CHAPTER 8

Salinity in Punjab Watercourse Commands and Irrigation System Operations

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FOREWORD

FIELD RESEARCH SPECIFIC to "Managing Irrigation Systems to Minimize Waterlogging and Salinity Problems," an IIMI Pakistan project financially supported by the Government of the Netherlands, was formally initiated in 1989. An initial phase of detailed field research in selected canal system commands in Punjab and Sindh provinces will be followed by a second phase in which recommended management interventions are field-tested in action during the five-year life of the project. In Punjab, it has been possible to organize and implement a substantial portion of the primary research phase in conjunction with the field activities of other IIMI Pakistan projects, facilitating the sharing and wider use of more generic irrigation system data and information resources, and avoiding costly duplication of effort. Most importantly, it has made possible the integration of a range of primary data, analyses, and initial findings on irrigation system operations and performance across distributary canal commands, the large hydraulic units which constitute the Indus Basin irrigated agriculture system. This paper reports the preliminary results of that joint research effort.

Interestingly, while the technical objectives in the project paper call, inter alia, for reliable field data to quantify the relative contributions of the several possible sources of waterlogging, no such requirement for primary field data to quantify the sources of (secondary) salinity was included in the original project design. Possibly the effects of waterlogging were assumed to be far more severe than those of salinity on productivity of irrigated agriculture in Pakistan. More likely, there was inadequate recognition of the degree to which such salinity in Punjab is now disassociated from waterlogging. Also, in Pakistan generally and the Punjab especially, the absolute incidence of waterlogging has been greatly reduced, first by the installation and operation of public sector deep ("drainage") tubewells through the Salinity Control and Reclamation Project (SCARP) programs and, more recently, as a consequence of the rapidly growing exploitation of groundwater for irrigation by private sector shallow tubewells, which are now estimated to exceed 280,000 units.

The project paper also specified that IIMI's research will focus on "the irrigation and drainage environment conditions of incipient (and, as yet, not apparent) waterlogging and salinity problems," and two field research locales were anticipated for this purpose; one each in Punjab and Sindh.[36]

In Punjab, where IIMI-Pakistan was already conducting research on canal system performance and constraints on irrigated agriculture below the outlet in selected distributary commands of the Lower Chenab Canal (LCC) system, the choice of field-research sites was not based on any knowledge of incipient conditions of salinity or waterlogging. Indeed, in early 1989, conventional wisdom in Water and Power Development Authority (WAPDA) and other irrigation and agricultural agencies was that groundwater in Farooqabad Sub-Division in the Upper Gugera Branch command was generally of good quality ("sweet" or "fresh"), but moderately to strongly saline throughout much of Bhagat Sub-Division in the Lower Gugera Branch command. Subsequent IIMI field surveys confirmed that water tables were commonly more than three meters (3m) below the soil surface in both locales, and standing water in low areas around Pir Mahal was the result of surface ponding rather than high water tables.

These conditions did not, however, invalidate either command area within the LCC system being appropriate sites in which to address key salinity issues. Preliminary analyses of various field data being collected for IIMI's research on the conjunctive management of surface water and groundwater systems were already beginning to reveal unrecognized, even largely unanticipated, salinity problems, first in Farooqabad Sub-Division and later in Bhagat Sub-Division. The work of R. L. Johnson, an IIMI research fellow who conducted a study of latent groundwater demand in part of Farooqabad Sub-Division, was of particular importance in this respect.[37]

This report is based upon primary field data collected in watercourse and distributary canal command areas of both research locales — Farooqabad and Bhagat Sub-Divisions — without a strict separation between the two sites. Our rationale for this approach is that, in terms of tubewell water quality and the problems of secondary salinization, both areas present a very similar picture. Although a more detailed understanding is currently available for conditions in Farooqabad, because data collection began earlier there than in Bhagat, enough is already now known about the widespread and increasing reliance in Bhagat upon tubewells that are pumping marginal or poor quality water to conclude that our findings have more than localized implications. Moreover, the factors that we hypothesize are causing or intensifying secondary salinization problems which will require new, environmentally sophisti-

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[36] Because of serious law and order problems throughout much of rural Sindh since September 1989, it has not been possible to initiate the substantial field-research program that has been planned there. However, in collaboration with the Soil Survey of Pakistan, a reconnaissance survey of soil conditions in the command of the Hasan Ali Branch canal in the Fuleli Canal system (near Hyderabad) has been underway since March 1990, and the tabulation of official data with irrigation and agriculture agencies was begun in early July.

[37] See Robert L. Johnson, *Latent Groundwater Demand in Pakistan's Punjab: Theory and Applications*, (Ph.D. dissertation, Ithaca, NewYork: Cornell University, 1991) for details of this research.

cated, often linked and sustained irrigation management interventions at main as well as secondary system level if the threat to the sustainability of irrigated agriculture in large areas of the Indus Basin is to be reduced. Nonetheless we are aware that the management interventions required are unlikely to be the same everywhere.

As the root cause of the problems, we identify the growing imbalance between the availability of good quality canal water and of poor quality groundwater as one proceeds down the system, the distributary, and the watercourse. The solution therefore depends on the possibility of ending or at least mitigating the inequity of distribution of the two sources of irrigation water. Some of the distribution-related issues and irrigation management implications are tentatively addressed in the final portion of our discussion.

THE STUDY AREAS: AN INTRODUCTION TO THE IRRIGATION ENVIRONMENT

Primary measurement data have been collected by IIMI and its research collaborators for a large number of sample watercourses, off-taking from Lagar and Mananwala distributaries in Farooqabad Sub-Division, Upper Gugera Branch, and from Pir Mahal and Khikhi distributaries in Bhagat Sub-Division, Lower Gugera Branch. These data have also been used in one or more of IIMI-Pakistan's other research projects (e.g., distributary-level canal performance and conjunctive management of groundwater and surface irrigation systems). The data now available cover a wide range and include spatial and temporal variability in discharges in the canal system, public and private tubewell operations and the extent of groundwater usage at watercourse and farm-level, to seasonal crop surveys, and the water and salt balances of crop root zones in selected areas. In some cases, data are available from as far back as August 1987; in other instances (e.g., for water and salt balances), data availability is only since kharif 1989.

Our discussion of the incidence of salinity is based largely upon primary data collected in the command areas of two watercourses served by Mananwala Distributary and two off-taking from Pir Mahal Distributary. Mananwala Distributary off-takes from Upper Gugera Branch in Farooqabad Sub-Division, Upper Gugera Division, about 68 km downstream from Khanki Barrage, the headworks of the Lower Chenab canal LCC system (Figure 8.1). Pir Mahal Distributary off-takes from Lower Gugera Branch in Bhagat Sub-Division, Lower Gugera Division, more than 200 km further downstream. Both are in the LCC East Circle, and the entire LCC system comprises the Faisalabad Zone of the Punjab Irrigation Department.

Mananwala Distributary is 45 km in length and its design discharge is 5.2 cu.m. It supplies 125 sanctioned outlets (either directly or from three minors) and serves a cultivable command area (CCA) of 27,064 ha. The average sanctioned discharge of its outlets is 30 l/s. The distributary was designed for two levels of cropping intensity. This means that some outlets, those serving 50 percent intensity command areas, have a design water allocation of 1 l/s per 7.5 ha, whereas others have 75 percent intensity service areas with a slightly more generous water allocation standard of 1 l/s per 5 ha. In size and service area, Mananwala is a fairly typical distributary in the LCC system.

The first sample watercourse is located at a reduced distance (RD) of 71,683 ft (henceforth RD 71) and the other is at the tail, at RD 143,850 ft (RD 143). RD 71 is situated in approximately the middle reach of the Mananwala Distributary. It has a cultivable command area (CCA) of 288 ha, and a watercourse discharge of 38 l/s. The service area is split in two by a road, and only the northern area, with a CCA of 187 ha, was studied. A deep public (SCARP I) tubewell discharges groundwater into the main, lined watercourse where it is mixed with canal water in a ratio of about 2 to 1. In addition, there are 18 shallow private tubewells operational in the command area.

RD 143 is located at the tail of Mananwala Distributary and has a CCA of 87 ha. Canal water rarely reaches the outlet for RD 143, and then only during periods when cultivators' irrigation requirements are low (e.g., between the seasons or occasionally after a heavy monsoon shower). One SCARP tubewell provides most of the water for irrigated agriculture in the service area, although there are four private tubewells operational here and others under development.

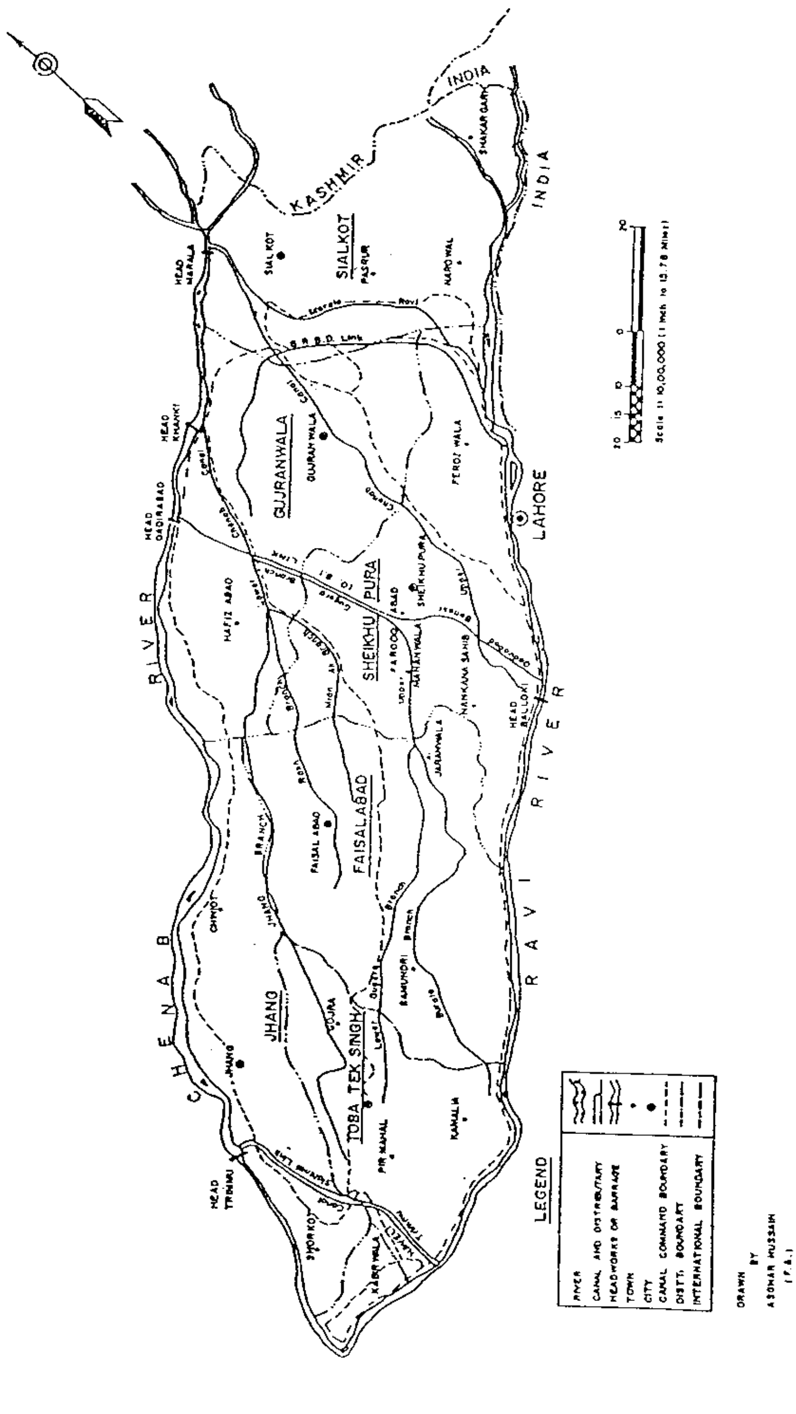
At Bhagat Head regulator, Lower Gugera Branch canal is divided into four distributaries, one of which is Pir Mahal. This canal is 47.5 km long and has a design discharge of 4.67 cu.m for a CCA of 14,891 ha. Pir Mahal directly supplies 50 sanctioned outlets and 40 others off-take from its four minors. The average design discharge of these outlets is 35 l/s. The distributary was designed as a 75 percent intensity channel, with a seasonal cropping ratio between kharif and rabi seasons of 1:2 in its service area.

Watercourses selected for the study of water and salt balances in Pir Mahal command are situated at RD 89 and RD 133, in the middle and tail reaches of the distributary, respectively. The CCA of outlet RD 89 is 173 ha, and the design discharge of the watercourse 46 l/s; for outlet RD 133, these values are 220 ha and 44 l/s, respectively. The amount of canal water that usually reaches the head of RD 133 is insufficient, however, and farmers can irrigate only those fields which are close to the watercourse *mogha*. Consequently, large portions of the command area of RD 133 are completely dependent on irrigation water supplies from tubewells.

A few public tubewells were installed in the tail watercourse commands of Pir Mahal Distributary and Junejwala Minor between 1975 and 1977. These were among the 101 tubewells installed under the Shorkot Kamalia Pilot Project (SKPP) programme as part of an accelerated effort for controlling waterlogging and salinity in the lower Rechna Doab. Here, priority was given to areas with fresh groundwater where the tubewells would serve the double purpose of providing drainage and supplementing irrigation supplies. Tubewell development under this programme continued in the area until 1985.

Contrary to the general perception, private tubewell development has been almost as active in the service area of Pir Mahal Distributary over the past 3-4 years as it has been in Mananwala Distributary command. For example, a tubewell census completed by IIMI in mid-1990 in the 23 outlet commands of Junejwala Minor, Pir Mahal's largest off-taking distributary, revealed the surprising average private tubewell density of more than 7 per 100 ha.

Figure 8.1. Rechna Doab, Punjab, Pakistan.



The service areas of the seven distributaries that constitute Farooqabad Sub-Division, including Mananwala, are wholly within the Punjab rice-wheat agroecological zone. Rice, especially the high-value basmati variety, is the predominant crop in this region during kharif wherever irrigation water supplies are sufficient, while wheat is the principal crop during rabi. In addition to these two major crops, sugarcane and various fodders are grown year-round as well as a range of seasonal fruits and vegetables for both cash income and domestic consumption.

The command areas of Pir Mahal and other Bhagat Sub-Division distributaries fall in the transition zone between the rice-wheat agroecological zone and the cotton-wheat belt of Punjab further to the southwest. Here, cotton is more frequently the main crop during kharif season, and wheat predominates in rabi. However, elsewhere rice remains a significant though a more localized crop where water supplies are relatively abundant (parts of Pir Mahal command and elsewhere). As in the Mananwala service area, sugarcane and various fodder crops are also grown throughout the year, the proximity of a large sugar mill in Kamalia stimulating the production of sugarcane in much of the area. Sesame (an oil seed crop) and vegetables are grown throughout the Pir Mahal command area during kharif, and perennial citrus fruits occupy a considerable and still expanding area. In short, the irrigated agriculture system in IIMI's study areas is characterized by a diversity of crops grown and by large acreages devoted to key crops in Pakistan's agricultural economy.

Topographically, the interfluvial region through which the Upper and Lower Gugera Branch canals flow is flat with little natural drainage. It is underlain by a deep, high-yielding unconfined aquifer that is relatively homogeneous and highly anisotropic. Bennett et al. (1967) provide a detailed hydrologic description of the aquifer, giving the mean values of hydraulic conductivities as 1.2E-3 and 1.5E-5 m/s in horizontal and vertical directions, respectively. The much lower vertical transmissivity is due to the presence of clay layers in an otherwise fairly coarse sandy aquifer. The specific yields with the water table in the sand layer and the clay layer are, respectively, 0.15 and 0.06 (ibid.). It is desirable, therefore, to install tubewells so that the screen length will not fall within the thick clay layers.

Historically, following the extensive construction and operation of canals in the Rechna Doab, significant areas began to suffer from both substantial waterlogging (defined as conditions with water tables within five feet of the land's surface) and salinity. By the mid-20th century, the severity and extent of these problems provided the impetus for the first Salinity Control and Reclamation Project (SCARP I), initiated in the central Rechna Doab in 1960, and subsequently for other SCARP and smaller-scale public tubewell deep drainage projects. Today, the depths of water tables in the Mananwala and Pir Mahal commands range between 3 and 8 m, with gradients towards the tail ends of the distributaries. In the Mananwala region, the primary source of aquifer recharge appears to be seepage from two large canals that pass north to south across the head of the Mananwala Distributary (i.e., the Upper Gugera Branch, carrying about 180 cu.m in this reach, and the Qadirabad-Balloki Link Canal, which carries around 540 cu.m). Recharge to the groundwater in the area of the Pir Mahal Distributary is probably in large measure from the Ravi River, which flows at a distance of only 12 km from some parts of the downstream half of the distributary.

According to the Soil Survey of Pakistan (Bashir Choudhri et al. 1978), most of the salinity in Punjab is ancient, produced as the result of soil-forming processes over thousands of years, greatly predating the rise in water tables associated with the introduction of canal irrigation. Saline patches were recognized as occurring within good land in an intricate spatial pattern when lands were being developed for irrigation. Although larger saline tracts could be, and were, excluded from design canal command areas, the inclusion of smaller patches of salinity within larger extents of good soils was inevitable. Indeed, some of them were subsequently reclaimed, but in other areas reclamation attempts were far less successful.

Conventional wisdom in Pakistan brackets waterlogging and salinity as the "twin menaces" of irrigated agriculture in the country. One is almost preconditioned to assume, therefore, that with the reduction of waterlogging in large parts of the country, (especially in Punjab, through the extensive development and operation of SCARP tubewells, followed more recently by private tubewells) the problem of salinity has largely been solved as well. But as early as 1978, the Survey of Pakistan warned that this was not the case:

> The secondary salinity, which is of much greater concern than that akin to waterlogging, is the build-up of high sodicity in first-rate, non-saline agricultural land caused by irrigation with low-quality tubewell waters. This type of salinity was introduced with (the) accelerated use of groundwater. The symptoms of the sodicity of soils are widespread, as observed from hardening of topsoil, decrease in rate of infiltration and inadequate seed germination, especially of alkali-sensitive crops. This mode of salinization is treacherous, as it operates insidiously and the farmers, due to (the) slow rate of soil deterioration, become aware of the problem (only) after considerable damage has been done (ibid.).

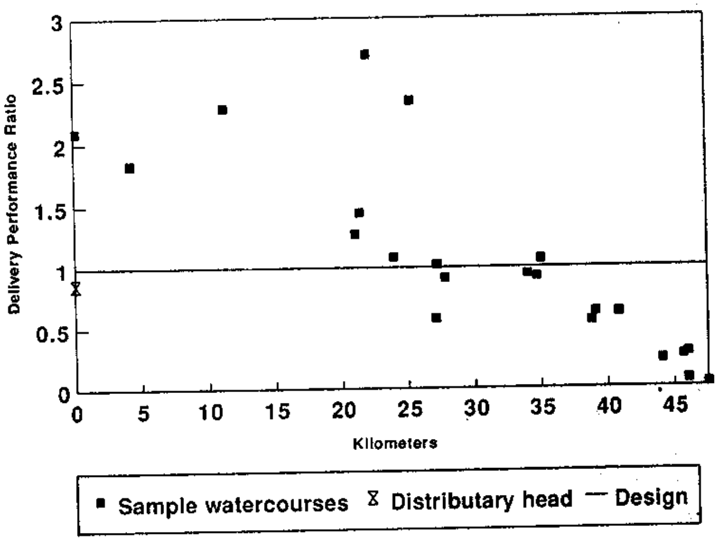
Much of what we report in the following discussion of IIMI's initial research findings in Punjab concerning irrigation management interventions for the control of salinity, and our analysis and interpretation of them, reinforces and substantiates this early, perceptive observation.

DISTRIBUTION OF WATER SUPPLIES: SURFACE IRRIGATION SYSTEMS

The initial findings of IIMI Pakistan research on the operations and performance of distributary channels in the LCC system of Punjab have been extensively reported elsewhere (Vander Velde and Bhutta 1989; Bhutta 1990; Vander Velde 1990). Therefore, only a brief overview and update are required here.

Analysis of primary measurement and observational data collected through monitoring activities on selected distributaries in both Farooqabad and Bhagat Sub-Divisions has demonstrated that the long-standing system performance objective of equity in surface-water distribution is now rarely achieved and almost never sustained at the secondary canal level. Outlets in the tail reaches of distributaries seldom obtain more than a fraction of their design or sanctioned discharge at the watercourse head, in contrast to outlets in the upper reaches which commonly receive substantially more than their design discharge.[38] This pattern has been observed, for example, for Pir Mahal Distributary (Figure 8.2), and it is clear that consistently low levels of maintenance of distributary channels are one primary cause. The consequence is that farmers in the command areas of tail watercourses experience, on average, less than one-fifth of the access to surface water supplies that farmers served by watercourses in the head reach of the distributary enjoy (Figure 8.3).

Figure 8.2. Pir Mahal Distributary: Water distribution equity .

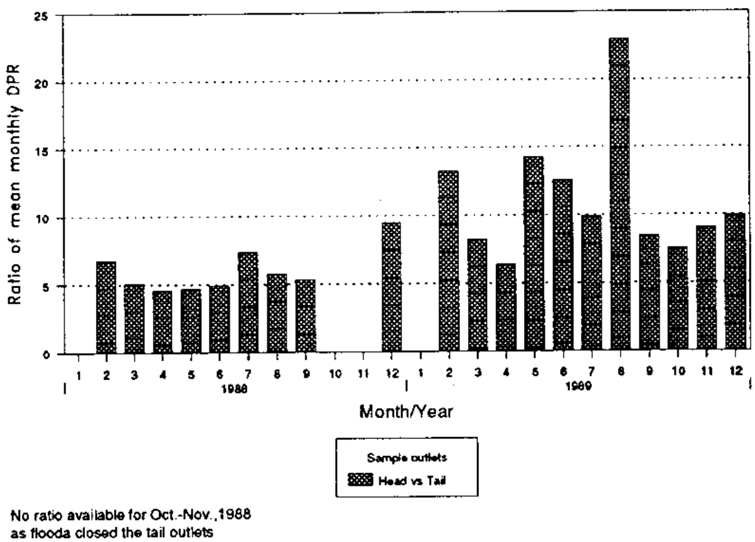


Bhagat Sub-Division

When the discharge entering the distributary head falls below 70 percent of design, an occurrence observed in some LCC system distributaries for as much as one-third of the annually available operational days (Bhutta 1990), water supplies to tail outlets simply collapse, and farmers there receive no water from the canal at all. Canal operations in the Bhagat Sub-Division effectively illustrate the case. There, surface water supplies delivered by Lower Gugera Branch to the tail of the main system are usually insufficient for all six distributaries to operate simultaneously at full supply level. An inter-distributary program of rotational operations is therefore followed for

[38] The measure used here to describe water distribution equity among or between outlets along a distributary is *Delivery Performance Ratio*(DPR). The DPR is the ratio of actual discharge received at the outlet to its design or sanctioned discharge.

Figure 8.3. Pir Mahal Distributary: Equity between sample outlets



much of the year at Bhagat Head. Data obtained for distributary-head conditions here over several months in 1990 reveal significant inconsistencies in the equitable implementation of scheduled rotational operations (Figure 8.4).[39] In particular, Pir Mahal Distributary is operated at less than 70 percent full design supply for a disproportionate amount of time, contrasting dramatically with the frequency with which Khikhi and Dabanwala distributaries are operated in excess of 100 percent of design full supply discharge.

It must be said that, heavy silt accumulations and serious embankment erosion in Pir Mahal Distributary, especially in its head reach, due to deferred or neglected channel maintenance, preclude its operation at design full supply discharge for sustained periods of time, in any case. These physical conditions have also necessitated the adoption of a program of internal rotational operations between the main channel tail reach and its off-taking minors. One consequence of the resulting pattern of canal operations is that the frequency of days without canal water at the heads of watercourses in Pir Mahal command increases markedly in the tail reach of the distributary (Figure 8.5). These farmers are without surface water supplies for more than 50 percent of the time during extended periods throughout the year.

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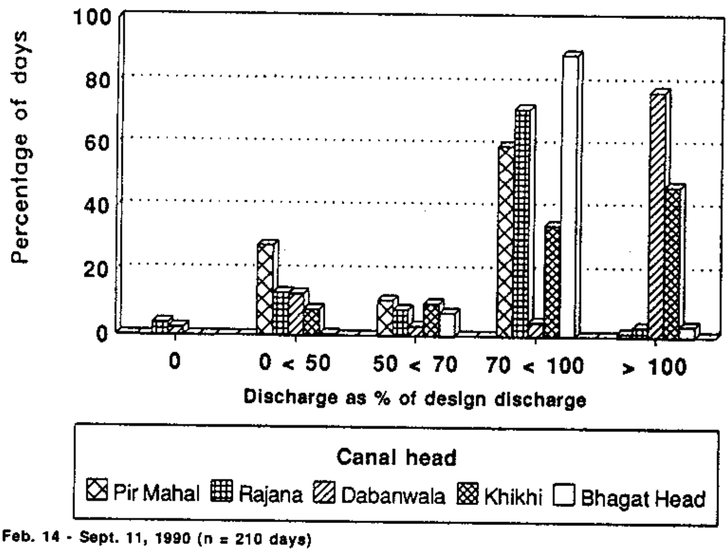
[39] Telog automatic stage recording data loggers were installed at each of the four distributary heads, and they have been operational since the resumption of Lower Gugera Branch canal operations following the 1990 annual maintenance closure period.

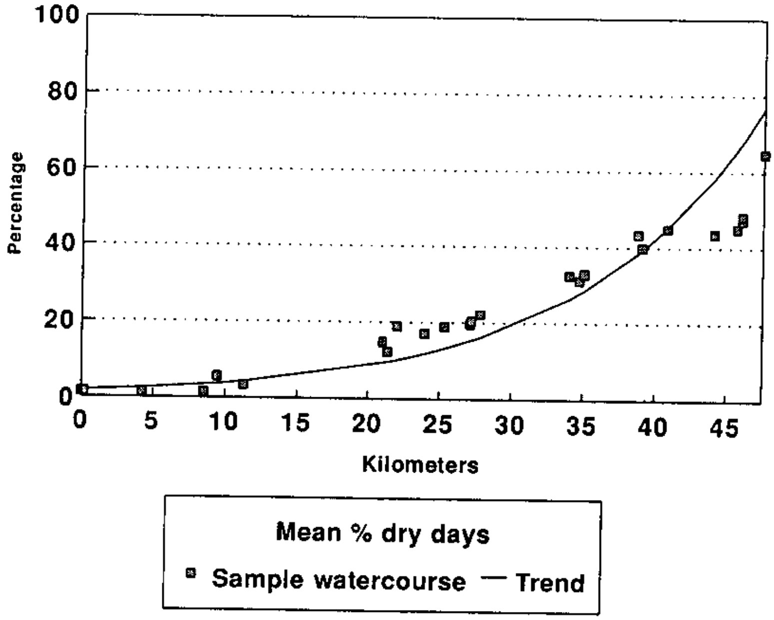
Even when distributary head discharge conditions are relatively steady at or near design full supply level, tail watercourse commands are often deprived of even modest surface water supplies by many large and small quasi-legal and illegal interventions upstream to obtain additional canal water. This situation has been regularly observed over the past three years in Mananwala Distributary command. Figures 8.6 and 8.7 show the pattern of water distribution to groups of sample outlet at head, middle, and tail locations in terms of weekly mean DPR for every other week over a twelve-week period marking the onset of the 1990 kharif season. From mid-May on, most tail outlets received no water at all, marking the onset of kharif rice cultivation activities in extensive areas of the upper two-thirds of Mananwala command and the resumption of illicit irrigation operations there to sustain the rice crop through numerous embankment "punctures," syphons, and irregular pipe outlets.

Figure 8.4. Bhagat Head rotational operations: Equity between distributaries.



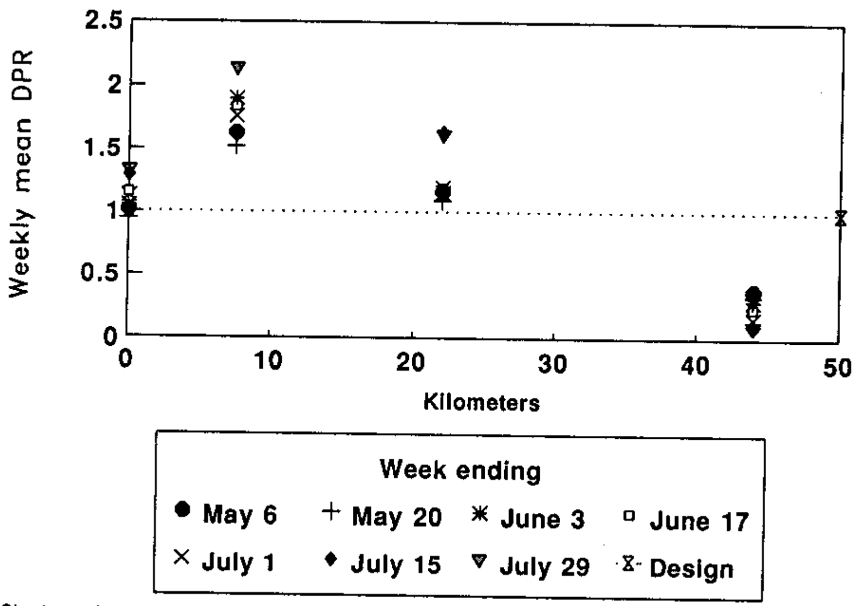
Variability in distributary flows upstream is passed on to the discharges of downstream off-taking watercourses. The effect is most pronounced for tail-reach outlets, and farmers in those command areas experience the further disadvantage of greater unreliability in the delivery of whatever share of surface water supplies reaches them. Mananwala Distributary operations (Figures 8.8-8.11) better illustrate this condition than does Pir Mahal because of the complex program of rotational deliveries practiced in the latter, even though careful head-gate operations at Mananwala do minimize the effect of variability in main system flows entering the distributary system. The conditions shown are for eleven *warabandi* weeks (Monday through Sunday) covering the first half of kharif 1990, May through July. It will be immediately observed

Figure 8.5. Dry days of Pir Mahal Distributary Outlet: Kharif 1988 and 1989.



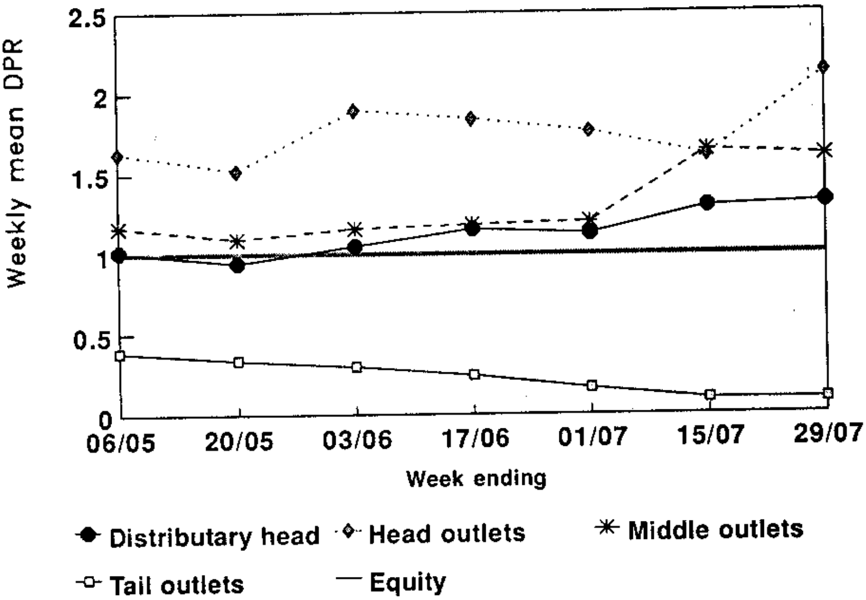
(n > 200)

Figure 8.6. Mananwala Distributary: Selected weekly mean DPR of sample outlets.



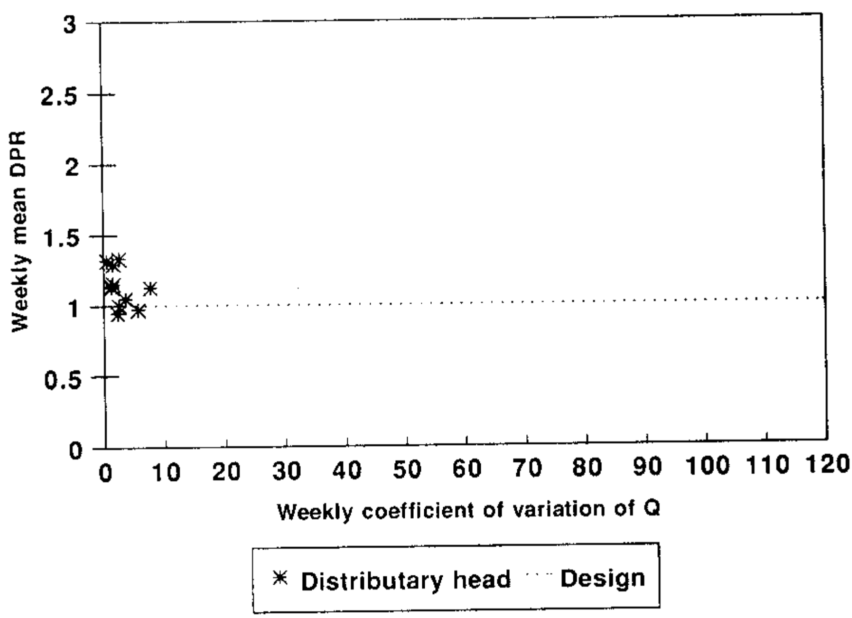
Clusters of sample watercourses
May thru July, 1990 only

Figure 8.7. Mananwala Distributary: Changes in mean DPR of sample outlets.



NB: May thru July, 1990

Figure 8.8. Mananwala Distributary Head: Equity versus variability, kharif 1990.



May-July, 1990 (11 weeks)

Figure 8.9. Mananwala Distributary Outlet RD 24R: Equity versus variability, kharif 1990.

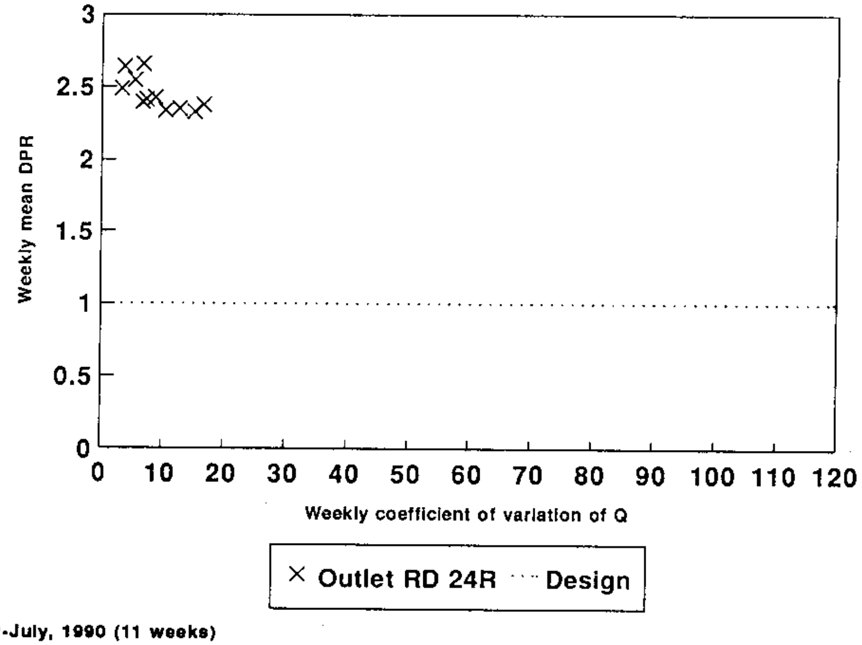


Figure 8.10. Mananwala Distributary Outlet RD 71R: Equity versus variability, kharif 1990.

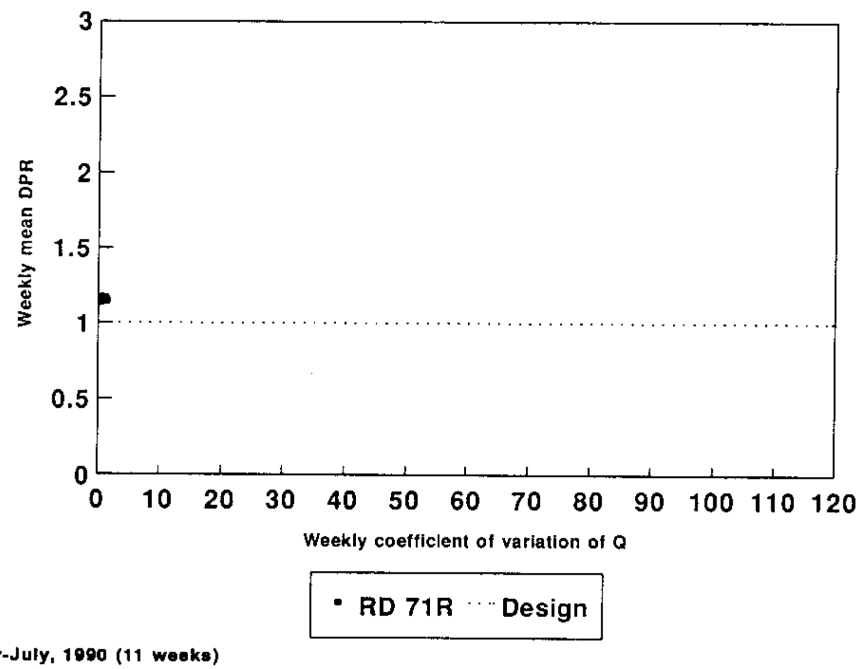
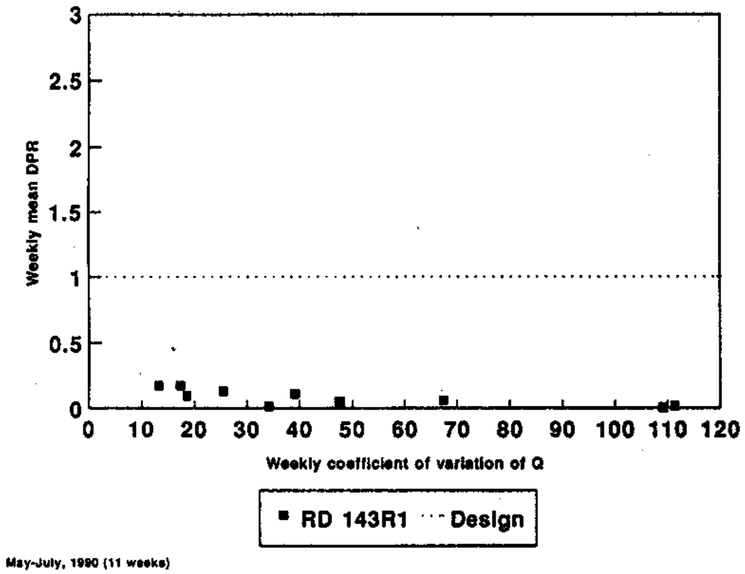


Figure 8.11. Mananwala Distributary Outlet RD143R1: Equity versus variability, kharif 1990.



that for the distributary head, as well as for a head and middle watercourse, weekly mean DPR is near to, or well above, design. Variability associated with these flow conditions is correspondingly low, the coefficient of variation being well under 20 percent in the majority of instances. Variability of flows at a large tail watercourse, however, increases markedly as weekly mean DPR declines to virtually zero over the period.

DISTRIBUTION OF WATER SUPPLIES: GROUNDWATER IRRIGATIONS SYSTEMS

In the face of the increasing inability of the surface irrigation system to deliver water equitably in any usable amount to many watercourse heads in the lower reaches of distributary channels for extended periods of the year, the farmers' only apparent recourse is groundwater development. Indeed, it was the extensive program of public groundwater development in large areas of the Rechna Doab commanded by the LCC system — the SCARP deep drainage tubewells to control waterlogging installed in the early 1960s — that first provided greatly enhanced water supplies at the watercourse level and spurred two major, almost simultaneous, changes in irrigated agriculture there. These soon spread throughout much of Punjab. On the one hand, the three- or four-fold increase in water supplies at the watercourse level meant that the previous design low cropping intensities of the surface irrigation system — typically in the range of 50 percent-75 percent — could be exceeded, and annual cropping intensities in canal commands rose rapidly to well over 100 percent. On the other hand, the greater abundance of irrigation water now available to farmers meant that large acreages could be planted with more remunerative, but more water intensive, crops such as rice and sugarcane.

The unforeseen and relatively rapid decline in the amount of fresh groundwater pumped by these deep tubewells — due to the shorter than anticipated bore life, frequent breakdowns in pumps and motors, poor maintenance levels, power supply constraints, high operating costs, and inadequate budgetary resources — does not mean that the contribution of public tubewells to the irrigation water supplies of farmers has now become insignificant. Farooqabad Sub-Division falls wholly within the SCARP I area, and Johnson (1990) has reported that the average annual utilization rate of 11 public tubewells located in the command areas of Mananwala Distributary and neighboring Lagar Distributary was 64 percent in 1988-1989, based on the number of hours that each well was operational with electric power available.

In the sample of nine Lagar Distributary watercourses where public tubewells remain operational, detailed monitoring and measurement of their operations throughout the 1988-89 agricultural year were carried out. The data revealed that public tubewells provided, on average, 43 percent of all irrigation water available to farmers in rabi and nearly 30 percent of irrigation supplies available in kharif.

Nevertheless, the amount of groundwater supplied by public tubewells that remain in operation has declined substantially from levels achieved in their early years of operation. They no longer provide a threefold or greater increase in water availability at the watercourse command — in the Lagar study, average irrigation supplies from the public tubewells exceeded those from the distributary by only 25 percent in either season. Indeed in many watercourse commands throughout SCARP I, the public tubewell is no longer operational at all.

It has been the rapid development of private, shallow tubewells throughout the 1980s that has offset the declining productivity of the public deep tubewells and in large measure made it possible for farmers to maintain high cropping intensity levels and cropping patterns, with substantial areas planted to more water-consumptive, less drought-tolerant crops. The growth in numbers of private tubewells has been most rapid in Punjab (Figure 8.12).

The censuses of tubewells done by IIMI in 35 watercourse commands of Mananwala, Karkan (Minor) and Lagar distributaries reveal that the average density of private tubewells in Farooqabad Sub-Division is about 5 per 100 ha of gross command area (GCA).[40] This density of private tubewells, in a SCARP area where private tubewell installation was formally restricted and controlled, is considerably higher than what published official data have indicated (Figure 8.13). The implication is that the pace and pattern of private tubewell development may well have been substantially underestimated for large areas of Punjab.

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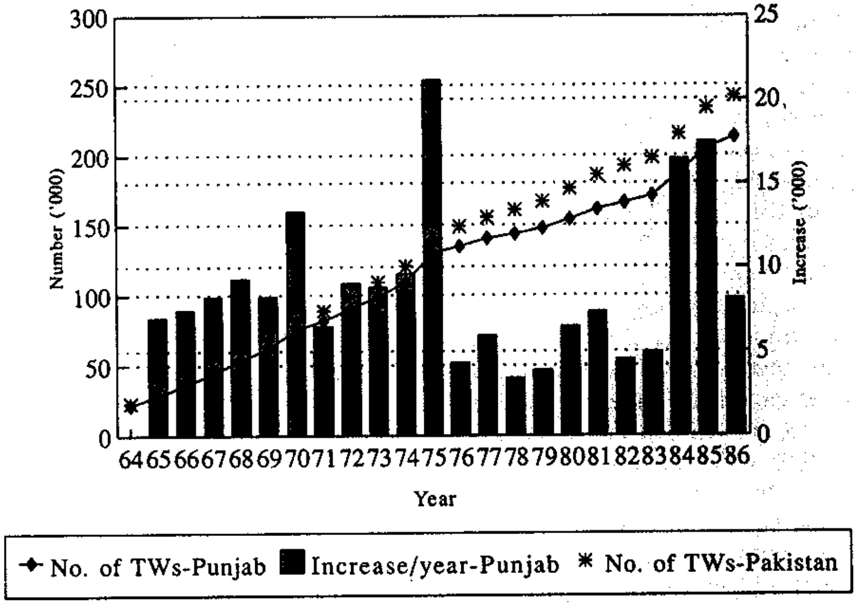
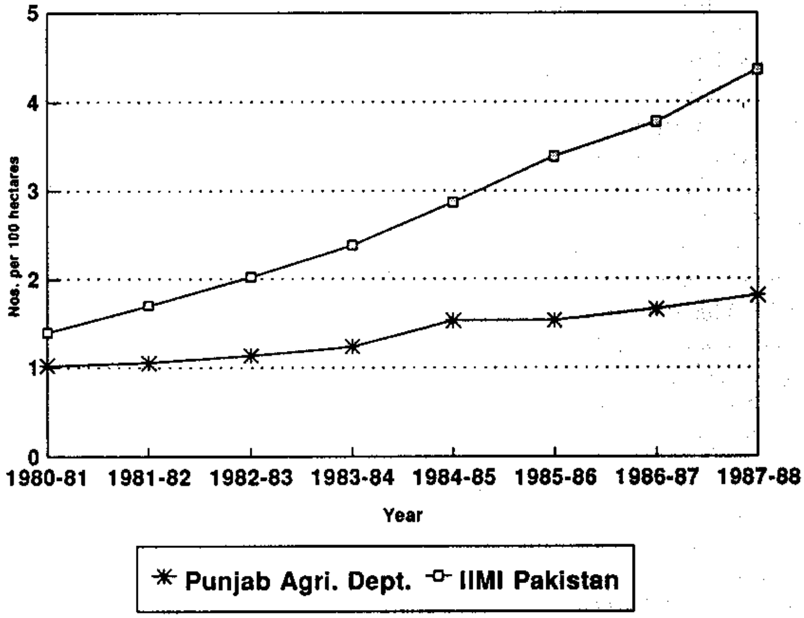
[40] Watercourse gross command area (GCA) is used here rather than cultivable command area (CCA) because CCA more strictly applies to the irrigable service area of the surface system. Many farmers have installed tubewells not only to supplement their surface supplies, but also to bring additional areas, not served by the surface system, under irrigated agriculture.

Figure 8.12. Private tubewell development in Pakistan and Punjab.



Source: WAPDA, 1988

Figure 8.13. Densities of private tubewells: Punjab Agriculture Department data versus IIMI data.

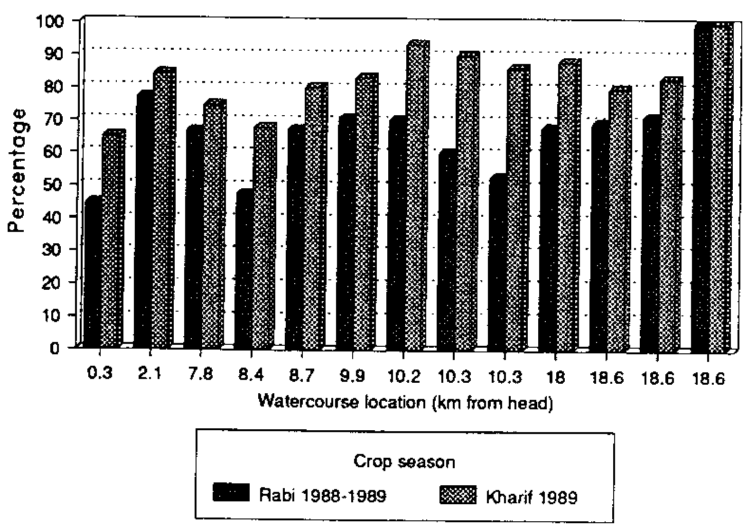


IIMI = Farooqabad SD canal watercourses
PAD = Sheikhupura District

In any event, the actual availability of water in watercourse command areas continues to exceed the original surface system design values of 1 l/s per 5 or 7.5 ha noted above. In fact, IIMI data for 13 watercourse commands of Lagar Distributary indicate that the average proportion of groundwater to all irrigation water available to farmers at the pump head and the outlet was 67 percent for the rabi season, rising to over 80 percent in kharif. Figure 8.14 shows the spatial distribution of this pattern for different watercourse commands at increasing distances from the distributary head.

The ratio of groundwater to surface water annually available to farmers in Lagar command ranged between 1.2:1 and 14.7:1 for the 13 watercourses studied. If the extreme value of 14.7:1, which occurred in a tail-end watercourse, is ignored, the average annual ratio of groundwater to surface water is 2.8:1. It is therefore reasonable to assume that on average, groundwater from public and private sources contributes about 70 percent of the total irrigation water used in irrigated agriculture in Farooqabad Sub-Division.[41] Significantly, data collected in the command area of watercourse RD 89, Pir Mahal Distributary, in kharif 1990, indicated that during July and August, groundwater contributed 72 percent of the total irrigation water used by farmers in the area.

Figure 8.14. Percent of groundwater in total irrigation water used: Lagar Distrbutary command.



[41] At IIMI's 1989 Internal Program Review, Johnson and Vander Velde reported on the de facto conjunctive management of surface water and groundwater in these distributary and watercourse command areas.

These findings provoke the tentative conclusion that groundwater resources are providing a substantially greater proportion of total irrigation supplies now utilized by farmers in many canal command areas in Punjab than previously suspected. They may also imply a rate of aquifer exploitation already in excess of recharge, at least locally if not over larger areas. Perhaps most important is the fact that no agency or organization in Pakistan is systematically monitoring what appears to be a fundamental (and possibly short-lived) transformation of the water resource basis of the Indus Basin irrigated agriculture system.

THE WATER BALANCE

There are several reasons for seeking to ascertain the water balances of watercourse command areas. First, we want to know how much water is consumed by crops and how much is lost to groundwater, contributing to aquifer recharge and perhaps water table rise. The Second concern is to determine what proportions of the irrigation water that farmers use are derived from canal supplies and from groundwater. Once the proportionality of supplies and their quality have been determined, the key issue of whether the salt content in the crop root zone is likely to increase or decrease can be tackled.

In several sample watercourse command areas in the LCC system, water flows into the watercourse from the secondary canal system and discharges from public and private tubewells have therefore been recorded by IIMI field teams over sustained periods in 1989 and 1990. Additionally, irrigation applications have been measured in fields of sample farmers in these watercourse commands, to evaluate farmers' irrigation practices. Seasonal irrigation applied to wheat during rabi 1989-90 is presented in Table 8.1. All irrigations in Mananwala were from public tubewells, and all but two irrigations in Pir Mahal were from private tubewells.

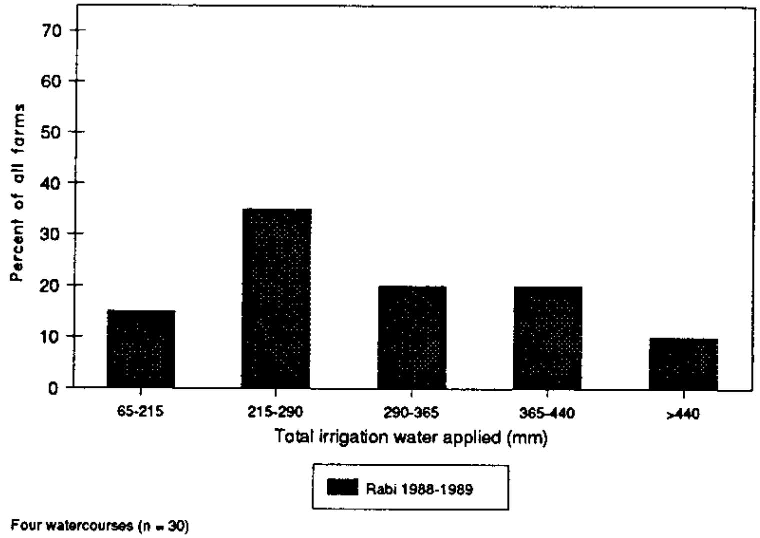
Although the average seasonal irrigation is about the same in both areas, the variability of seasonal irrigation is greater in Mananwala command than in Pir Mahal command, as can be seen from the standard errors. The average amounts applied per irrigation differ significantly (5 percent level) between the two areas. It is not clear why some farmers apply much more water than others, or why a farmer applies twice as much water from the same tubewell to one field as to another. This is especially true for Mananwala area, where the variability in irrigation applications is greater than in the Pir Mahal area. Apparently, farmers in the Pir Mahal area attempt to make more optimal use of their irrigation water.

Histograms depicting irrigation applications to wheat during rabi 1988-89 and to sugarcane during kharif 1989 are shown in Figures 8.15 and 8.16. The data reflect farmers' practices in watercourses of Mananwala and Pir Mahal distributaries, in addition to the sample watercourses mentioned above. The median irrigation application for wheat in the Mananwala area is 290 mm. Median values for irrigation of sugarcane are 480 mm in Mananwala and nearly the same, 485 mm, in Pir Mahal. The histograms again illustrate the wide range of irrigation applications practiced by farmers; some obviously overirrigate while others apply hardly enough to make it worth their while harvesting the crop.[42]

Table 8.1. Wheat irrigation in two LCC distributary canal commands: Rabi 1989-1990.

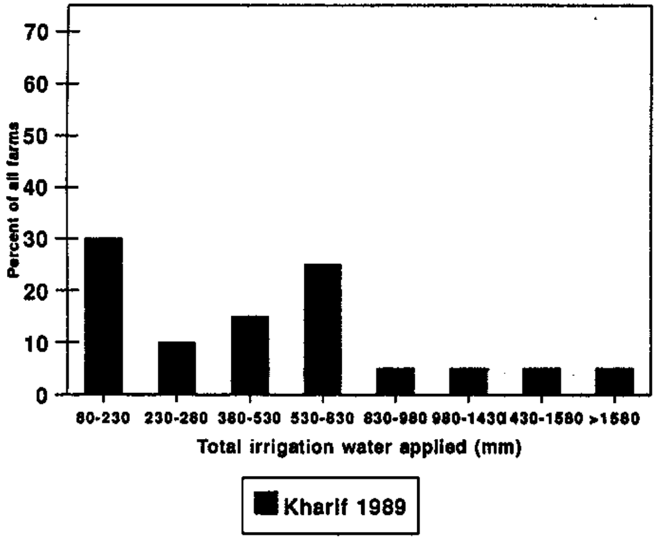
	Mean total irrigation (cm)	Std. error	Mean application (cm)	Std. error	Average no. of irrigations	Total rainfall (cm)
Mananwala	22.0	2.1	7.0	0.42	2.5	14.7
Pir Mahal	21.2	0.7	6.2	0.16	3.8	9.6

Figure 8.15. Irrigation of wheat: Mananwala Distributary command.



[42] The data used in Figures 8.15 and 8.16 were obtained from a much larger sample of farmers in four districts of Punjab which will be reported on in greater detail elsewhere. Mean and median values of irrigation applications determined for the larger sample are significantly higher than the values mentioned here for Mananwala and Pir Mahal. The inclusion of data from Gujranwala District, which is not short of water, in the larger sample probably explains the difference. The results from the larger survey also strengthen the conclusion that irrigation practices of Punjab farmers vary widely.

Figure 8.16. Irrigation of sugarcane: Mananwala Distributary command.



Four watercourses (n = 30)

Substantial variability in both watercourse and tubewell discharge has been observed.[43] Variability in watercourse discharge is largely a function of distributary performance, as previously discussed. Variability in tubewell discharge, observed for all types of tubewells, results from a variety of factors. For electric tubewells, it is often a consequence of voltage fluctuations or an increase in drawdown of the water table following many hours of sustained pumping operations. In diesel- and tractor-powered tubewells, significant fluctuations in discharge can also result from changes in engine speed with throttle adjustments. Long-term decreases in tubewell discharge can be expected with motor wear and tear, as well as from the deterioration of screens.

The operating hours of tubewells have been determined through farmer interviews, from the calibration of the electric meters against individual wells and motors, and from the recordings of vibration meters. Although there are bound to be errors associated with all observations and measurements relating to both tubewell discharges and operating hours, IIMI data now provide the most reliable and extensive information on tubewell irrigation operations within surface system canal commands available in Pakistan.

Some components of the water balance for a watercourse command area have not been measured, but have been deduced from previous studies done elsewhere. An example is the case of conveyance losses in watercourses, which have been reported

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[43] Temporal variability in the discharges of watercourses and various tubewell types have also been monitored with automatic stage recorders.

by Trout et al. (1980) and WAPDA (1984). Thus, a conveyance efficiency of 55 percent — the average reported for SCARP areas — was used in the water balance study of Mananwala watercourse RD71.[44]

Losses from nonrice crops depend on the assumed value of field application efficiency. WAPDA (1978) has estimated these efficiencies for a range of irrigation conditions, and its determination of an average application efficiency of 58 percent for tubewell-supplemented watercourse commands could be used for Mananwala watercourse RD71. However, modeling studies (discussed below) indicate that percolation losses from the irrigation of nonrice crops depend on soil characteristics and are probably lower than those previously reported by WAPDA. Hence, an application efficiency of about 70 percent may be attainable where water is in short supply. Losses from rice fields were measured during kharif 1989 and 1990 from the rate of decrease of water levels in ponded rice fields, corrected for evaporation losses. The measured rate in RD71 was 5.8 mm/day for the 80 percent of the time that the fields were observed to be ponded or moist.

Table 8.2 shows the estimated quantities of water reaching the water table and being abstracted from it over a period of 78 days during kharif 1989. Each quantity is a total volume for the period, converted to an equivalent depth over the CCA of the watercourse. Conveyance losses and losses from rice fields contribute most to the groundwater recharge. Between the two values of the application efficiency used, 58 percent and 70 percent, there is only a relatively small change in the residual.

Table 8.2. Water balance at the water table in Mananwala RD71: Kharif 1989.

Application Efficiency	58%	70%
Conveyance losses	179 mm	179 mm
Application losses	43 mm	31 mm
Percolation losses from rice fields	166 mm	166 mm
Distributary losses	15 mm	15 mm
Change in aquifer storage	6 mm	6 mm
Pumped abstractions	– 398 mm	– 398 mm
Residual	11 mm	0 mm

Obviously, the continuing uncertainty of some values of the water balance in Table 8.2 permits only a few general observations. Over the study period, recharge and

[44] Although this watercourse is lined, it is in poor condition and there is no reason to assume a higher efficiency because, as Wachyan and Rushton (1987) have reported, while perfect lining will prevent all seepage losses, linings that have cracks and other imperfections result in only small reductions in conveyance losses.

discharge from the aquifer appear to balance. This is supported by observations of water table depth in 20 observation wells distributed throughout the command area of RD71, which revealed an increase of around 1 m coinciding with the onset of percolation from rice fields, followed by a return to the original level at the end of the field study. The fall in the water table during the second half of the study period is ascribed to the noted increase in tubewell abstractions. The fact that percolation from rice fields is of the same order of magnitude as the daily evaporation-cum-transpiration rates indicates that the soils in the area are too light for efficient rice cultivation. In fact, rice fields were often observed to be dry. As submergence of rice fields also is intended to suppress weed growth, it is not surprising to find considerable weed growth in these rice fields. Farmers do not seem to mind this, however, as weeds are cut for fodder.

The contribution of rainfall to water table rise remains undetermined in this research. However, it is considered to be small, because no sharp rise in water table was observed after a 100-mm storm early in the study period, or from later smaller storms. If 20 percent, a value reported by Michael (1978), of the 100-mm storm had percolated to the water table, a rise in water levels of around 133 mm could have been expected in the following 3 to 4 days. This was not observed, and it is concluded that most of the rainfall entered the soil profile as storage, either in or below the root zone.

WATER QUALITY

The suitability of irrigation water for agriculture should be evaluated on the basis of the specific conditions of use, including the crops grown, soil properties, irrigation management, cultural practices, and climatic factors. The ultimate method for assessing the suitability of water for irrigation should consist of predicting the composition and matric potential of the soil water resulting from the use of the water, and interpreting such information in terms of how soil conditions are affected and how the crop would respond under any set of climatic variables (Rhoades 1972). Published tolerances of agricultural crops for salinity apply from the late seedling stage to crop maturity. There are not sufficient data to compare salt tolerance at different growth stages, but it appears that tolerance during germination and early seedling stage for some of the more tolerant crops may be lower. This may explain the frequently observed poor stands of wheat, for instance, which is a medium tolerant crop.

The SCARP Monitoring Organization (SMO) of WAPDA uses three long-recognized criteria for classifying irrigation waters, i.e., the electrical conductivity (EC), the residual sodium carbonate content (RSC), and the sodium absorption ratio (SAR). The usable or "fit" class extends to EC of 1.5 deciSiemens per meter (dS/m, equal to mmhos/cm), RSC to 2.5 meq/l and SAR to 10.[45] The limits of these classes have continued to be applied to determine the suitability of water quality for irrigated agriculture as though no progress has been made in the understanding and interpretation of water quality subsequent to the publication of Handbook 60, in 1953, by the United States Salinity Laboratory, Riverside, California. Current guidelines for the interpretation of water qualities (e.g., Ayers and Westcot 1985) put the upper limit for no restriction in use at an EC value of 0.7 dS/m, i.e., less than half the value currently followed by the SMO.

The effect of sodium, as expressed in the SAR value, depends on the EC value, but a general upper limit for no restriction on irrigation usage of the water now would be set at 6 or 7, again much less than the SAR value of 10 still used by SMO (Lennaerts et al. 1988). For sodic waters, as in much of Punjab, an adjusted SAR is recommended as a generally better index (Rhoades 1982), wherein the calcium concentration is taken as the concentration that will result in the soil solution upon equilibration of the soil and irrigation water. Sodium adsorption ratios of typical tubewell waters increase by around 25 percent when they are calculated as adjusted SAR values. This reinforces the notion that it is not advisable to classify tubewell water with SAR up to 10 as suitable for irrigation use undiluted.

The official view of WAPDA is that "the usable waters are not expected to create any salinity or sodicity problems in the soil and can be safely used to raise all type of crops climatically adapted in the area even without mixing with canal water provided efficient drainage is practiced" (WAPDA no date). It needs no further explanation that in water-short environments, such as has been observed at the tail ends of distributary channels and watercourses, drainage is neither practiced nor needed as no excess water can be given. Moreover, as has been seen, there are scant opportunities in these locations to implement the recommended practice of mixing or using canal and "marginal" quality groundwater at a one-to-one ratio.

The first detailed consideration of tubewell water quality was undertaken by IIMI in the command area of the Lagar Distributary in 1988 and 1989 (Vander Velde and Johnson 1989; Johnson 1990). The water quality of a large number of tubewells in Lagar command was determined as part of a study of tubewell performance carried out in collaboration with the Punjab Irrigation Department's Irrigation Research Institute. A similar, though larger, study of tubewell and surface-system operations was initiated in kharif, 1990 in a sample of watercourse commands in the Mananwala Distributary system. The Irrigation Research Institute again has done tubewell discharge calibration and water quality sampling.

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[45] WAPDA's EC and SAR values for "marginal" irrigation water (i.e., that which is recommended to be used mixed 1:1 with canal water) are 1.5 < 2.7 dS/m and 10 < 18, respectively. When EC > 2.7 dS/m and SAR > 18, water is too harzardous to be used for irrigation without extensive mixing with good quality water at unspecified ratios. In fact, two different classifications of the suitability of water for irrigated agriculture are widely used in Pakistan. That established by WAPDA, and referred to in this paper, is the least conservative and possibly the most widely followed in the country. A more conservative classification is followed by the Directorate of Land Reclamation of the Department of Irrigation, Punjab. Usable or fresh water has an EC < 1.0 dS/m in this case, although the upper limit of SAR remains unchanged at 10.

Data for 137 tubewells, 69 percent of the total in the command area of Mananwala Distributary, are shown in Figures 8.17 and 8.18. Histograms reveal the spatial distribution of two water quality criteria, EC and SAR, of 31 tubewells in the head reach, 46 tubewells in the middle, and 60 tubewells in the tail reach of Mananwala Distributary.[46] The differences between the mean values of EC and SAR for head, middle, and tail watercourse commands are significant (1 percent level), indicating deterioration of tubewell water quality towards the tail of the distributary.

The pattern is the same for another 50 tubewells (out of a total of 104) in the command of Karkan Minor, offtaking from the Mananwala Distributary at RD 76 (i.e. 23 km from the head of Mananwala Distributary). The values of both EC and SAR are higher along Karkan Minor, than for a comparable distance along Mananwala. If the tubewell data for Karkan Minor are also grouped according to head, middle and tail, the mean values are 1.4 dS/m and 9.2 for EC and SAR, respectively in the head reach, 2.0 and 12.4 in the middle reach, and in the tail reach 3.0 and 18.2. A similar spatial pattern of marked decline in the quality of water pumped by both public and private tubewells from head to tail watercourses in Lagar Distributary command also was found in research carried out there in 1989 which covered about 175 tubewells.

Further analysis of 85 tubewells in the Mananwala command area revealed that even according to the SMO's less conservative criteria, merely 30 tubewells are producing water that is considered fit for irrigation. If the more restrictive and recent FAO criteria (Ayers and Westcot 1985) are applied, none of the tubewell water would be found suitable for direct use in irrigated agriculture, without first being mixed with water of a better quality.

Two possible explanations can be considered for the apparent decline in water quality towards the tail of the distributary. First, more irrigation water is applied per unit cropped area in the head reach because of the combination of the greater availability of canal supplies augmented by tubewell water, the generally better quality of irrigation water that is available, and the larger area planted to more water consumptive crops.[47] Alternatively, the primary source of recharge in the area (the Upper Gugera Branch and the Q-B Link canals, as previously noted), is closer to the head of the distributary than to its tail reach. Evidence for accepting or rejecting either hypothesis is insufficient at present and it is bound to require substantial research on aquifer behavior. Moreover, it may be that the observed decrease in groundwater quality towards the distributary tail can be ascribed to a combination of the two and perhaps other phenomena.[48]

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[46] Residual sodium carbonate (RSC) has not been included in this discussion because an analysis of previous RSC data revealed that the laboratory determinations of RSC were highly unreliable. Moreover, the soundness of using RSC for evaluating suitability of irrigation water has begun to be questioned as a result of the underlying assumptions related to quantitative precipitation.

[47] Canal water quality is markedly better than the best quality tubewell water, with ECs at about 0.2 dS/m for canal water versus 0.6 dS/m for the best tubewell water.

[48] Our colleague, Dr. R. Sakthivadivel, has suggested that the vertical differential hydraulic gradient existing between the distributary head and tail also could contribute significantly to accelerated salinity differences between these locations.

Figure 8.17. Frequency distribution of EC: Mananwala Distributary command.

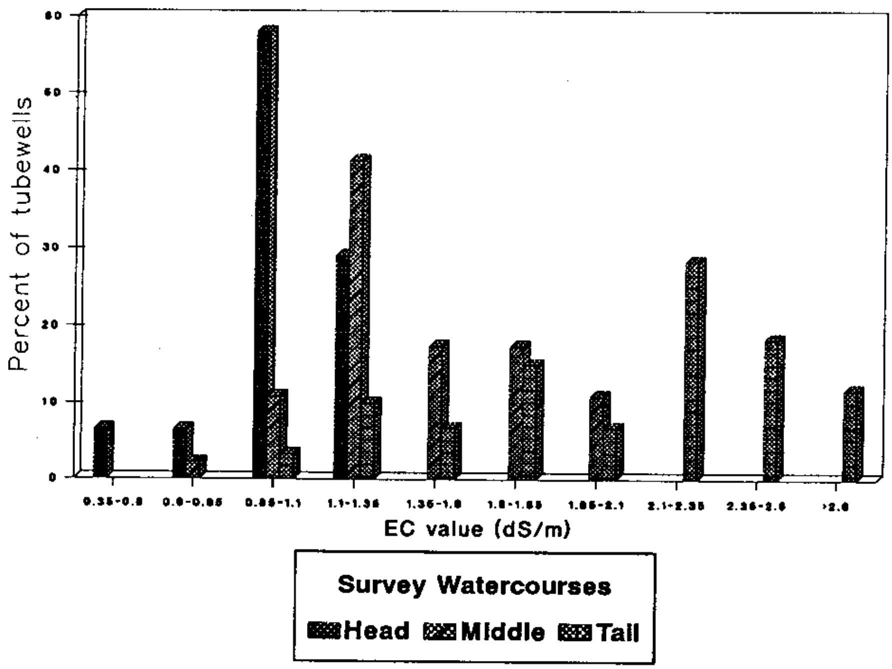
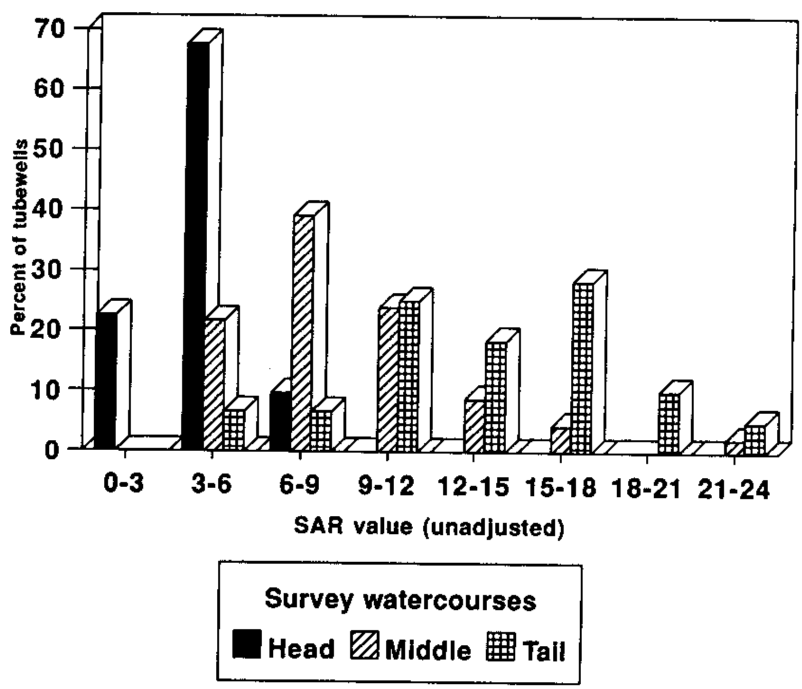


Figure 8.18. Frequency distribution of SAR: Mananwala Distributary command.



It is important to note that the installation of the majority of tubewells in the command area is comparatively recent. Forty-three percent of the tubewells in the head reach watercourses were installed after 1987, as were 40 percent in the middle reach, but merely 11 percent at the tail. By contrast, 40 percent of the tubewells in the tail reach watercourses were installed before 1985, but only 20 percent in the middle and 6 percent in the head reach are more than five years old. Clearly farmers in tail watercourse commands felt the need to install tubewells at an earlier date than did those in the middle and head reaches of the distributary. This is not surprising, of course, considering that tail-end farmers must have begun experiencing persistent shortages and greater variability in canal-water supplies at a much earlier date.

Evidence that proximity to sources of groundwater recharge is the primary cause for better quality tubewell water to be found in head reach watercourses is circumstantial at best. Although the head watercourses of Mananwala Distributary are within an area that is certainly recharged by losses from the parallel Upper Gugera Branch and Q-B Link Canals, the distributary's alignment is such that its middle reach is actually farthest away from apparent sources of recharge. Mananwala tail is slightly closer to Upper Gugera Branch, which it roughly parallels at a distance of about 10 km. However, it is unlikely that Upper Gugera Branch alone (now the only apparent source of aquifer recharge insofar as the much larger Q-B Link Canal is no longer flowing parallel to it, having continued on its course in a southerly direction) can provide anything like the amount of recharge that the two canals together do for the Mananwala head area. Nor can the observed similar decline in groundwater quality between head and tail watercourses within Lagar Distributary command be readily ascribed to increasing distance from recharge areas, since there is no significant locational change throughout its alignment, relative to the same apparent source of recharge. What is needed here, of course, as elsewhere throughout the commands of Punjab's many canal systems, is a much more accurate and detailed understanding of aquifer recharge and behavior than is presently available.

If deterioration of groundwater is indeed substantially a consequence of the seepage of saline water from lands irrigated with marginal or poor quality tubewell water, it is important to note that the process is apparently relatively fast. Public tubewells pump, on average, from a depth of 50-100 m, and private ones from 15-30 m.[49] With a water table at about 5 m depth, it has taken only 5 years (the median age of tubewells in Mananwala's tail reach) to worsen groundwater quality down to at least 15 m. Records of public tubewells should show a decline in water quality if the effect has reached even greater depths. However, data collected by WAPDA's SMO point to a tightening of the water quality values (poor quality tubewells improving and good quality tubewells deteriorating), without a significant change in average water quality over time (Johnson 1990).

Interestingly, Kung (1990) has recently described preferential flow paths in sandy vadose zones (the layer between the water table and the root zone) as the mechanism through which groundwater contamination can take place over a short period of time.

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[49] In public tubewells, the screen begins at a depth of around 45 m and extends to about 100 m; private tubewells are screened from a depth of about 15 m to 30 m.

He is of the opinion that "funneled flow" occurs widely in most vadose zones. Because preferential flow paths recharge the water table at distinct points, the dispersive nature of these point sources of contamination at the water table should lead to a wide scatter of quality values over short distances, which is precisely what has been found in all IIMI study areas when sampling groundwater quality in observation wells and from tubewell discharges.

SALINITY IN SOIL PROFILES

To assess the likelihood of a salinity problem for conventionally irrigated and established crops, the mean salinity of the major root zone, i.e., where most of the water extraction occurs, should be determined. To avoid a salt problem anywhere in the cropped area, the maximum salinity observed should be taken as the salt index for the field. But if salt problems are permitted to occur in about 15 percent of the area, the sum of the mean and the standard deviation could be used as the salt index (Rhoades and Loveday 1990). The value of the salt index thus obtained can then be compared with that of the salt tolerance of the crops to be grown. Salt tolerances of established crops based on growth and yield have been reported (e.g., ibid.) in terms of their threshold values and percentage decrease in yield per unit increase of soil salinity in excess of the threshold.

Soil salinity is conventionally expressed in terms of the electrical conductivity of the extract of a saturated soil paste (ECe in dS/m). It has been suggested (ibid.) that improvements in diagnosis can be made by using the salinity of the soil solution per se, rather than that of the saturation extract, since the latter does not account for the increase in salinity that the soil water undergoes between irrigations due to soil water depletion.

Electrical conductivity measurements were made in situ in fields of sample farmers during rabi 1989-90 and kharif 1990 with a resistance bridge and salinity sensors that are meant to be left in place in the root zone to monitor salinity changes during the season.[50] Results from 182 fields sampled in this way are shown as histograms of mean profile salinity in Figure 8.19. As was expected, profile salinity ranges widely, and was higher in the tail watercourse commands, Mananwala RD143 and Pir Mahal RD133, than elsewhere.

For the interpretation of these values, it should be realized that an EC value of 5 dS/m corresponds to an osmotic potential of -2 bars, 10 dS/m to -4 bars, etc. The effects of osmotic potential and matric potential (decreasing as the soil dries from water absorption by plant roots) are additive. In general, photosynthesis and transpiration are reduced when the total potential — the sum of matric and osmotic components — drops below -4 to -5 bars.

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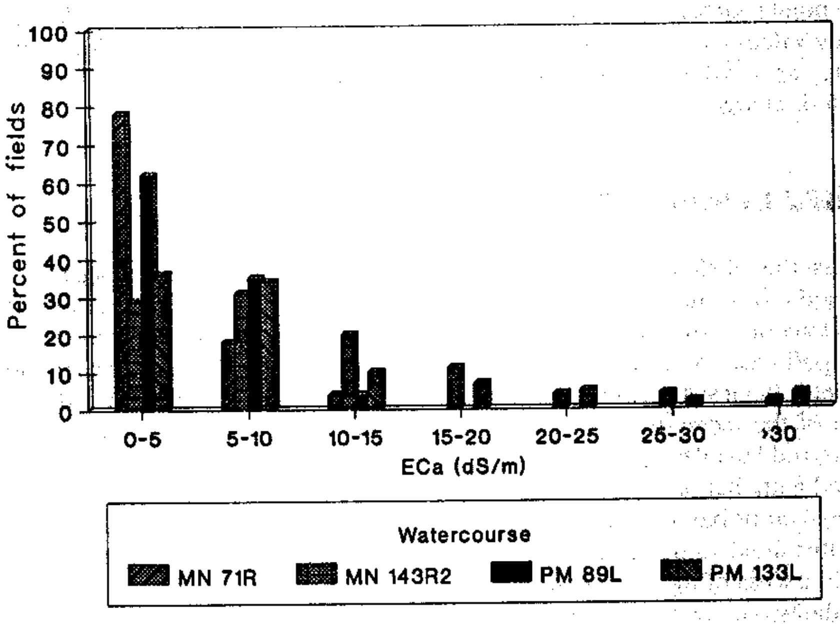
[50] Because of physical interference with the equipment, the sensors could not be left in the field. Soil samples were therefore taken from farmers' fields to the IIMI's field station, where the sensors were then buried in the samples and the EC determined after equilibrium had been reached.

Figure 8.19. Soil salinity of four watercourse commands of Mananwala and Pir Mahal distributaries.



In one-third to one-half of all fields sampled in the tail watercourse commands, profile salinity was found to be sufficiently high to reduce crop photosynthesis even when the soil is at field capacity. Even in the middle reach watercourse commands, profile salinity in 5 percent of the sampled fields had reached such a level; significantly, those levels were concentrated in the tail areasof those watercourses. In short, under such conditions crops are stressed despite the fact that there is plenty of moisture in the soil. It is not surprising, therefore, that crop yields in these locations are below expected, let alone potential, levels.

The conversion of the apparent electrical conductivity values (ECa) to the more familiar ECe values for calculating expected yield decreases, is not straightforward since the conversion factor to be used depends upon both the clay content and the soil water content at the time the ECa values were determined. For the average conditions represented by the soil samples, an ECa of 10 dS/m could be expected to cause a decrease of up to 40 percent in yield of a medium tolerant crop such as wheat, and a decrease of as much as 60 percent in the yield of sugarcane, which is medium sensitive to salinity. These are only indicative values, since the absolute salinity tolerances of crops also vary depending upon climate, soil conditions and cultural practices. Moreover, other factors which could be limiting crop production have not been considered in these estimates.

SODICITY

Sodicity may induce Ca deficiency and various other micronutrient deficiencies because the associated high pH and bicarbonate levels repress their solubilities and concentrations. All of the tubewell water surveyed and results shown in Figures 8.17 and 8.18 have high pH values — merely 15 out of 85 have a pH below 8 — as well as high bicarbonate values.

In contrast to normal and saline soils, sodic soils typically have reduced permeabilities and poorer tilth, resulting from a loss of structure and clay migration with the movement of sodic soil water. Soil permeability and tilth responses to irrigation should be assessed in terms of the salinity of the infiltrating water and the SAR value predicted to result after irrigation, using the adjusted SAR of the irrigation water. Some other soil parameters (e.g., clay mineralogy and content, organic matter content) are known to affect the acceptable levels of EC and adjusted SAR.

In the absence of information on the aggregate stability of the sample soils, a general guideline relationship based on EC of the irrigation water and SAR of the topsoil, has been used to assess sodicity hazards of irrigation water (Rhoades 1982). The combinations of mean EC values and mean SAR values for all tubewells surveyed in head, middle, and tail watercourse commands of Mananwala Distributary, as shown in Figures 8.17 and 8.18, barely fall inside the range of unlikely permeability hazard. About one-quarter of the tubewells in the tail-reach watercourses, however, have EC and SAR values that are within the range of waters likely to cause permeability problems.

In April 1990, field staff carried out a rapid appraisal survey to record the visual presence of salinity — either as surface salting or obviously salt-affected crops — in the command areas of 7 watercourses of the Mananwala Distributary, including RD71 and RD143, covering a total of 1,206 ha. At the same time, the presence of dense, hard layers was also assessed by probing the soil with a narrow probe to feel the resistance in the top 50 cm of the profile. An increased resistance could be a possible indication of clay migration and reduced soil permeability. In 4 percent of the total area surveyed, the effects of salinity were observed and in 76 percent dense layers were present. However, when just the tail-reach areas of watercourses and distributaries are considered, these proportions are 17 percent for presence of salinity and 79 percent for dense layers. By contrast, for head-reach areas only, there was less than a 1-percent incidence of salinity and a 51-percent occurrence of dense layers. These data strongly reinforce the conclusion of a general deterioration in soil conditions towards the tail within distributary canal commands due to secondary salinity.

In addition, saturated conductivity was determined by IIMI field teams with a Guelph permeameter in over fifty fields in sample watercourse commands of both Pir Mahal and Mananwala distributaries. Infiltration rates were determined with single ring infiltrometers in an equal number of sample fields. Large spatial variability of saturated permeability and basic infiltration rates were observed, and zero values for both parameters were often recorded in salt affected fields. The median values of the (non-zero) saturated permeability rates were used to characterize the soil for modeling purposes, which is discussed in greater detail below.

With respect to the problem of sodicity, the field observations we have just described point towards a structural decline of soils resulting from irrigation with sodic irrigation waters. This has important implications for the reclamation of soils by leaching.

SALT BALANCE

The removal of salts from the root zone, to maintain the soil solution at a salinity level compatible with the cropping system, requires a downward flux of water and salts in the soil below the root zone. The fraction of infiltrated water that passes through the root zone is called the leaching fraction. A salt balance has been attained if, through this leaching process, the total salt content in the root zone remains constant. Hence, sufficient irrigation water, combined with rainfall, must be applied over and above the evapotranspiration needs of the crop, so that there is excess water to pass through and beyond the root zone and to carry away salts with it. This excess water is referred to as the leaching requirement.[51]

In order to predict the long-term consequences of irrigation with undiluted tubewell water of questionable quality, it is important to know the effect of sustained irrigation on soil salinity.[52] Through computer modeling and simulation of water and salt balances, it is possible to assess the effect of current farming practices on the build-up or removal of salts from the profile.

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[51] Recently, the concept of leaching requirement has been criticized (e.g., Smith and Hancock 1986). It has been argued that with the practical problems of water management at field level it is likely that the leaching fraction (i.e., the amount actually applied in excess of consumptive use requirement of the crop) will be more than the calculated leaching requirement, unnecessarily increasing the salt load of the drainage water. Leaching *fractions*, plausible under normal farming practices, have been calculated through the simulation of salt and water balances.

[52] Soil salinity was monitored in the field under sustained saline irrigation in northern India by Bajwa et al. (1986). The study was carried out on a well-drained loamy sand of lighter structure than most of the soils in our sample areas. Moreover, the irrigation water which was synthesized, had a combination of EC and SAR which puts it further into the range of unlikely permeability hazard than most of the tubewell water we have observed. This combination of differences suggests that the results of Bajwa's study are of limited applicability to the research reported here. Nevertheless, it is of interest to note that salinity increased rapidly in the soil profile during the initial years. After five years, the average soluble salt content in 0-90 cm profile did not vary appreciably and the mean ECe under sustained saline irrigation remained similar to the EC of the irrigation water.

Two computer models for water balance and salt balance have been used for this purpose.[53] The input data requirements of the model refer to basic properties of soils and plants. These include dependence of matric potential and unsaturated conductivity on water content; root depth during the season and fractional amount of active roots in a particular increment of depth; initial conditions of water content and soil solution concentration versus depth; boundary conditions of potential evapotranspiration rate, rainfall and irrigation amounts; and the presence or absence of a water table. The model has been tested under various environmental conditions (e.g., Nimah and Hanks, 1973) and used to generate results over several years which would otherwise be too costly to obtain through field studies (Hanks 1984). In general, good agreement is obtained between computed and measured water contents and salinity profiles. But the effect of salinity on crop yield is less frequently accurately predicted by the model.

We have used Hanks' model to simulate water and salt movement into and out of the root zone for three major crops grown in the command of the LCC system: cotton during kharif, wheat during rabi, and sugarcane over both seasons. Evapotranspiration rates were calculated from meteorological data and the other boundary conditions, including the initial water content and salt concentration derived from measurements in the field. Sand and clay contents were determined from representative soil samples collected when water table observation wells were installed in the sample watercourses of each distributary canal command. This information, combined with the measured saturated conductivities, was used to identify characteristic soil types based on soil data compiled by Wosten (1987, also Wosten and Van Genuchten 1988). The soil physical parameters, required as input for the model for the three soils chosen for modeling — a sandy loam, a silt loam, and a clay loam — were those characteristic for each type.[54]

Simulations were done for both the median EC value and the 75 percent value (i.e., values exceeded by 25 percent of the samples) of irrigation water qualities being pumped by tubewells and used by farmers in tail-end watercourse commands (see

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[53] R.J. Hanks, Utah State University ,was kind enough to make these models available for use by IIMI Pakistan. They are described in greater detail by Childs and Hanks (1975) and Hanks (1984). As with all models that are simplifications of complicated processes in reality, many critical assumptions must be made. In this case, the key assumptions involve the soil properties and the root extraction term. Although various attempts have been made to make these models more "realistic" by including additional plant factors, this has not resulted in better predictability when they are applied to actual field situations. The problem is further confounded, because as more parameters are included in the model, its use becomes restricted to research institutes with facilities for measuring the required data. The model, as used, already requires information that is not readily available in Pakistan (see Kijne 1989).

[54] An initial test of the validity of this approach was made during Rabi 1989-90 on six wheat fields in the command area of RD 133, Pir Mahal Distributary. The wheat fields were on two different soil types, and the model predicted the salinity and water content profiles at the end of the season satisfactorily. Detailed results of this work will be reported separately elsewhere.

Figures 8.17 and 8.18). Median irrigation applications for wheat grown in Mananwala Distributary command, and for cotton and sugarcane grown in Pir Mahal Distributary command, were used as input in the model. The results of these simulations are presented in Table 8.3.

Table 8.3. Simulated water and salt movement for irrigated wheat, cotton and sugarcane in the LCC system.

Crop	Soil	IR+R	Eciw (cm)	Rel EVT (dS/m)	Leaching fraction	Fractional change in root profile salinity
wheat	SaL	38.9	2.1	1.0	0.47	−0.58
wheat	SaL	38.9	2.5	1.0	0.47	−0.58
wheat	SiL	38.9	2.1	0.99	0.28	−0.35
wheat	SiL	38.9	2.5	1.0	0.28	−0.24
wheat	ClL	38.9	2.1	1.0	0.02	−0.24
wheat	ClL	38.9	2.5	1.0	0.02	+0.46
cotton	SaL	66.4	2.1	1.0	0.26	+0.20
cotton	SaL	66.4	2.5	1.0	0.26	+0.39
cotton	SiL	66.4	2.1	1.0	0.04	+0.80
cotton	SiL	66.4	2.5	1.0	0.04	+0.80
cotton	ClL	66.4	2.1	1.0	0.18	+0.57
cotton	ClL	66.4	2.5	1.0	0.17	+0.89
cane	SaL	109.9	2.1	0.85	0.21	+0.03
cane	SaL	109.9	2.5	0.85	0.21	+0.22
cane	SIL	109.9	2.1	0.72	0.09	+1.26
cane	SIL	109.9	2.5	0.72	0.09	+1.74
cane	ClL	109.9	2.1	0.74	0.23	−0.50
cane	ClL	109.9	2.5	0.74	0.23	+0.53

Notes: R = Rainfall
IR = Irrigation
ECiw = Electrical conductivity
EVT = Evapotranspiration
SaL = Sandy loam
SiL = Silt loam
ClL = Clay loam

It is immediately observed that the actual leaching fractions for wheat and cotton in sandy loam are greater than that in either the finer textured silt loam or clay loam soils. In the cases of cotton and sugarcane, the leaching fraction is smallest in the silt loam. The change in profile salinity, expressed as the ratio of profile salinity before and after the growing season, varies according to the salinity of the irrigation water and the leaching fraction. The largest increase in profile salinity takes place in sugarcane grown on silt loam with irrigation water of 2.5 dS/m, i.e., an increase of 1.7 times in a single season. Another important observation is that leaching is far more effective for wheat during the cooler rabi season — leading to a decrease in profile salinity for most of the modeling combinations — than for crops grown during the hot kharif season, even though monsoon rainfall exceeds that from winter rains.

It would be interesting to know how long it would take to bring farmers' fields at tail ends of distributaries and watercourses back to acceptable salinity levels by irrigation with canal water only, or with a mixture of canal water and tubewell water. We have been unable to address this important issue through modeling as yet, because the model requires further modification so that some adverse effects of long-term irrigation with saline water can be considered, e.g., degradation of soil structure and reduction of hydraulic conductivity. Nevertheless, at this juncture, it is reasonable to assume that so long as the soil structure is not affected, the build-up of profile salinity is reversible and reclamation should not take much longer than it took the salts initially to accumulate in the profile. However, where clay migration in the profile has led to compacted layers and sharply decreased hydraulic conductivities, the reversal process will be very slow.

CONCLUSIONS: IRRIGATION MANAGEMENT IMPLICATIONS

The foregoing analysis and discussion of a large body of measured and observed data confirm the existence of a disturbing pattern of increased salinity-related problems in irrigated agriculture as location changes in the surface irrigation system with increasing distance from the head of both distributary channel and watercourse commands. The source of salt accumulation in the crop root zone of soils is the tubewell water of doubtful quality used by farmers for irrigation. Serious and persistent inequity in the distribution of high quality canal water within distributary commands, which is also mirrored at the watercourse level, has meant that farmers in middle- and tail-reach locations have become increasingly dependent upon pumped groundwater to meet the bulk of their crop water requirements. For reasons that are not well-understood at this juncture, the quality of groundwater pumped by tubewells generally decreases within distributary command areas from the head to the tail. Farmers in the tail areas therefore face a double handicap: they receive a far smaller proportion of their share of canal water than do farmers upstream along the same distributary, especially in the head reach, and the groundwater in these locations, which must be used to obtain any crop, is of poorer quality than elsewhere.

It is well-known that the sustained use of poor quality irrigation water without adequate leaching of salts from the root zone has important consequences for the long-term productivity of irrigated agriculture. This is likely to be one reason for generally lower crop yields observed in our sample areas, although no attempt has been made to relate actual crop yields with either the presence of salts in the root zone profile or the salinity of irrigation water. Because there are many other potential reasons for the low yields of agricultural crops in Pakistan, a separate program of targeted field research by an appropriate specialized national organization is needed to quantify the effects of salinity in this respect.

It should be realized that irrigated agriculture can successfully use water for irrigation that is more saline than that found in the command area of Mananwala and Pir Mahal distributaries. However, that would require mixing saline water with better quality canal water for irrigation, at least during germination and other sensitive crop growth stages, or changing production to more salt-tolerant crops (e.g., fodder crops) or agroforestry, or adopting some combination of these two approaches. Recent examples of the reuse of drainage water for irrigation illustrate the potential use of brackish waters (e.g., see the recent review by Westcot 1988).

Theoretically at least, mixing canal water and tubewell water for irrigation is a feasible alternative for farmers. But the problems faced by farmers attempting to do so, as well as the attendant management implications, are well-illustrated in the following examples which draw upon the "real world" conditions of irrigated agriculture in the sample areas of our studies. During peak months, canal water constitutes about 28 percent of the total water used in agriculture in the sample areas. For a tubewell water quality of 1.8 dS/m (the median EC value of the entire Mananwala tubewell water quality sample), and 0.4 dS/m for canal water, mixing in the ratio 0.72 : 0.28 produces an average water quality of about 1.4 dS/m. It will be immediately noted, however, that this average EC value is still in the range of waters now recognized as being unsuitable for irrigation without mixing with better quality water. Moreover, the actual quality of the mixed water becomes worse toward the tail-end distributary commands, because of the decreasing proportion of canal water to pumped groundwater that can be mixed, and the increasingly poorer quality of groundwater in the mix.

Therefore, assuming no significant changes in current cropping patterns, management interventions with the objective of bringing the average EC value of the mixed irrigation water available to middle and tail watercourse commands below 1 dS/m, for instance, seem certain to require, and must somehow produce, greater quantities of canal water for mixing than are presently available at these locations. That is a formidable challenge, but management opportunities do exist to greatly improve the current pattern of equity in distribution of canal water at the distributary level as, for example, was demonstrated by previous IIMI/PID action research on selective canal maintenance (Vander Velde and Bhutta 1989; Vander Velde 1990). However, present conditions of distributary system performance also reflect the increasing failure of existing institutions to observe and enforce long-standing rules and procedures of irrigation system operations and administration in Punjab. That situation raises critical institutional issues that require both carefully designed and sensitively implemented research before a fuller range of appropriate management responses can be developed with potential to restore water distribution equity conditions to acceptable levels. Unfortunately, as the following more extreme example illustrates, the amounts of water made available through such efforts, will probably be insufficient to meet mixing requirements.

Since the median EC value of tubewell water in the head reach of the Mananwala Distributary is less than 1 dS/m, farmers there could rely completely upon tubewell water to meet the needs of irrigated agriculture without changing their current crop mix or incurring secondary salinity problems. In such a hypothetical situation, all canal water would then be available for mixing in middle- and tail-reach watercourses. In order to produce an average EC water quality value of 1.04 dS/m for middle-reach farmers, 36 percent of the canal water now available would be required for mixing in. However, the remaining 64 percent of canal supplies would, when mixed with available groundwater, result in an average EC water quality value of only 1.23 dS/m for tail-reach farmers. Thus, given the comparatively low proportion of canal water currently available and used in meeting irrigated agriculture requirements during peak consumption months, it is still not possible to bring irrigation water quality to within acceptable limits throughout the entire canal command area, even if head-end farmers were to use no canal water at all! The fact that average water quality during peak periods remains above 1 dS/m in part of the command area may not be harmful, provided, of course, that in other months of the year water quality is below the harmful limit and salts can be leached from the soil profile. Unfortunately, there is no evidence from current irrigation practices that this conditionality can be or is being met.

Changes in cropping patterns, as suggested above, may also be a means of sustaining agricultural production with poor quality irrigation water. So far, we are unaware of any systematic research that has focused upon farmers' responses to the adverse effects of poor quality water supplies and secondary salinity. Johnson (1990) has reported higher proportions of cropped areas under rice and sugarcane, and smaller areas under vegetables and orchards in holdings irrigated with tubewell waters of more than 1 dS/m in the Lagar command area. This finding, and our field observations elsewhere, confirm that farmers are aware of the harmful effects of prolonged irrigation with poor quality tubewell water. Hence, it is conceivable that farmers are already deliberately responding to these conditions through changes in their cropping patterns. Whether or not a productive irrigated agriculture can be sustained through such changes is a subject that requires both monitoring and continued evaluation of several dependent variables — including aquifer discharge and recharge, groundwater quality, and canal system performance — for which effective institutional mechanisms do not yet exist.

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