land. By enlarging or rearranging the fields the number of branches can be reduced. Figure 8 shows the same area with the same size fields irrigated with only 2 farm branches, which will effectively reduce transient losses by as much as 25 per cent. Such reorganization may require land consolidation, will require land

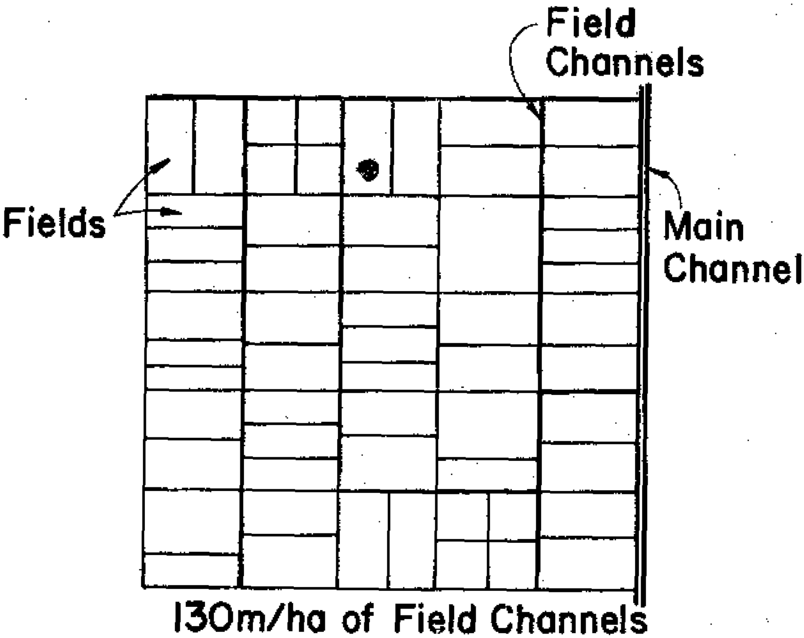

Figure 7 : Present field and channel layout on a 10 ha "square" of land

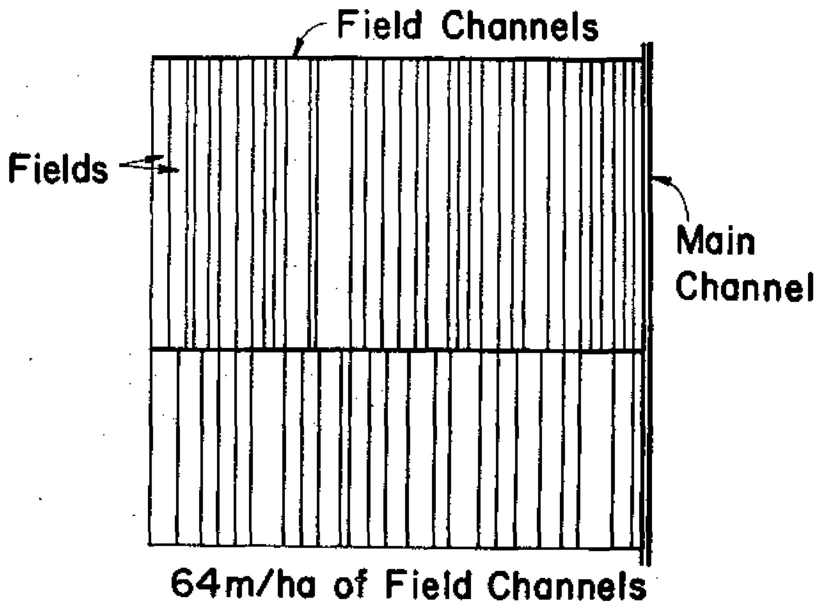

FIGURE 8 : Proposed field and channel layout with a 50 per cent decrease in field channel length

velling, and will lead to a slight decrease in water application unifor-ity. The relatively small channel water savings will not justify the land rming costs, but if land levelling is being done to save water application sses, field and channel reorganization is desirable.

The existing warabundi rotation system minimizes the filling and aining of channels within a given layout. However, on soils with high ater holding capacity which do not require weekly irrigation, the rota-on times and intervals could be extended which would allow each rmer to irrigate more of his land during each rotation while using only few additional channels.

Converting to an "on-demand" delivery schedule, although preferable the field, would greatly increase the transient loss, overshadowing any eld level gains. Allowing neighboring farmers to trade turns or portions f turns (which is practiced, but is presently illegal) would provide some exibility without increasing transient loss.

The dead storage loss could be eliminated by smoothing and raising e channel beds. However, high channels require more land and labor to nstruct, are more difficult to maintain, and tend to have higher steady ate losses, overshadowing gains from eliminating dead storage loss.

The high seepage loss is caused by the macroporosity. The flow paths n be eliminated by tearing down and reconstructing the banks. How-ever, the causes of the macroporosity will not be eliminated by this acti-ty and will return to the banks to resume their activity.

The major burrowing pests in Pakistan watercourse banks are rodents (*nesokia indica* and *bandicota bengalensis*). The rodents are naturally attracted to the banks which are permanently above water, undisturbed for several years, and covered with a vegetative cover. The nesokia also feeds on roots of the bank grasses. Due to this ideal ecosystem, chasing the rodents out is difficult. Eliminating (killing) the rodents, which regenerate to the carrying capacity of the environment very quickly, from a system which is central to village life, would require an intensive, sustained, and very carefully applied poisoning program.

One solution is to destroy and reconstruct the banks after regular time intervals. This practice is followed in several western U.S. irrigated areas where the field channels are plowed in each fall and remade each spring. The economic reconstruction interval for Pakistan watercourses has not yet been determined but appears to be between 4 and 8 years. Firmly compacting clean (without decomposing vegetative matter) soils and maintaining vegetation free banks will discourage burrowing, remove cover, and reduce the food supply, thus slowing rehabitation. The only more permanent solution is to isolate the flowing water from the macropores with durable impermeable lining.

Since most of the seepage is into the upper banks, eliminating the macropores in the upper banks will greatly reduce seepage loss. Thus, reconstructing only the upper banks, compacting soil cores in the banks, or lining only the banks will eliminate most of the seepage loss.

The dramatic increase in loss rates with increasing flow depths also implies that anything which temporarily increases the flow depth, such as vegetation growth (increased roughness) or increased flow rates, will increase losses, and that a regular channel cleaning program will reduce water loss. Akram, et al. (1981), measured loss decreases of over 50 per cent after channel cleaning which decreased the flow depths 100 mm. Figures 9 and 10 show projected losses and savings of cleaning programs at various time intervals.

Losses from junction areas can be decreased by rebuilding the channels and bringing in extra soil to build future check structures, or by providing portable or installing permanent structures. The structures have the added advantages of improved water control and labor savings.

IMPROVEMENT TECHNIQUES

After testing and evaluating several combinations of channel improvements, three improvement packages were chosen to most practically and economically reduce losses from Pakistan watercourses:

- improved cleaning and maintenance,
- earthen renovation, and
- lining.

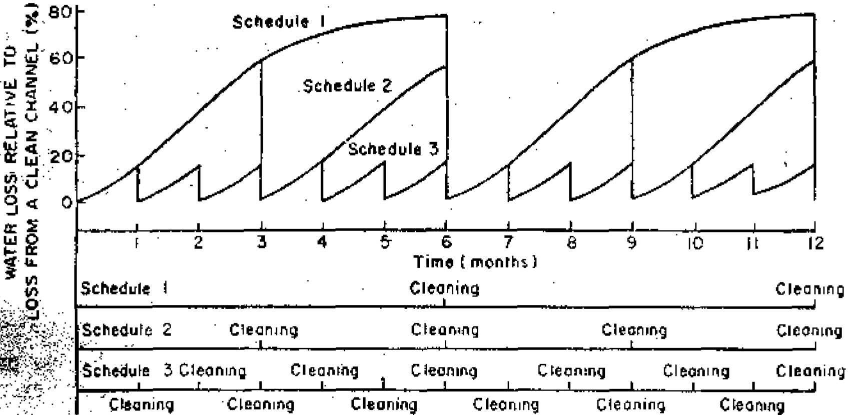

FIGURE 9 : Conveyance loss fluctuations over time on a hypothetical conveyance channel system under a semi-annual, quarterly and monthly cleaning schedule, based on the Manning's roughness coefficient fluctuating between 0.03 and 0.06 and a loss vs. depth relationship as shown in Figure 3.

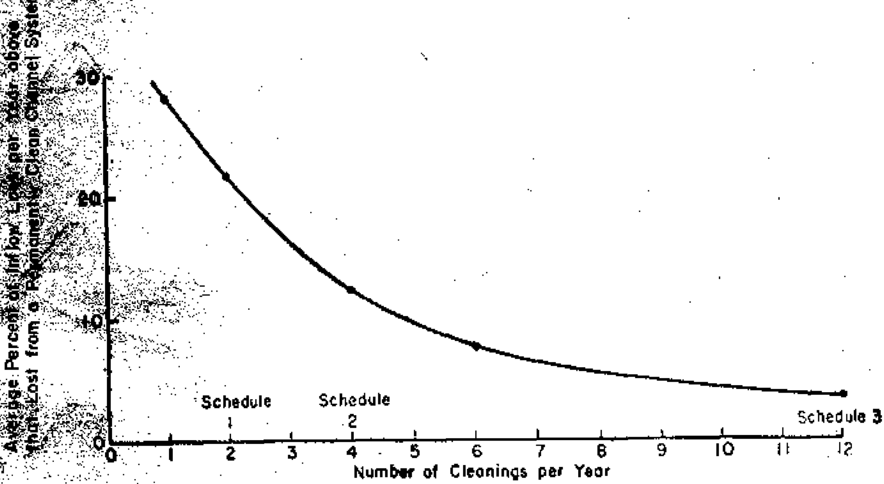

FIGURE 10 : Excess conveyance water lost per year from the hypothetical channel system used in Figure 9 vs. the number of cleanings.

Improved cleaning and maintenance involves bringing in soil to strengthen weak or low existing channel banks and junction areas, filling in ponds in the channels, removing overgrown vegetation from the banks, and then instituting a regular program of cleaning vegetation and sediment from the channels and maintaining the banks. These improvements will eliminate much of the visible leakage and short term breaks and will reduce seepage loss. Initial measurements indicate that losses can be reduced 20 to 30 per cent with these improvements.

The improvement has a relatively short life and requires regular reapplication. No engineering is required. Farmers, if convinced of the benefits, organized, and given the power to induce participation, can carry out the work.

Earthen renovation involves destroying the existing channels and reconstructing them of clean, compacted earth (Figure 11) according to engineering design based on hydraulic principles and topograhic surveys. Permanent structures are installed at the major junctions. Some field channels are eliminated if commanded land is leveled and can be reorganized.

This improvement will eliminate the visible and short term losses, part of the transient loss, high losses from junction areas, and the excess

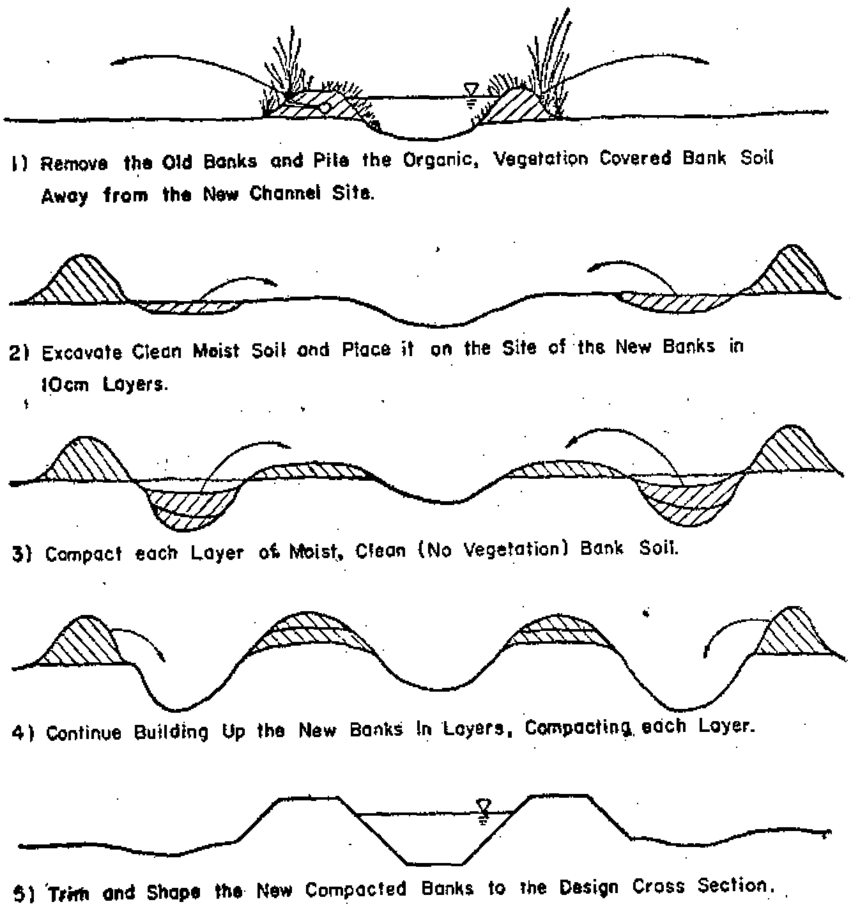

FIGURE 11 : Suggested procedure for manual reconstruction of earthen channels.

seepage. Measurements indicate initial water saving of 50 per cent of the original loss.

To extend the savings beyond a year or two, the improvements must be maintained (Figure 12). As pests return to the banks and continue burrowing activities, the savings will decline and the channel banks will need to be rebuilt after 4 to 8 years. Core compaction can extend the effective life.

Earthen renovation is carried out jointly by a government agency (the On-Farm Water Management (OFWM) Directorate of the Department of Agriculture) and the farmers. The agency provides the engineering design, technical supervision, and structures, and organizes the farmers. The farmers, after forming a Water Users Association and a supervision committee, provide the labor and promise to maintain the improvements.

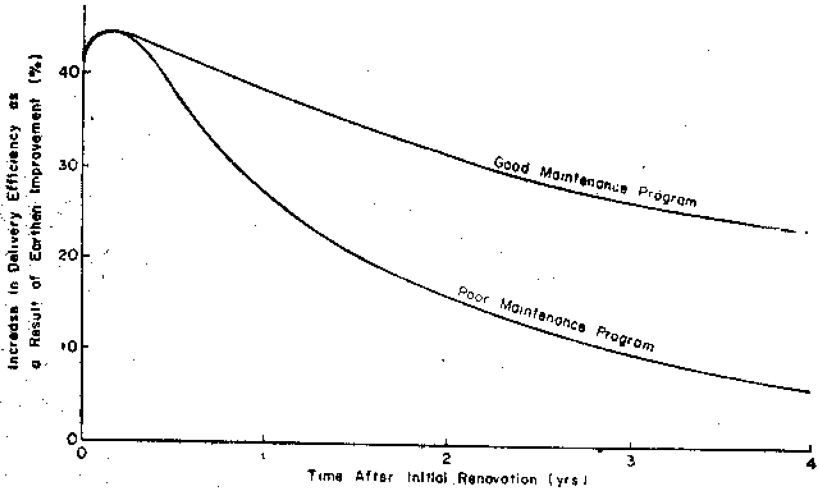

FIGURE 12 : Hypothetical examples of the decrease of water savings from earthen renovation with time with a good and poor maintenanee program

Channel lining is lining the watercourses with durable, impermeable material. Brick masonry rectangular and concrete trapezoidal linings are the most practical and economical in Pakistan. Such lining requires the same engineering design and utilizes the same structures as earthen renovation. Lining can save nearly all the conveyance loss except surface evaporation, and is projected to have an economic life of 20 years. However, poorly installed lining continues to lose water to seepage and will last only a few years.

The OFWM directorate provides the materials and engineering design and helps the farmers organize a Water Users Association to provide the skilled and unskilled labor. Farmers will bear increasing proportions of the material costs in the future.

IMPROVEMENT STRATEGIES

Which improvement technique to apply is an economic and financial question dependent on the cost of the improvement, the value of water, the amount of water saved, and the funds available. The amount of water saved per unit length depends upon the initial water loss rate, the per cent of loss saved by a given technique, and the amount of time a given channel section is full. If the loss rates are fairly constant through the main channels of a watercourse system, the benefits will primarily depend on the channel usage times, which vary widely in the branching rotational systems. Figures 13 and 14 show usage times for different percentages of the main channel portions of two conveyance systems, one dominated by a long main channel and the other composed of several branches.

Reuss (1978) developed equations to determine what part of a system with a given loss rate should be improved based on the water savings and improvement costs.

$$t = \frac{C}{31.5\, V Q_L f} \tag{1}$$

where: t = the fraction of a year a given section is full,

C = the annualized unit costs of the improvement. (\$/m/yr),

f = the fractional water loss saved by the improvement,

V = the unit value of the water (\$/m^3), and

Q_L = the original loss rate per unit length (L/s/km).

Any section full more than t can be economically improved with the technique.

If two improvement alternatives are to be applied to a system, the portion economically improved with the higher cost and water savings alternative can be calculated by:

$$t = \frac{C_h - C_1}{31.5\, V Q_L (f_h - f_1)} \tag{2}$$

where

C_h = the annualized unit cost of the higher cost improvement alternative (\$/m/yr),

C_1 = the annualized unit cost of the lower cost improvement alternative (\$/m/yr),

f_h = the fractional water loss saved by the higher cost alternative, and

f_1 = the fractional water loss saved by the lower cost alternative.

With the required cost, loss, and savings information and knowledge of channel usage and water values, the improvement techniques can be optimally allocated.

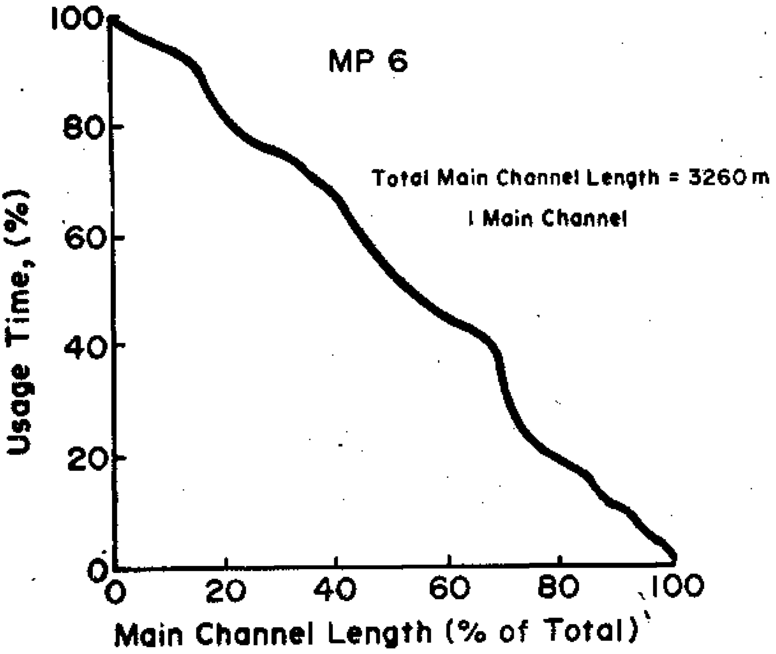

FIGURE 13 : Usage time vs. main channel length for a watercourse with one long main channel

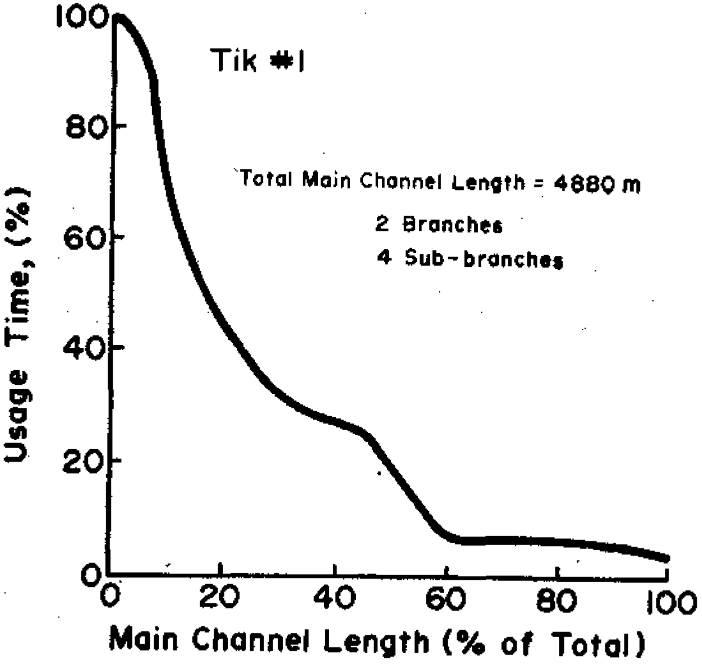

FIGURE 14 : Usage time vs. main channel length for a watercourse with several major branches

In Pakistan, an average watercourse loses 10 L/s of flow per kilometer length and irrigation water is worth about US$ 0.020/m³. Channel lining has an annualized cost of about $1.80/m and can save 90 per cent of the lost water. Earthen renovation costs $0.38/m/yr and can save 50 per cent of the loss. Improved cleaning and maintence costs only $0.20/m/yr and can save 30 per cent of the loss. Thus, according to Eq. 2:

$$t = \frac{\$1.80/\text{m/yr} - \$0.38/\text{m/yr}}{31.5 \times 0.020/\text{m}^3 \times 10\, L/\text{s/km} \times (0.9-0.5)} = 0.56$$

or any channel full more than 56 per cent of the time should be lined. This implies that about 50 per cent of the main channels in the system depicted in Figure 13 and 15 per cent of those of Figure 14 should be lined. Similarly, according to Equation 2 any channel used more than 14 per cent of the time should be earthen renovated.

Using average Pakistan watercourse values, it was estimated that about 20 per cent of the main channels should be lined. However, financial constraints have generally limited lining to 10 to 15 per cent. Lining 15 per cent of the main channels and earthen renovating the remainder will save about 65 per cent of the losses in the main channels or 35 per cent of the total conveyance loss (since 45 per cent of the loss occurs in field branches).

Field branches, because of only occasional usage, would not merit improvement at the assumed uniform loss rate. However, loss rates are initially higher from farmers' branches and after improvement of the main channels, these loss rates will increase further due to the decreased main channel losses and the increased flow rates and depths in the branches. Little of the water saved from the main branches will reach the fields. Thus, because of these high branch channel loss rates, it will be economical to increase the branch channel capacities and improve their maintenance. An improvement is required all the way to the field to realize the water savings. These field branchs improvements which are carried out by individual farmers will save 30 per cent of the branch losses and increase total savings to about 50 per cent of the initial loss.

WATERCOURSE IMPROVEMENT PROGRAM

Once three techniques were chosen and evaluted and an optimum improvement strategy determined, a Pilot Project was initiated in 1978. In this project 1500 watercourses were to have been earthen renovated with about 10 per cent of the main channels which either exhibited unusually high losses, flowed through village areas, or were full most often, being lined. The farmers agreed to provide labor for the improvements, improve their own branches, and to maintain the improvements. The pilot phase allowed the agencies involved to develop the required administrative and training institutions to support the program and for the project to gain national support.

The program is now moving from the pilot stage into a nationwide program. By June, 1981, over 1,200 watercourses had been renovated and 56 field teams were trained and working in the field (Water Management

Wing, 1982). The World Bank, Asian Development Bank, and U.S. AID have presently provided over U.S. $100 million in funding for the continued expansion of the program, targeting to improve all of the 89,000 watercourses in 20 years.

Recognizing the time required to improve all of the watercourses, the Government of Pakistan has instituted a "Crash" program of cleaning and maintenance which includes the formation of Water User Associations to carry on the activity and the provision of a few permanent structures at critical junction areas. By March, 1982, over 34,000 watercourses had been improved under this program which can provide immediate benefits. However due to the short life of "Crash" improvements, the program will not eliminate benefits to be derived from the main watercourse improvement program.

PROBLEMS STILL TO BE SOLVED

Although the watercourse improvement program is strongly supported by the farmers, goverment officials, and donor agencies, and is proceeding well, several problems still exist. First, even at an optimistically projected improvement rate, 20 years will be required to improve all 89,000 watercourses in Pakistan, while the life of the improvements are projected at less than half that time. The process must be accelerated in order to be reapplied at the required intervals.

The major constraint to accelerating the program is the training of the engineers and technicians needed to design and oversee construction. Pakistan does not produce sufficient numbers of engineers who are willing to undertake the laborious field tasks involved. Efforts are now being made to train technicians to carry out more of the field work.

A second weakness in the program is that, although channel maintenance has improved, the famers still are not adequately maintaining their systems. Involving the farmers in the improvement process, both in decision making and provision of labor, has been crucial in convincing them that the system is theirs to use and maintain, but often has not been sufficient motivation. Their financial contribution may further induce them to better care for the channels and structures. A major constraint to improved maintenance has been the lack of a recognized, legally sanctioned organization through which the farmer can arrange for and enforce participation in needed maintenance work. Water User Association laws recently adopted in two provinces should alleviate that constraint. An increased extension effort to convince farmers of the need for improved maintenance may also yield results.

A final and undoubtedly the most difficult problem remaining is that of teaching the farmers to effectively use their increased water supply at the field level. Special water management extension agents are being trained to teach and demonstrate improved water use to farmers on improved watercourses, but the effort is not equal to the task. Improved field water use will require a long-term concerted effort by the agricultural research agencies and extension service and firm support of the whole government.

SUMMARY AND CONCLUSIONS

In response to the need for increased agricultural production in the water short Indus Basin, a Water Management Research Project was carried out over 11 years to isolate problems and develop and test solutions. A major finding was that the watercourse conveyance system loses 30 to 50 per cent of the diverted water before reaching the field. While extensive conveyance loss measurements were being carried out to convince government officials of the magnitude of the the problem, specific causes were diagnosed and solutions proposed and tested. Practical solutions were put together in the form of economical improvement packages:

(1) improved cleaning and maintence,

(2) earthen renovation and permanent division structures, and

(3) channel lining.

These packages were then combined into optimum watercourse improvement strategies which require lining about 15 per cent of the main channels, earthen renovating the remainder of the main channels, and improving maintenance of the farm branches. This improvement strategy can save about 50 per cent of the water loss.

After applying these techniques for 5 years in a pilot program during which training and administrative institutions were developed, the process is now being applied on a country-wide level.

The major conclusions of the efforts are:

(1) water loss from village and farm level irrigation conveyance systems averages 40 per cent.

(2) burrows and other flow paths cause very high seepage rates into the upper channel banks.

(3) improved cleaning and maintenance and earthen renovation can save a significant portion of the water loss and often more economically than channel lining.

(4) farmers are willing to make a large investment in improving their irrigation system if the benefits are obvious.

(5) channel improvements must be maintained to reach a reasonable life and farmers must be orgainzed and given legal sanctions to carry out cooperative maintenance.

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