Salinity and Irrigation Operations in Punjab, Pakistan: Are There Management Options?

by
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In 1989, IIMI began a five-year research project in Pakistan into salinity and waterlogging with funding from The Netherlands. These syndromes -- labeled the "*twin menaces*" in Pakistan -- have long afflicted extensive areas of irrigated farmland in the country. The project's aim is to identify, through detailed field investigations in selected canal system commands in Punjab and Sindh provinces, specific management interventions that can help keep salinity and waterlogging under better control. A second phase of applied research will field-test promising remedial approaches.

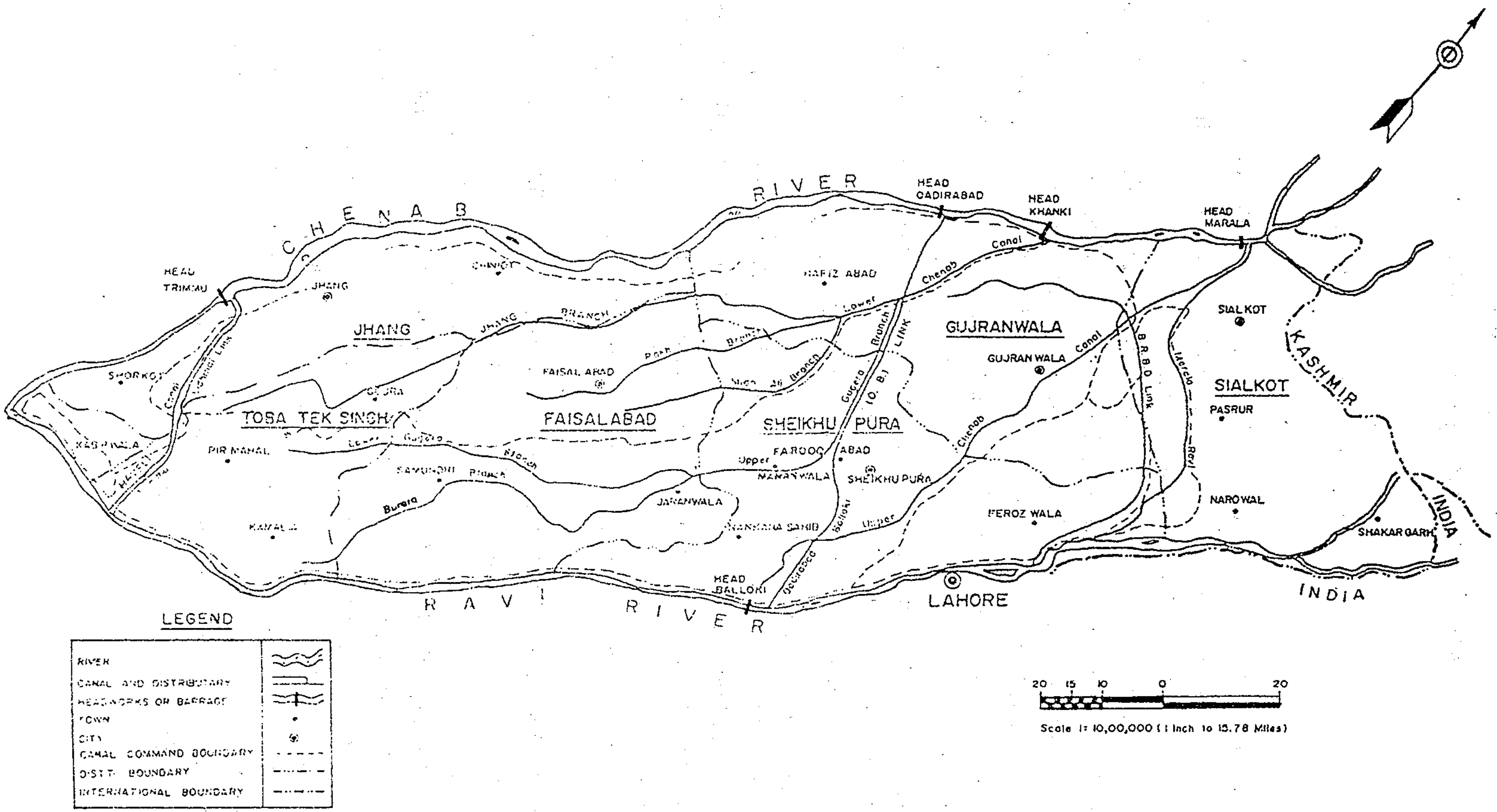
In Punjab, it was possible to draw upon resources and findings developed through other IIMI Pakistan projects already under way. Beside reducing time, effort and costs, this approach offered an unusual opportunity to integrate a range of data and findings relating to system operations and performance across several distributary canal commands. These large hydraulic units are the basic "building blocks" of irrigated agriculture in the Indus Basin.

IIMI's research was planned to focus on "irrigation and drainage conditions of incipient and not yet apparent waterlogging and salinity problems." However, at the original research project design stage, it was not realized that salinity in Punjab is now largely dissociated from waterlogging. Waterlogging has been greatly reduced by the installation and operation of public sector, deep tubewells through SCARP (Salinity Control and Reclamation Project) programs begun in the 1960s. More recently, the rapidly growing exploitation of groundwater for irrigation by the private sector using shallow tubewells -- now about 300,000 countrywide -- has greatly enhanced the "vertical drainage" effect of the SCARP wells.

The study sites selected were distributary canal commands over 200 km apart served by Gugera Branch Canal in the Lower Chenab Canal (LCC) system traversing Punjab's Rechna Doab (Figure 1). Here, research on canal system performance and constraints to irrigated agriculture below the outlet was already well underway. By 1989, field observations and considerable anecdotal evidence from farmers indicated that these areas incorporated a suitable range of incipient conditions of salinity.

Further field surveys revealed that water tables were commonly more than 3 m below the soil surface in both locales, making incipient waterlogging an unlikely problem. However, other data collected for IIMI's research on the water conjunctive management of surface water and groundwater systems were beginning to reveal an emerging problem of secondary salinization in both places. Though still largely unrecognized, this condition was not unanticipated in Pakistan as early as 1978. At that time, the Soil Survey of Pakistan warned that:

Figure 1. Rechna Doab, Punjab, Pakistan.



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. (Bashir Choudhri et al. 1978).

We reason that the root cause of this salinity phenomenon, discussed in greater detail below, is the widespread and increasing reliance by farmers in the lower or more peripheral reaches of canal commands upon groundwater for irrigation. Tubewells, frequently pumping marginal to poor quality water, have become the widespread response of many farmers to increasingly inadequate and unreliable deliveries of good quality canal water down the system, to distributaries and watercourses.

The solution to this salinity problem depends largely on the possibility of ending or substantially reducing the inequity in distribution of these two sources of irrigation water. The several factors we hypothesize as causal or intensifying of secondary salinization problems will require new, environmentally sophisticated, often inter-linked as well as sustained irrigation management interventions *at main as well as secondary system level* to ameliorate if not remedy the threat posed to the sustainability of irrigated agriculture in large areas of the Indus Basin. It also should be emphasized that the management interventions required are unlikely to be everywhere the same.

The Irrigation Environment

The topography of the Rechna Doab, the interfluvial region over which the Lower Chenab Canal system flows, is relatively flat with a land surface gradient ranging from about 0.25 m per km in the north and northeast to less than 0.2 m per km to the south and southwest, down doab. It is underlain by a deep, high-yielding, generally unconfined aquifer that is relatively homogenous and highly anisotropic. The hydraulic gradient in the upper half of the Rechna Doab is steeper than the topographic gradient, but flattens out markedly in the doab's lower reach (Greenman et al. 1967). In their detailed hydrologic description of the aquifer, Bennett et al. (1967) give mean values for horizontal and vertical hydraulic conductivities, respectively, as 1.2E-3 and 1.5E-5 m/s. The much lower vertical transmissivity is due to the presence of clay layers in an otherwise fairly coarse sandy aquifer. Specific yields for the water table in the sand layer and the clay layer are 0.15 and 0.06 (*ibid.*), respectively; thus, measures are usually taken to ensure that the occasional clay lenses are screened off when tubewells are installed.

Our discussion of irrigation operations and salinity problems is based largely upon primary data collected in the command areas of two large, fairly typical distributaries in the LCC system. Mananwala Distributary off-takes from Upper Gugera Branch in Farooqabad subdivision, Upper Gugera division, about 68 km downstream from Khanki Barrage, the headworks of the LCC system (Figure 1). Pir Mahal Distributary offtakes from Lower Gugera Branch at Bhagat Head regulator in Bhagat subdivision, Lower Gugera division, more than 200 km further downstream. In both subdivisions, SCARP public tubewells were installed more than 15 years ago to control waterlogging; a secondary benefit of these public wells was the supplementation of surface water supplies. Recently, private tubewell development has been extensive and rapid with local densities of 5-7 private wells per 100 ha now rather common.

Mananwala Distributary is 45 km in length and its design discharge is 5.2 m^3/s. It supplies 125 outlets, either directly or from three minors, and serves a culturable command area (CCA) of 27,064 ha. The average sanctioned discharge of its outlets is 30 lps. The distributary was designed for two levels of cropping intensity. Those outlets serving 50-percent intensity command areas have a design water allocation of 1 lps per 7.5 ha; other outlets command 75-percent intensity service areas and have a slightly more generous water allocation standard of 1 lps per 5 ha.

Pir Mahal Distributary is 47.5 km long and has a design discharge of 4.67 m^3/s for a CCA of 14,891 ha. It directly supplies 50 outlets and 40 others off-take from its four minors, and the average sanctioned discharge of these outlets is 35 lps. 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.

Mananwala Distributary is located in the Punjab rice-wheat agro-ecological zone. Rice, especially the high value basmati variety, is the predominant crop here during kharif season (mid-April to mid-October) wherever irrigation water is sufficient, and wheat is the principal crop in rabi season (mid-October to mid-April). Pir Mahal Distributary is in the transition area between this rice-wheat region and Punjab's cotton-wheat agro-ecological zone further to the southwest. Here, cotton is more frequently the main kharif crop, though rice is also grown; wheat continues to predominate in rabi.

In both distributary service areas, sugarcane, various fodders, seasonal fruits, oilseeds and vegetables also are grown for cash income and domestic consumption. Thus, overall, the irrigated agriculture system in these two study areas is characterized both by a diversity of crops grown and by large acreages planted to key crops in Pakistan's agriculture economy.

Following extensive canal development and operations in the Rechna Doab, from the 1920s on, significant areas began to be affected by substantial waterlogging -- defined in Pakistan as conditions with water tables within five feet of the land's surface -- and salinity. By mid-century, the severity and extent of these problems had become the impetus for the first SCARP (I) initiated in the north-central Rechna Doab in 1960. Subsequently, other SCARPs, large and small, were established throughout the country. Public tubewells of these projects are found in the command areas of both Mananwala and Pir Mahal distributaries.

In the commands of Pir Mahal and Mananwala, water tables today range between 3 and 8 m deep, with gradients towards the distributaries' tails. In Mananwala command, 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 m^3/s in this reach, and the Qadirabad-Balloki Link Canal, which carries around 540 m^3/s.[1] Recharge to the groundwater in Pir Mahal's service area in large measure is from the Ravi River, which flows as close as 12 km from parts of the downstream half of the distributary.

Distribution of Irrigation Supplies: Surface Systems

Findings from IIMI research in Pakistan on the operations and performance of distributary canals in the LCC system over several years show that the long-standing system performance objective of equity in water distribution is now rarely achieved and almost never sustained. When distributaries are operating at or near to full supply levels, outlets in the tail reaches seldom obtain more than a fraction of their authorized discharge *at the watercourse head*, in contrast to outlets in the upper reaches which commonly receive much more than their design discharge.[2] This condition is illustrated for Pir Mahal Distributary and its large subsidiary minor, Junejwala in Figure 2. It is clear that consistently low levels of maintenance inputs into distributary channels and their resulting deteriorated physical condition -- e.g., extensive accumulations of silt, severe embankment erosion -- is a primary cause of this situation.

The consequence is that farmers in the command areas of tail watercourses, on average, experience less than one-fifth the access to canal water that farmers served by watercourses in the head reach of the distributary have. When discharge at the distributary head falls below 70 percent of design, water supplies to tail outlets simply collapse, and farmers in those command areas receive no water from the canal at all.

In Bhagat subdivision, surface supplies in Lower Gugera Branch to the tail of the main system are usually insufficient for its six distributaries to operate simultaneously at full supply level. Consequently, inter-distributary rotational operations are practiced for much of the year at Bhagat Head. Discharge data reveal significant inconsistencies in the equitable implementation of rotational operations, however.[3] For example, during Kharif 1990 (Figure 3), Pir Mahal Distributary operated about 45 percent of the period at less than 70 percent of full supply; in sharp contrast, Rajana and Dabanwala Distributaries operated at 90 percent or more of full supply discharge for 70 percent of the same period.

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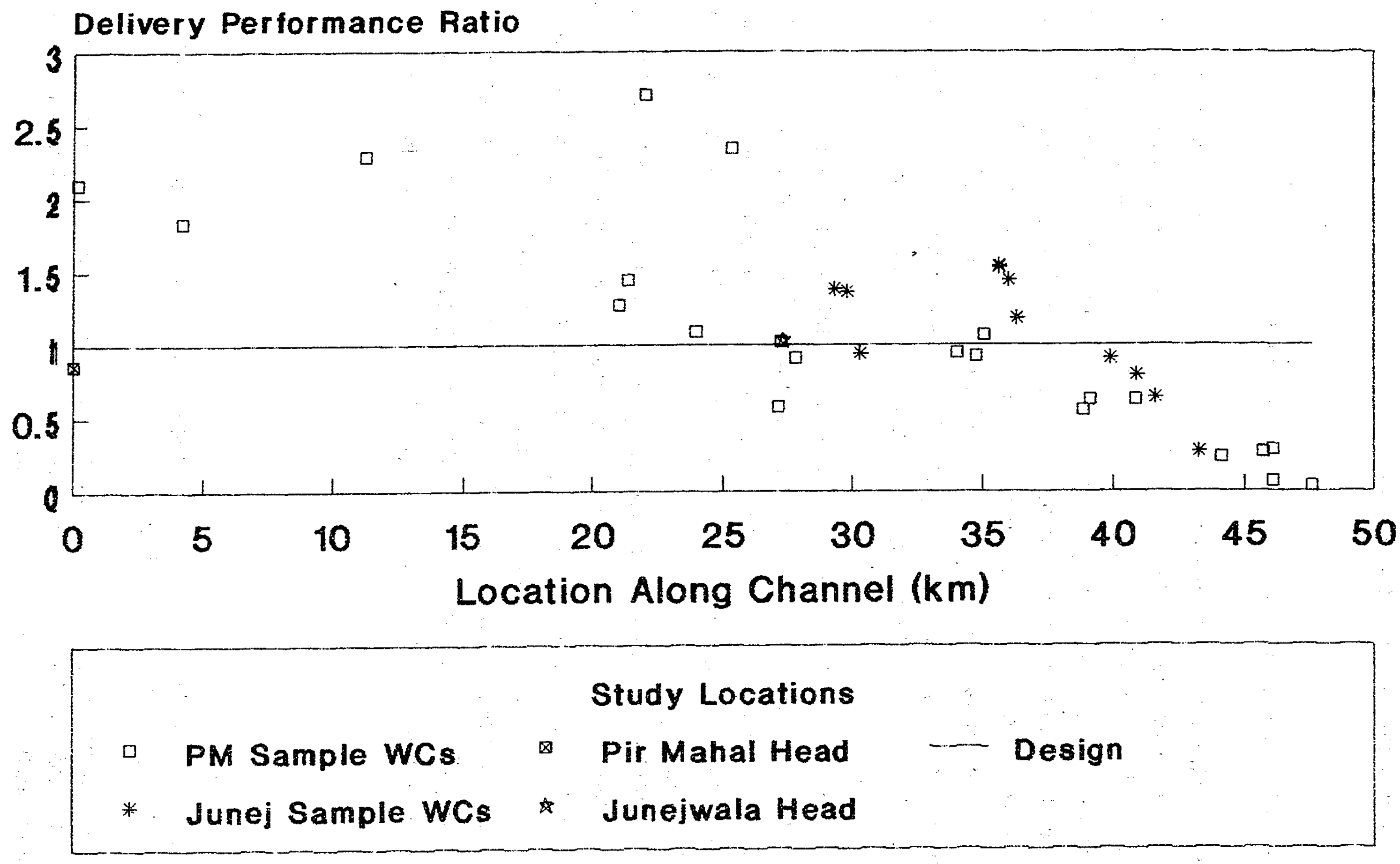
[1]See Greenman, et al. (1967) for a more detailed discussion of the important role of the canal system in aquifer recharge in the Rechna Doab.

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

[3]Telog automatic stage recording data loggers were installed at each of the four distributary heads. They were operational throughout kharif 1990 and rabi 1990-91 seasons.

Figure 2. Pir Mahal and Junejwala Minor Distributaries: Equity of Water Distribution.



Bhagat Sub-Division, 1990

The severely deteriorated physical condition of Pir Mahal Distributary also has required the adoption of an internal rotational delivery program to distribute canal water supplies between the main channel's tail reach and its offtaking minors. The persistent mismatch between the rotational program at Bhagat Head and the internal rotation practiced a little over half way down Pir Mahal at Junejwala Minor (Figure 4) interacting with poor channel hydraulic conditions significantly worsens surface water deliveries to downstream outlets. Not surprisingly, the frequency of days without canal water at watercourse heads increases markedly toward the tail reaches of the main channel and the offtaking minor. In kharif 1990, farmers in those watercourse commands were without surface water supplies as much as 50 to 75 percent of the time (Figure 5), and conditions for the entire year were only slightly better.

Yet, even when distributary head discharge conditions are relatively steady at or near full supply levels, tail watercourse commands often remain deprived of even the modest surface water supplies they might otherwise receive, particularly in kharif season. The emergence of this condition during the first three months of kharif 1990 is shown for Mananwala Distributary in Figure 6. The pattern is substantially the consequence of the combined and cumulative operations of many sanctioned and "arranged" seasonal pipes coupled with frequent large and small appropriations of water upstream through cuts, embankment leaks and occasional breaches of shorter duration (Figure 7).

Variability in distributary flows upstream is also passed on to the discharges of downstream offtaking watercourses. The effect is most pronounced for tail-reach outlets, and farmers in those command areas experience the further disadvantage of greater uncertainty of delivery of whatever share of surface water supplies reaches them.

Distribution of Irrigation Supplies: Groundwater Systems

Given the growing inability of the canal system to deliver useable amounts of water to many watercourse heads in the lower reaches of distributaries for much of the year, the only obvious alternative farmers have to meet the water requirements of their crops is through groundwater development. Indeed, extensive public groundwater development in the Rechna Doab -- the SCARP-I deep drainage tubewells to control waterlogging installed in the early 1960s -- initially provided greatly enhanced water supplies *at the watercourse level* and spurred two major, near simultaneous changes in irrigated agriculture, that soon spread throughout much of Punjab.

Figure 3. Rotational Operations at Bhagat Head Range of Distributary Discharge.

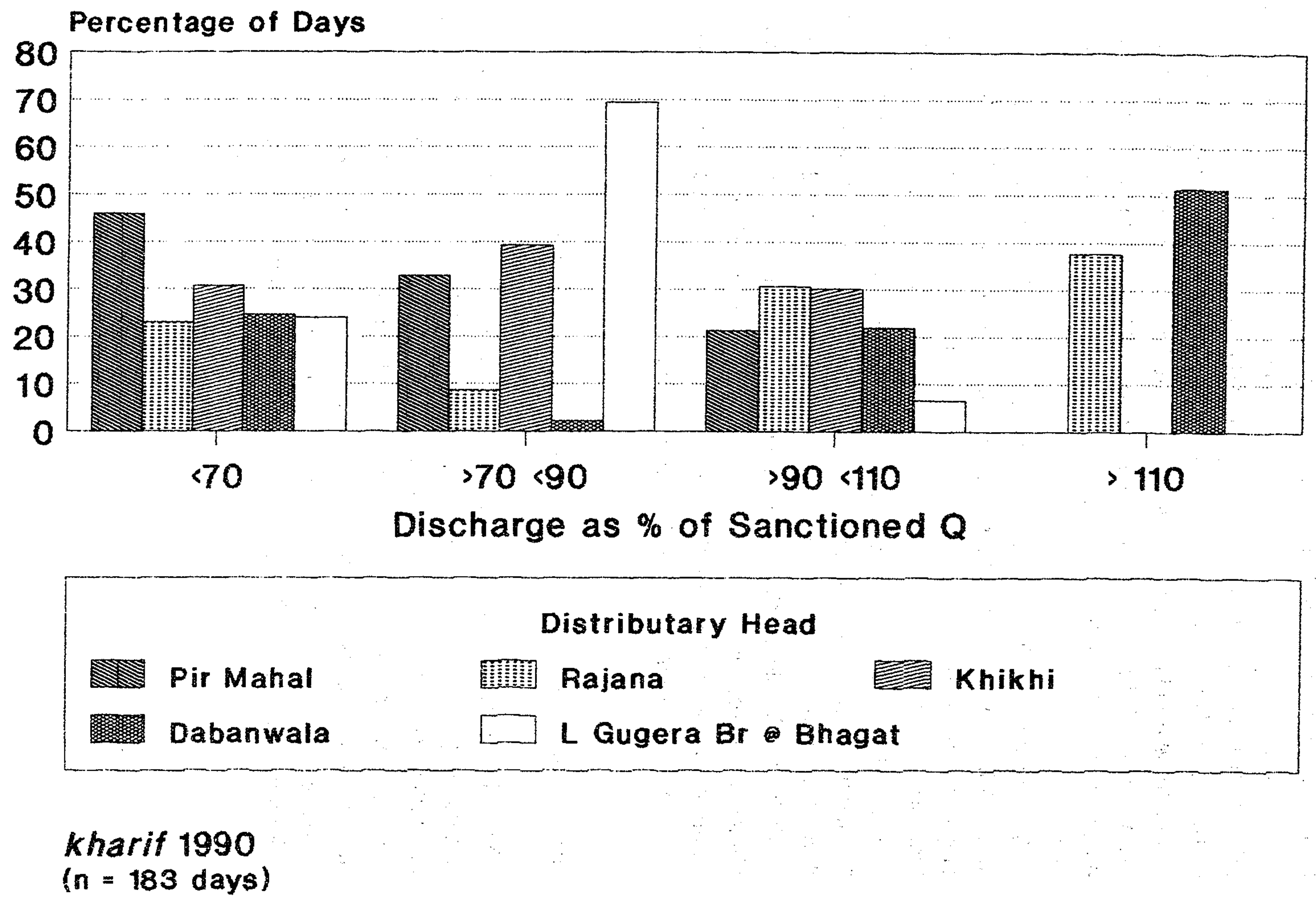


Figure 4. Pir Mahal Distributary Rotational Operations and Water Supplies.

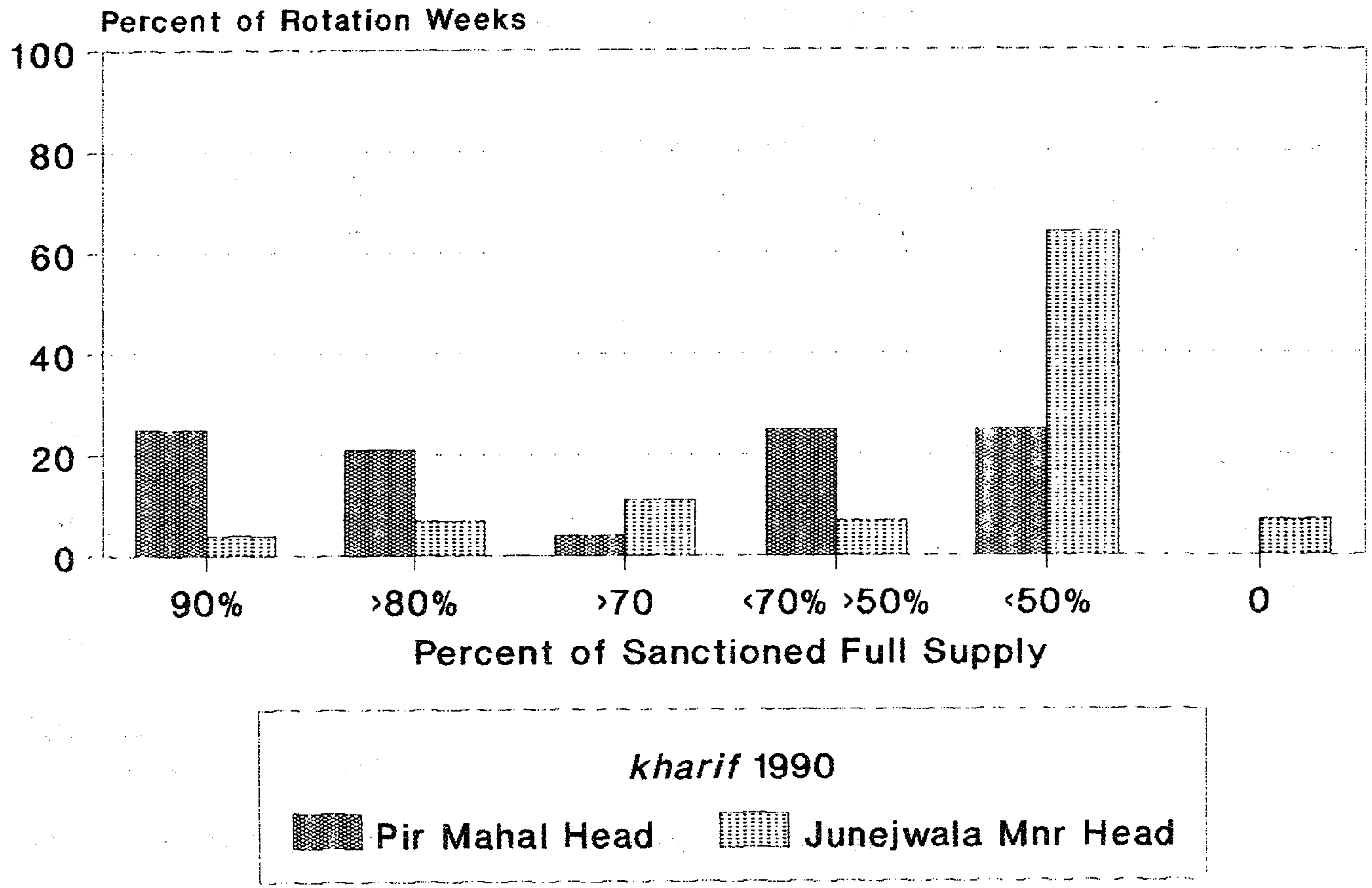
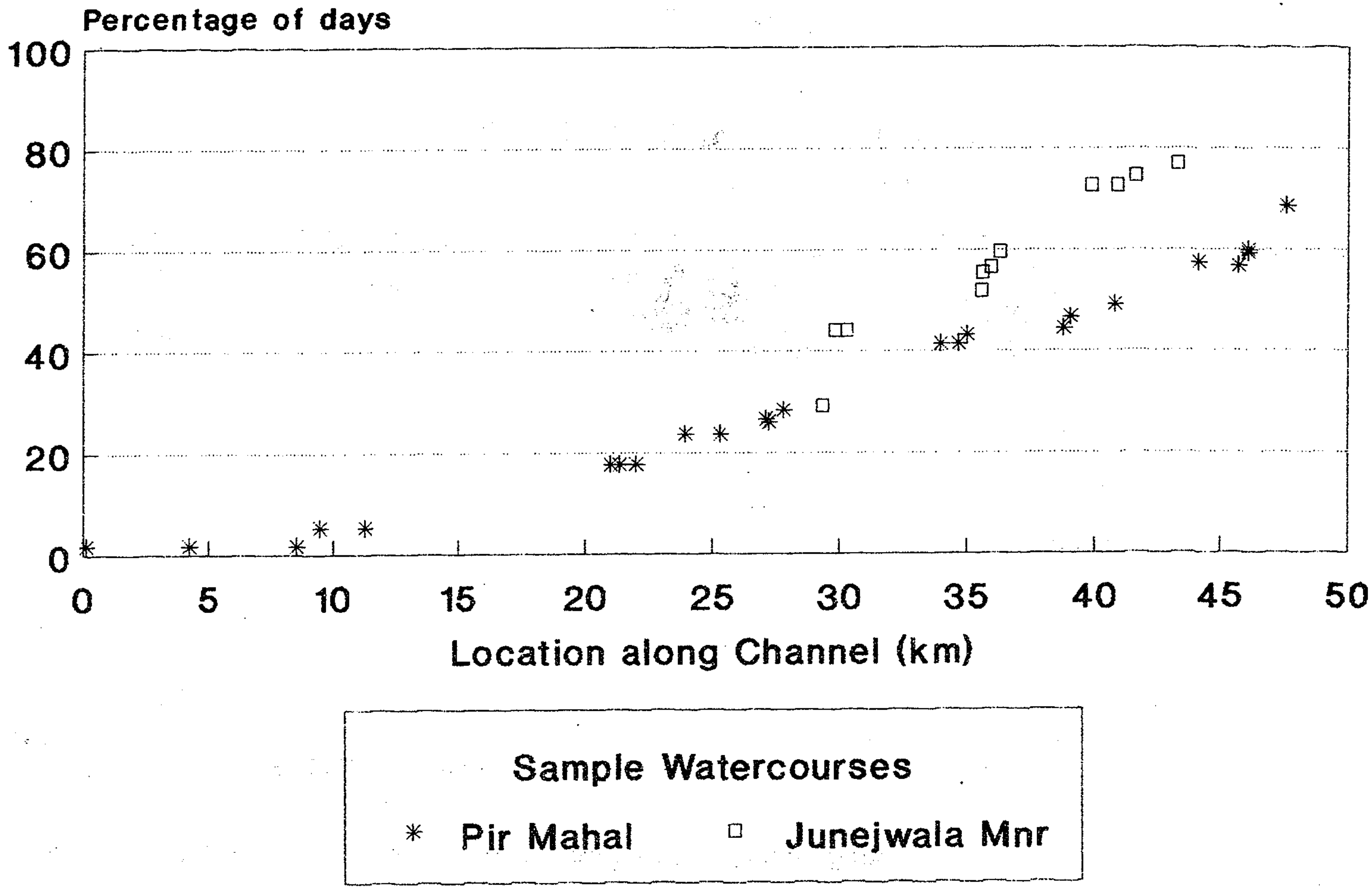


Figure 5. Pir Mahal Distributary and Junejwala Minor Outlet Dry Days: Kharif 1990.



Field Observations (n=169)

Figure 6. Mananwala Distributary Change in Sample WC DPR: Kharif 1990.

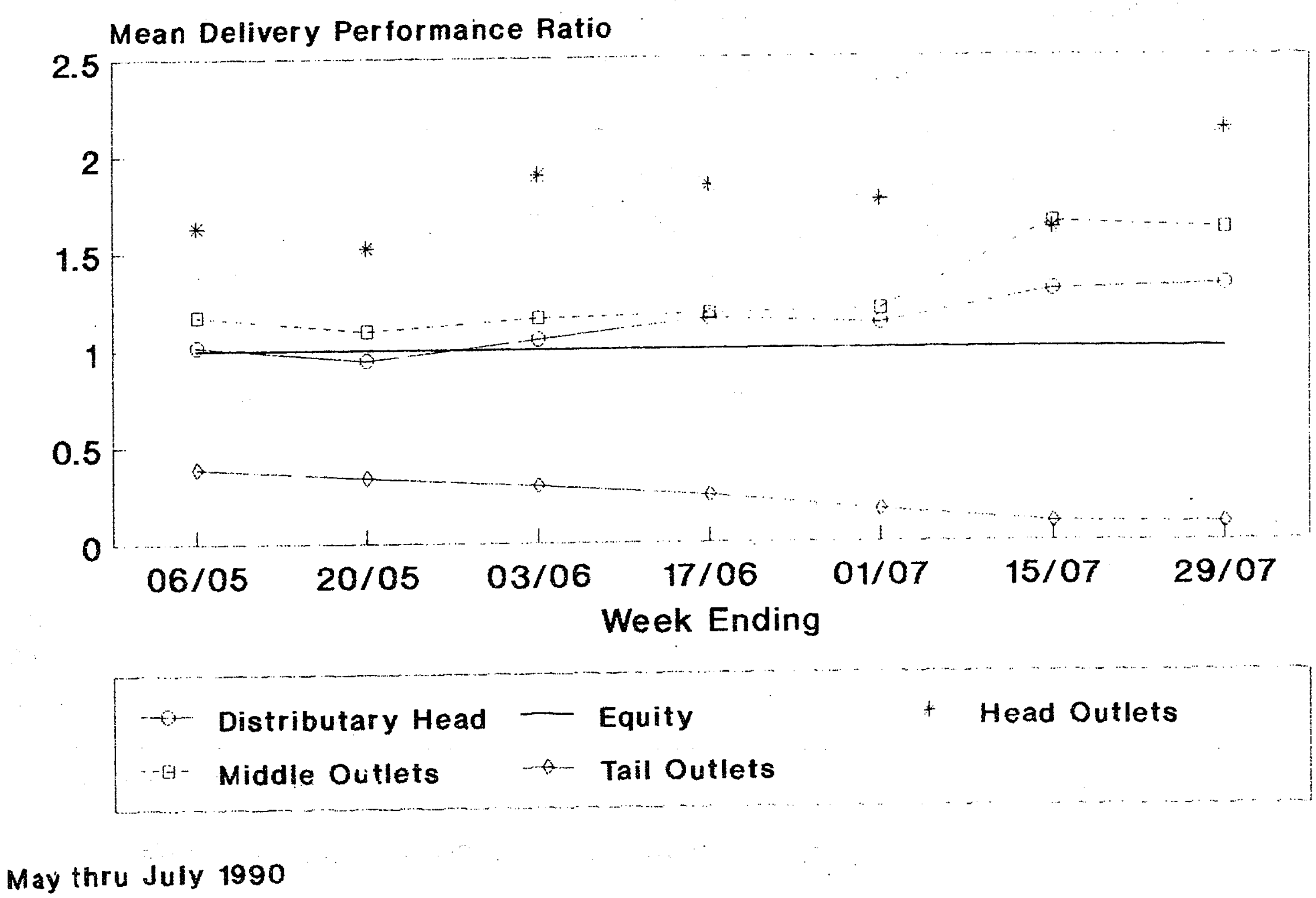
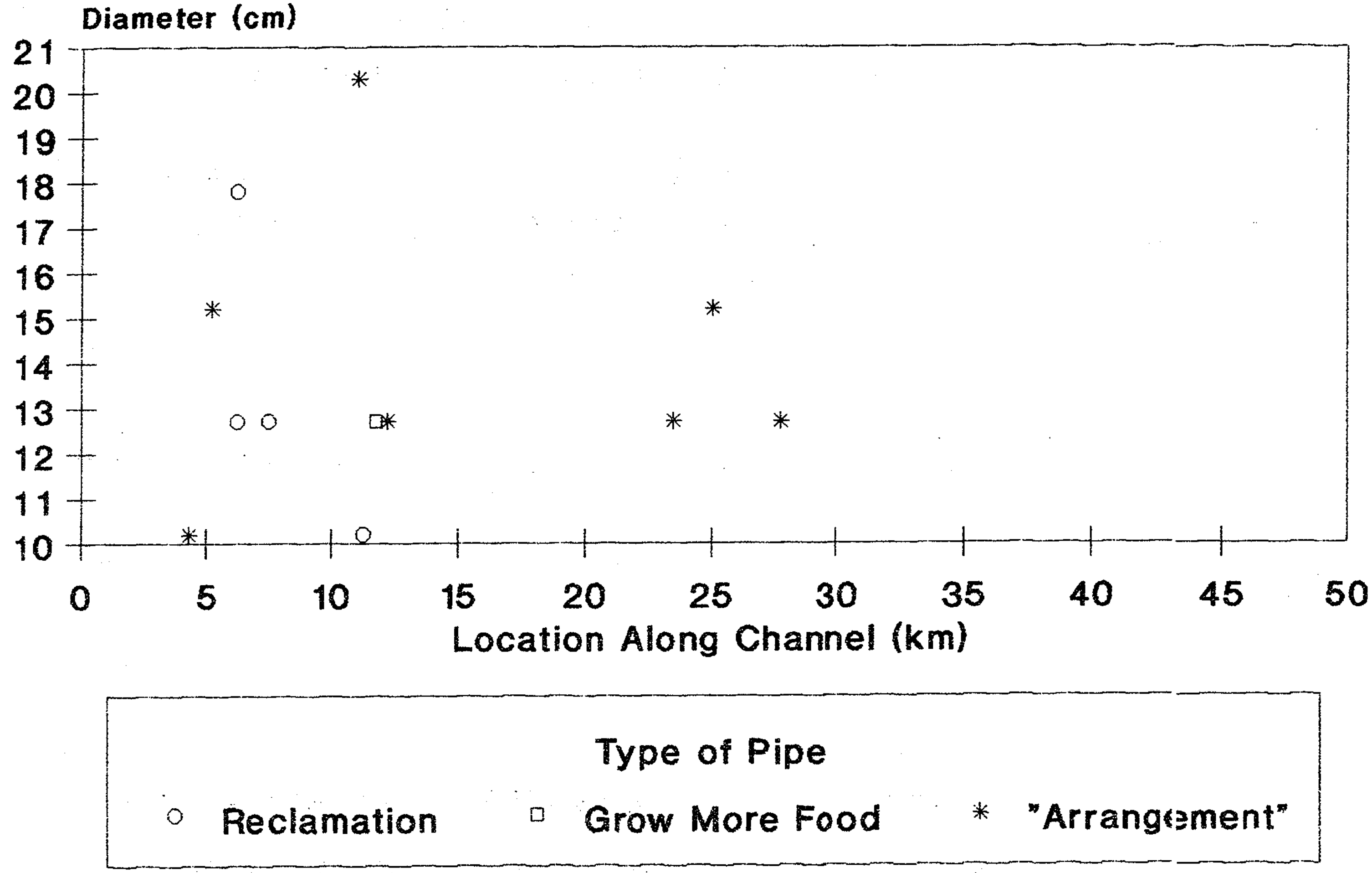


Figure 7. Mananwala Distributary Seasonal Pipes, Kharif 1990.



ID records; IIMI field observations

A three-fold or four-fold increase in water supplies at the watercourse level meant that the low design irrigated cropping intensities (50-75 percent) supported by the surface system could be exceeded. Annual irrigated cropping intensities in many LCC distributary commands rose rapidly to well over 100 percent. The greater abundance of irrigation water now available to farmers also meant that large acreages could be planted in higher value, more water-intensive crops such as rice and sugarcane.

The amounts of fresh groundwater pumped by these deep public tubewells have dropped sharply because of design and maintenance failures in bores and machinery, coupled with high operating costs that revenues from water charges fail to redeem. But that decline does not mean that water supplies to the farmer from this source are now insignificant. An earlier IIMI study showed that public tubewells in Lagar Distributary still provide about 43 percent of all irrigation water available to farmers in rabi and nearly 30 percent of irrigation supplies in kharif (Vander Velde and Johnson 1992). Even so, there has been a marked overall decline in the amount of groundwater supplied by the remaining operable public tubewells.

The rapid development of private, shallow tubewells throughout the 1980s has cushioned the declining productivity of the older public tubewells, particularly in Punjab (Figure 8). Undoubtedly, the increased availability of irrigation water from private tubewells has helped farmers either increase irrigated cropping intensities or sustain already high intensities of less drought-tolerant crops. Tubewell censuses in 35 watercourse commands of Mananwala, Karkan (Minor) and Lagar distributaries revealed that the average density of private tubewells in Farooqabad subdivision (Figure 9) is about 5 per 100 ha of gross command area (GCA).[4] This density of private tubewells, in a SCARP zone where private tubewell installation was restricted and controlled for two decades, is considerably higher than published official data suggest. A similar census in Junejwala Minor watercourses completed in 1991 indicated an average private tubewell density of about 7 per 100 ha GCA.

Hence, the actual availability of water in watercourse command areas continues to greatly exceed the original surface system design values of 1 lps per 5 or 7.5 ha. Other IIMI studies indicate that groundwater from public and private sources now can constitute 70 percent or more of the total irrigation water used by farmers in many distributary watercourse commands. This confirms a greater reliance upon groundwater as a source of overall irrigation supplies in many canal command areas in Punjab than heretofore suspected. These findings and those from other studies also strongly suggest that aquifer exploitation already may exceed recharge, at least locally if not over larger areas of Punjab (*cf.* NESPAK/SGI, 1991).

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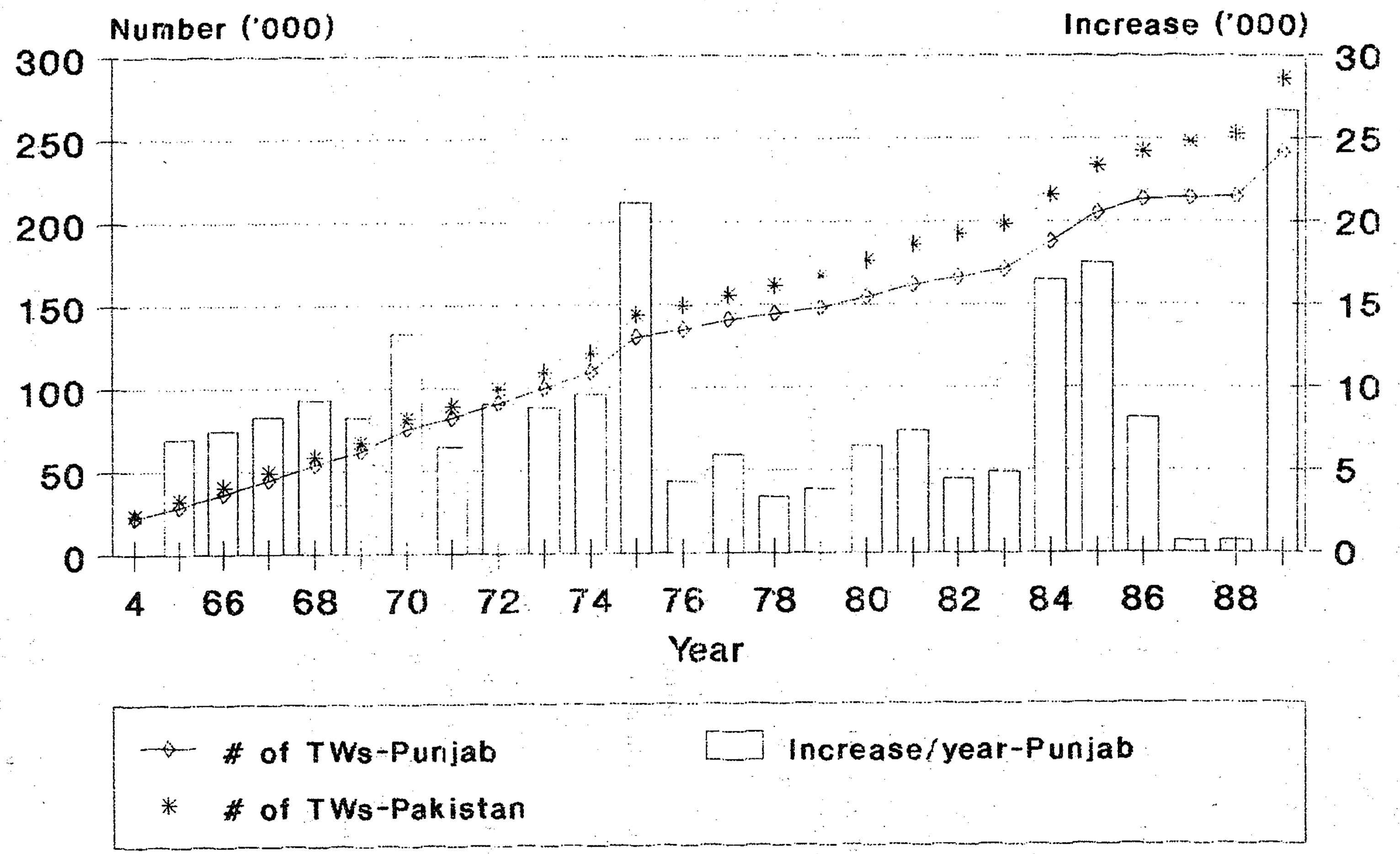
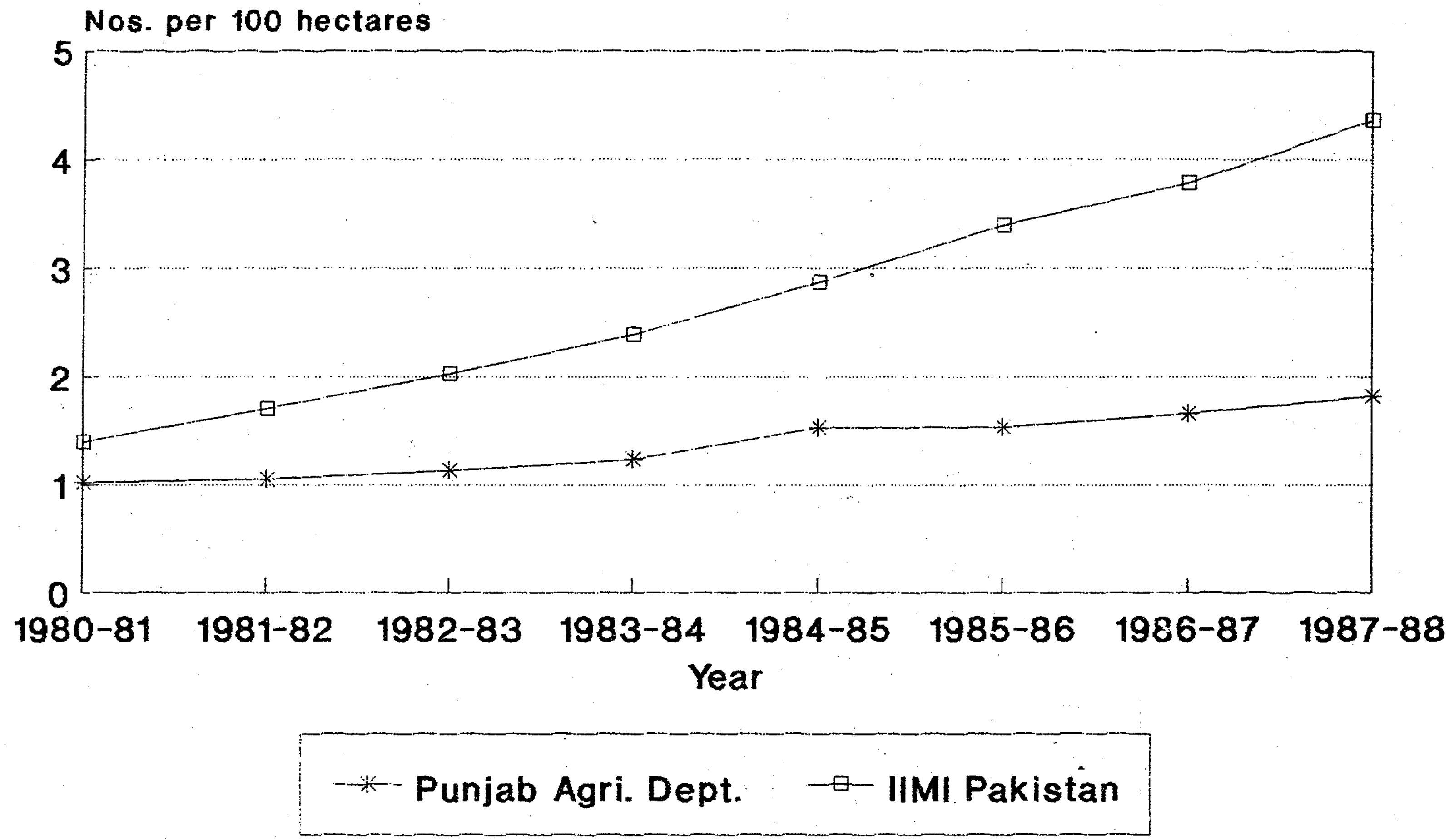
[4]The gross command area (GCA) of a watercourse is used here because culturable command area (CCA) more strictly applies to the irrigable service area of the surface system. Many farmers have installed tubewells not only to supplement their surface supplies, but also to bring additional area not irrigable by the surface system under irrigated agriculture.

Figure 8. Private Tubewell Development in Pakistan and Punjab.



Source: WAPDA, 1988 & NESPAK/SGI, 1991

Figure 9. Changing Density of Private Tubewells: Punjab Agriculture Department Data versus IIMI Data.



IIMI = Farooqabad SD Canal Watercourses
PAD = Sheikhupura District

The Water Balance

For several sample watercourses of Mananwala and Pir Mahal distributaries, water flows into the command areas from the canal system and discharges from public and private tubewells have been recorded for sustained periods from 1989 through 1991. Irrigation applications in fields of sample farmers in these watercourse commands also have been measured to evaluate farmers' irrigation practices. These data now permit a reasonably accurate determination of water balances for these command areas.

The objective here is three-fold: (1) to ascertain how much water is used consumptively by crops and how much is lost to the groundwater, contributing to aquifer recharge and a possible rise in water table; (2) to determine the proportions of irrigation water derived from canal supplies and groundwater that farmers use; and (3) once the proportionality and quality of irrigation supplies have been identified, to determine whether the salt content in the crop root zone is likely to increase or decrease.

The seasonal irrigation applied to wheat in rabi 1989-90 is shown in Table 1. Although the average irrigation is about the same in both areas, variability in seasonal irrigation, identified in the respective standard errors, is greater in Mananwala command than in Pir Mahal command. The average amounts applied *per irrigation* also differ significantly (5 percent level) between the two areas. It is not yet clear why some farmers apply much more water than others, or why a farmer will apply nearly twice as much water to one field from his tubewell than to another, notably in Mananwala watercourses where the variability in irrigation applications is greater than watercourses in Pir Mahal command. We can only conclude that farmers in the latter area apparently attempt to make more optimal use of their irrigation water than do those in the former.

Table 1. Wheat Irrigation in Two LCC Distributary Canal Commands, Rabi 1989-1990.

	Mean Total Irrigation (cm)	Standard Error	Mean Application (cm)	Standard Error	Total Rainfall (cm)
Mananwala	22.0	2.1	7.0	0.42	14.7
Pir Mahal	21.2	0.7	6.2	0.16	9.6

Figure 10 depicts sugarcane irrigation in four Mananwala watercourses throughout a kharif season. The median value of total irrigation for the season is 480 mm, only 5 mm less than the mean total irrigation that farmers in Pir Mahal also were observed giving sugarcane in kharif. The histogram illustrates the wide range of irrigation applications again practiced by farmers; some clearly over-irrigate while others apply hardly enough to make the harvest of the crop worthwhile.

In Table 2, the estimated quantities of water reaching the water table and being abstracted from it over a period of 78 days during kharif 1989 are given for a middle reach watercourse command of Mananwala Distributary. 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. There is only a relatively small change in the residual between the two values of the application efficiency used.

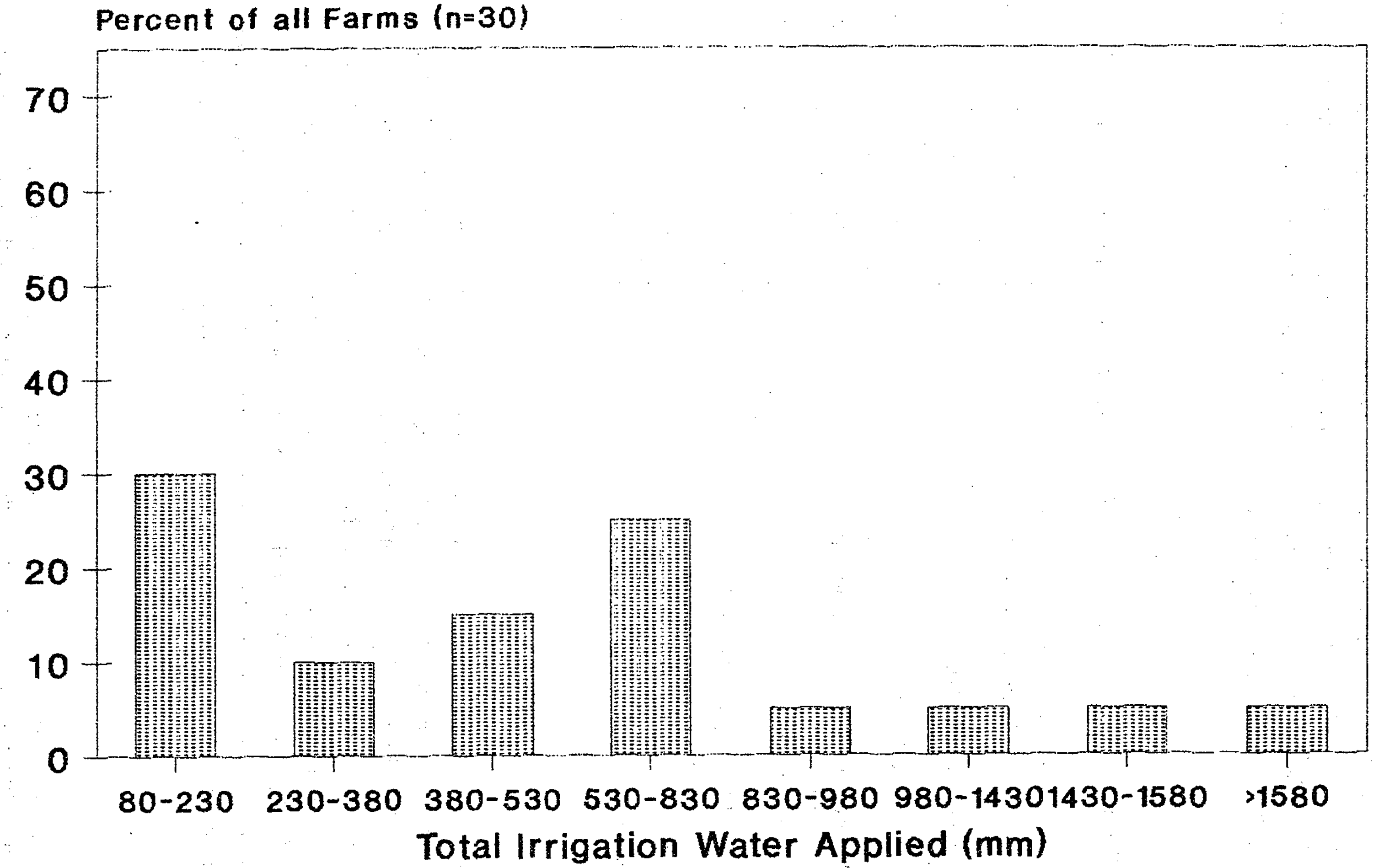
Table 2. Water Balance at the Water Table in Mananwala RD 71, Kharif 1989.

Application Efficiency	58%	70%
Conveyance losses	178 mm	178 mm
Application losses	43	31
Percolation losses from rice fields	166	166
Distributary losses	15	15
Change in aquifer storage	6	6
Pumped abstractions	-398	-398
Residual	10	2

Losses from rice fields were measured from the rate of decrease of water levels in ponded rice fields, corrected for evaporation losses, during both kharif 1989 and 1990. The measured rate in RD 71 was 5.8 mm/day for the 80 percent of the time that the fields were observed to be ponded or moist. Other components of the water balance have been deduced from previous studies done elsewhere in Punjab. A conveyance efficiency of 55 percent, the average previously reported for SCARP areas (Trout et al. 1980; WAPDA 1984) has been assumed for watercourse RD 71.[5] Losses from nonrice crops depend upon the assumed value of field application efficiency, and an average application efficiency of 58 percent is taken from WAPDA's (1978) estimation of such efficiencies for a range of

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

Figure 10. Mananwala Distributary Sugarcane Irrigation: Kharif 1989.



Four Watercourses

irrigation conditions. However, modeling studies show that percolation losses from irrigation of nonrice crops depend upon soil characteristics and may be lower than those previously reported by WAPDA. Therefore, an application efficiency of about 70 percent may be attainable where water is in short supply.

The continuing uncertainty of some values of the water balance in Table 2 means only general observations are possible. For a single kharif season, recharge and discharge from the aquifer appear to nearly balance, but over an extended period of several seasons, however, there is a clear downward trend in water tables in the tail watercourse commands of both Mananwala and Pir Mahal, more pronounced in the latter than the former. The contribution of rainfall to water table rise seems to be rather modest; no sharp rise in water table was observed after a 100 mm storm early in the study period, or from later smaller storms.

Water Quality

The suitability of water for irrigated agriculture should be determined on the basis of specific conditions of use, including the crop(s) grown, soil properties, climatic factors, and irrigation management and other cultural practices. Published salinity tolerances of agricultural crops generally are typical for the late seedling to crop maturity stage. It appears that tolerances during germination and early seedling stage may be lower, however, even for some otherwise more saline tolerant crops.

Three well-known criteria are used for classifying irrigation water for suitability of agricultural use in Pakistan. These are electrical conductivity (EC), residual sodium carbonate content (RSC) and the sodium absorption ratio (SAR), but the standards used are outdated. For example, in Pakistan, the upper limit of "good" water is an EC of 1.5 dS/m (equal to mmhos/cm), a RSC of 2.5 meq/l and a SAR of 10.[6] Present FAO (Food and Agriculture Organization of the United Nations) guidelines for water quality for agriculture, however, set the upper limit on unrestricted use at an EC of 0.7 dS/m, or less than half the value still considered safe in Pakistan.

The effect of sodium, expressed in the SAR value, depends on the EC value, but a safe upper limit now would be set at 6 or 7, again much lower than the SAR value of 10 still used in Pakistan. For sodic waters, common in much of Punjab, an *adjusted* SAR is presently recognized as the better index. The SARs of typical tubewell waters increase by about 25 percent when calculated as *adjusted* SAR values; thus, it is even less advisable to classify water with SAR up to 10 as suitable for undiluted irrigation use.

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[6]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 hazardous to be used for irrigation without extensive mixing with good quality water at unspecified ratios. Two different classifications of the suitability of water for irrigated agriculture are widely used in Pakistan. That adopted by WAPDA, and referred to in this paper, is the least conservative, but the most widely followed in the country. The Punjab Department of Irrigation's Directorate of Land Reclamation follows a more conservative classification; in this case, useable or "fresh" water has an EC < 1.0 dS/m, although the upper limit of SAR remains unchanged at 10.

In the view of Pakistan's Water and Power Development Authority (WAPDA) "...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* (emphasis added)." However, in water-short environments, such as the tail reaches of distributary canals and many watercourses, drainage is rarely observed and is not often possible because surplus water is seldom present. Moreover, there are scant opportunities in these locations to practice mixing canal water with "marginal" quality groundwater in the recommended one-to-one ratio for irrigation use.

Since beginning their collaborative research on groundwater irrigation systems in 1988, the Irrigation Research Institute (IRI) of the Punjab Irrigation Department and IIMI have evaluated the water quality of a large percentage of private and public tubewells in the command areas of Lagar and Mananwala distributaries. A separate and more limited water quality assessment was completed for tubewells in several watercourse commands of Junejwala Minor Distributary in 1991. Data for nearly 500 tubewells, over 95 percent of which are private, are now available.

Analyses of these data for the Mananwala Distributary system, for example, reveal significant differences (1 percent level) between mean values of water EC and SAR for private tubewells in head, middle and tail watercourse commands, indicating a sharp deterioration in water quality towards the distributaries' tails. Figures 11 and 12 illustrate the situation.

Possible explanations for the pattern include: (1) more irrigation water is applied per unit cropped area in the head reach because 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;[7] (2) 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 system than to its middle and tail reaches; (3) a more complex interaction of these two and, possibly, other phenomena.[8] While substantial research on aquifer behavior and change surely is needed before this spatial pattern of groundwater quality differences can be ascribed with confidence to any of several possible explanations, its existence in widely separated distributary canal commands is cause for genuine concern.

The age of private tubewells in the distributaries' command areas also appears to be a significant variable. In the Mananwala system command, about 40 percent of those in head and middle reach watercourses became operational *after* 1987; only 11 percent of the private wells at the tail are that young. In tail-reach watercourses 40 percent of the private wells, however, were installed *before*

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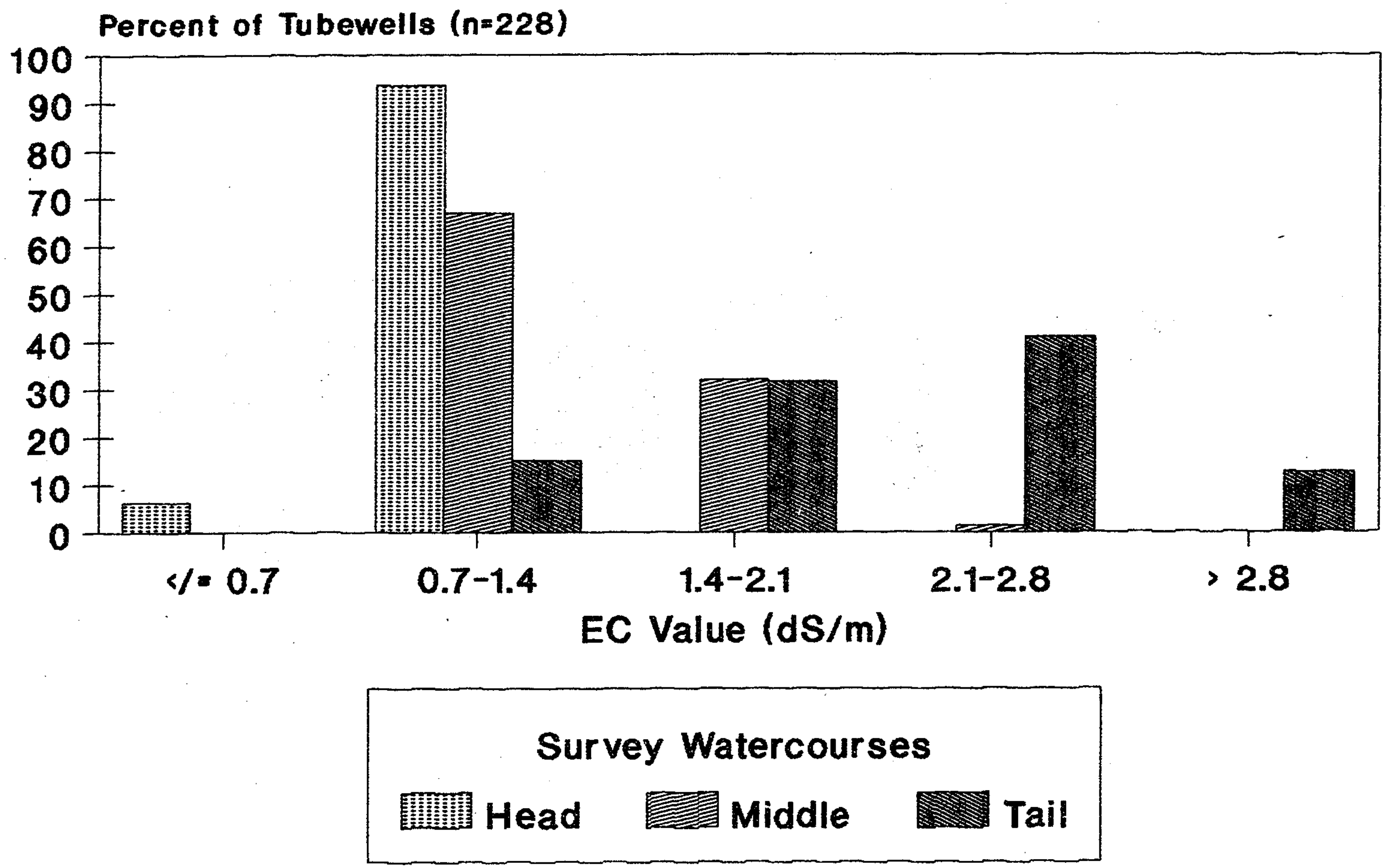
[7]Mananwala water quality is markedly better than the best quality tubewell water; ECs are about 0.2 dS/m for canal water versus 0.6 dS/m for the best tubewell water.

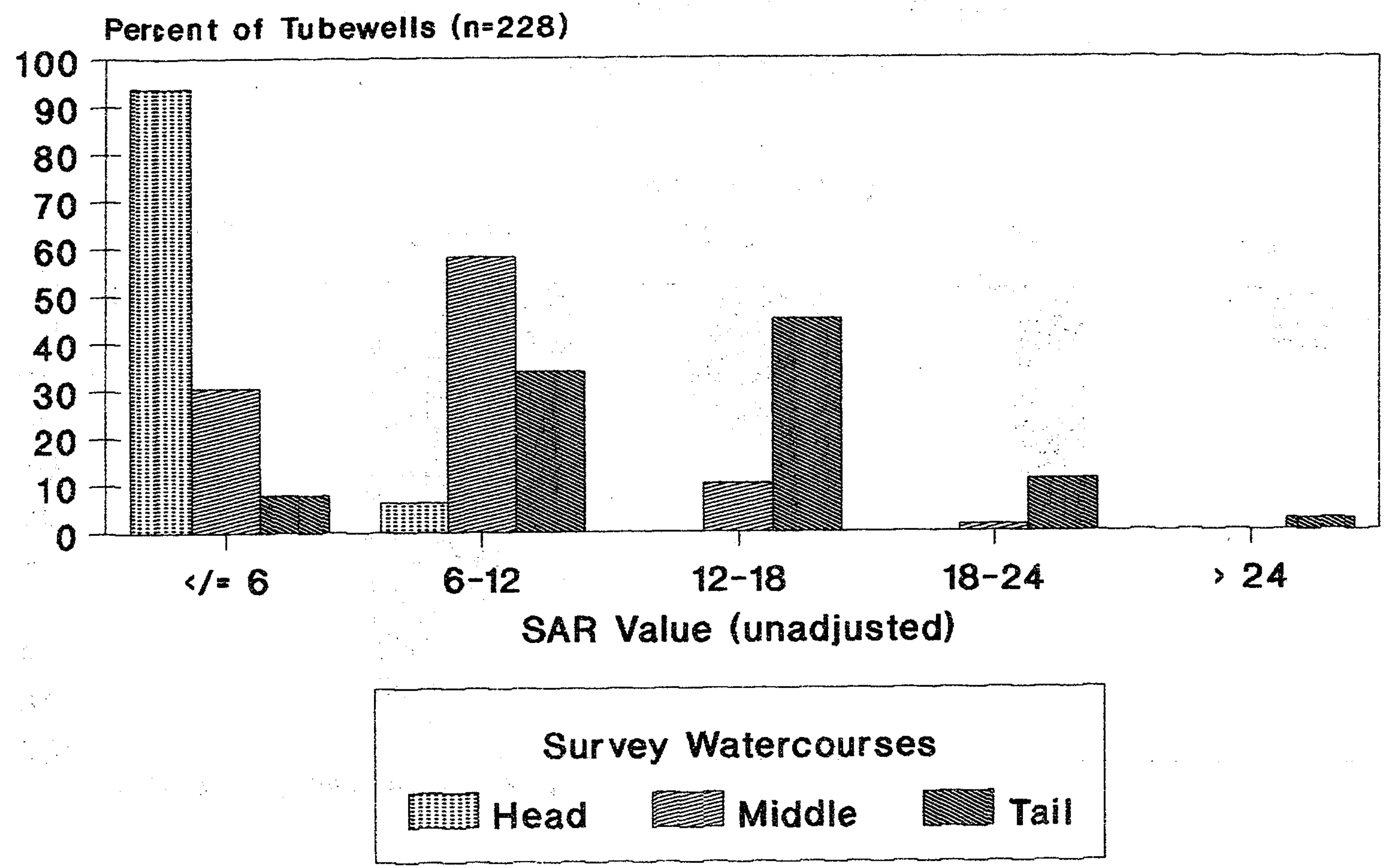
[8]Our colleague, Dr. R. Sakthivadivel, has suggested that the vertical differential hydraulic gradient existing between the distributary head and tail also could contribute significantly to accelerated salinity differences between these locations.

Figure 11. Private Tubewell Water Quality: EC, Mananwala Distributary System.



IRI-IIMI Data, 1990
Watercourse n=21

Figure 12. Private Tubewell Water Quality: SAR, Mananwala Distributary System.



IRI-IIMI Data, 1990
Watercourse n=21

1985, but only 20 percent and 6 percent, respectively, in middle- and head-reach service areas are more than five years old. Farmers in tail outlet commands clearly found it necessary to install tubewells sooner than those located in head- and middle-reach watercourses, hardly surprising, since they likely began experiencing persistent canal water shortages and greater variability in surface supplies at a much earlier date.

Insofar as deterioration of groundwater quality may be related to seepage of saline water from fields irrigated with marginal to poor quality tubewell water, it appears that the process is relatively rapid.[9] Private tubewells in Punjab typically tap aquifers in the range of 15-30 m, and public wells on average pump from a depth of 50-100 m. With the water table at about 5 m depth, it has taken only 5 years, the median age of tubewells in Mananwala's tail reach, for groundwater quality to worsen down to at least 15 m.

Field-Level Salinity and Sodicity

To assess the likelihood and significance of salinity problems for conventionally irrigated and established crops, the mean salinity of the major root zone, where most of the water extraction occurs, must be determined. In one-third to one-half of all fields sampled in the tail watercourse commands, profile salinity was found to be great enough to reduce crop photosynthesis even when the soil was at full field capacity (Figure 13). Unexpectedly, profile salinity in 5 percent of the sampled fields in middle reach watercourse commands also had reached this level, with the highest readings concentrated in the surface water-short tail areas of those watercourses. Under such conditions, crops are stressed even though there may be plenty of moisture in the soil.

It is, therefore, no surprise to find that crop yields in these locations often fall below expectations. For the average conditions represented by our samples and a medium salt-tolerant crop such as wheat, an ECa (apparent EC) of 10 dS/m may cause a reduction in yield up to 40 percent, or a decline as great as 60 percent in the yield of sugarcane, which is more sensitive to salinity.[10]

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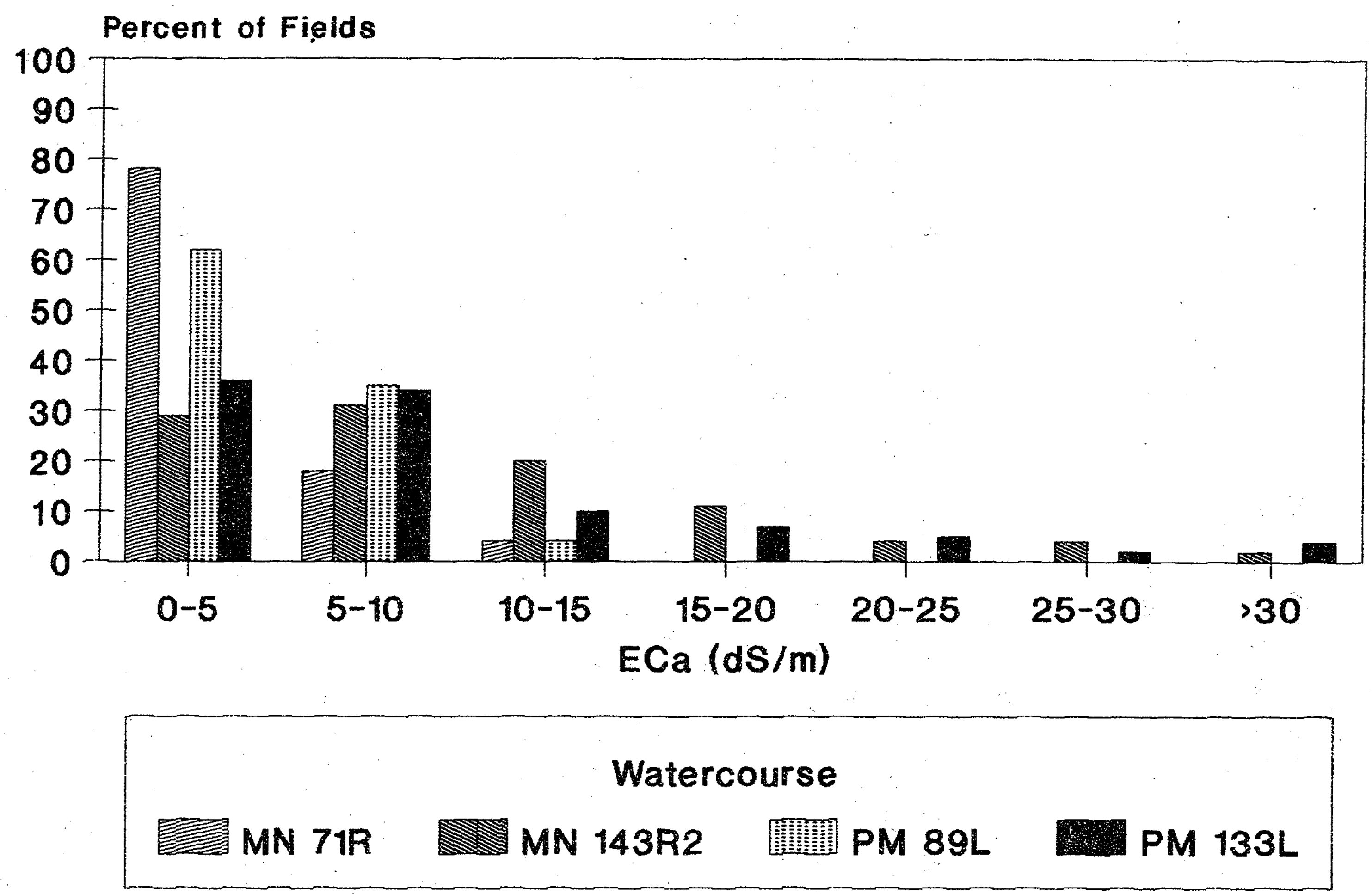
[9]Kung (1990) has recently described preferential flow paths in sandy vadose zones, the layer between the water table and the root zone, as the mechanism through which groundwater contamination can take place over a short period of time. He concludes that "funneled flow" occurs widely in most vadose 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 IIMI's middle- and tail-reach watercourse study areas when sampling groundwater quality in observation wells and from tubewell discharges.

[10]Rhoades and Loveday 1990. The data reported by Shahid et al. (1989) for cotton and sugarcane for Pakistan do not differ significantly from those reported by Rhoades and Loveday. These are indicative values only, because actual crop salinity tolerance can and does vary with ambient agronomic conditions, cultivation practices, and other production limiting factors. Recent work by Bajwa and Josan (1989), for example, shows that soil deterioration under irrigation water quality conditions somewhat more severe than we report here is rather fast, with negative effects upon rice yields in a rice-wheat rotation (a widespread cropping pattern in the secondary canal commands of Upper Gugera Branch of the LCC) greater than expected.

Figure 13. Soil Salinity: Four Watercourse Commands, Mananwala and Pir Mahal Distributaries.



Field observations also point to a structural decline in soils resulting from irrigation with sodic waters, a complication which poses an important obstacle to reclamation of saline soils by leaching.[11] Sodicity may induce calcium and various micronutrient deficiencies because of the high pH and bicarbonate levels it imposes. All tubewell water surveyed had high pH values -- only 25 percent of the samples had a pH below 8 -- as well as high bicarbonate values.

In contrast to normal and saline soils, sodic soils are typically hard to permeate and poor in tilth because of structure loss and clay migration with the movement of sodic soil water. Using rough guidelines combining mean EC values and mean SAR values, sodicity hazards of irrigation water were surveyed in tubewells in head, middle and tail watercourse commands of Mananwala distributary. Aggregate readings fell just within the borderline beyond which a permeability hazard is likely to arise. But water from 25 percent of the tubewells in tail-reach watercourses had EC and SAR values already within the range of waters likely to cause permeability problems.

The Salt Balance

Removal of salts from the crop root zone to maintain a salinity level compatible with the cropping system requires a downward flux of water and salts. Hence sufficient water from rainfall and irrigation must be provided to the crop, over and above the evapotranspiration needs, so that there is excess water to pass through and beyond the root zone to carry away salts. This excess water is usually referred to as the leaching requirement.

Computer modeling and simulation of water and salt balances permit an assessment of the effect of current farming practices on the build up or removal of salts from the soil profile. We have used Hanks' model for this purpose (Childs and Hanks 1975; Hanks 1984). This simulation model, which weighs basic properties of soils and plants against weather and water table conditions, was calibrated with field data to predict 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.

Simulations were carried out for both the median and the 75 percent EC values (values exceeded by 25 percent of the samples) of irrigation water being pumped by private tubewells and used by farmers in tail watercourse commands. Median irrigation applications for wheat grown in Mananwala Distributary command and for cotton and sugarcane grown in the command of Pir Mahal Distributary were used as input in the model.

Actual leaching fractions for wheat are sufficient to reduce profile salinity. For the other crops and for all soil textures tested with the model, profile salinity increased. The largest increase takes place in sugarcane grown on silt loam with irrigation water of 2.5 dS/m -- an almost twofold increase in a

[11]The results of a rapid-appraisal survey carried out in the commands of seven Mananwala watercourses in 1989 to record the presence of salinity -- either as surface salting or obviously salt-affected crops -- and dense, hard subsurface layers strongly hint at a general deterioration in soil conditions towards the tail of distributary canal commands due to secondary salinity.

single season. Another important observation is that leaching is far more effective for wheat during the cooler rabi season than for crops grown during the hot kharif season, even though monsoon rainfall exceeds that from winter rains.

It does seems reasonable to assume at this juncture that so long as the soil structure is not affected, the build-up of profile salinity is reversible. Reclamation should not take much longer than it took the salts to accumulate in the profile in the first place, except where clay migration has compacted the profile and lowered hydraulic conductivity.

Farmer Perceptions and Responses

Six farmers in each of ten watercourses in or adjoining the command areas of the study distributaries were surveyed in 1991 to identify the level of farmer awareness of salinity problems and the practices that farmers have adopted to manage or mitigate salinity impacts on their agriculture. Table 3 summarizes the proportion of farmers surveyed that recognized a salinity problem on their farms. Farmers identified three, often interdependent, causes for their salinity problems: (1) a shortage of canal water, especially Pir Mahal farmers; (2) the (poor) quality of their tubewell water; and (3) residual salinity associated with earlier waterlogging, especially Mananwala farmers.

Table 3. Farm Location and Salinity.

Farm Location in Watercourse	Percentage of Farms Salinity Affected
Head	45%
Middle	66%
Tail	90%
All farmers	66%

A full three-quarters of the farmers who claimed to have a salinity problem have tried one or more practices to manage salinity. Three broad categories of practices were identified: (1) physical activities (leaching, removing or adding soil), (2) using chemical amendments such as gypsum, and (3) biological interventions (specific crops and crop rotations, farm yard manure applications, green manuring). A very few farmers also try to manage their salinity by allocating canal water preferentially to saline fields. Farmers reported varying degrees of success with the approach(es) adopted, with most insisting that a "solution" to the problem of salinity is beyond their capacity and should be provided by government.

Explicitly, farmers identified two major constraints to greater success in managing salinity and reclaiming saline fields. Insufficient water supplies to permit satisfactory leaching was frequently cited, although it was observed in several such instances that irrigation water was sufficiently available for sugarcane to be grown. Concomitantly in these cases, it was clear that the possibilities for using available poor quality water to meet leaching requirements was not understood.

The economic cost of better managing salinity also was often noted, especially in the case of using gypsum and restoring soil fertility with fertilizers. Credit facilities to meet the capital requirements of physical and chemical practices to control salinity are largely unavailable to the average farmer. Moreover, there is considerable risk that any capital investment in such practices could be substantially offset by a further worsening of supplies of canal water and/or an increasing reliance upon poor quality groundwater. These factors may account for the stronger preference shown by farmers surveyed for biological interventions that admittedly are longer-term, but both less risky and lower in capital requirements.

Perhaps most importantly, the survey highlighted the poor flow to farmers of reliable information on how to manage salinity. Although 15 percent of the surveyed farmers reported receiving useful information on salinity from agricultural extension staff, "experienced" farmers were no less a source of such information. But, 70 percent of the farmers surveyed claimed they were unable to obtain any information at all on how to better control salinity on their farms.

Management Implications and Prospects in a Dynamic Environment

Measured and observed data confirm the existence of a disturbing pattern of increased salinity-related problems in Punjab's irrigated agriculture as location varies within distributary canal and watercourse commands. The primary source of salt accumulation in the process of secondary salinity is tubewell water of doubtful quality used in growing quantities by farmers for irrigation. Serious and persistent inequity in the distribution of high quality canal water within distributary commands, often mirrored at watercourse level, has meant that farmers in middle- and tail-reach locations increasingly depend on pumped groundwater to meet the bulk of their crop water requirements. For reasons that are not yet well understood, the quality of groundwater pumped by tubewells generally decreases between head and tail within distributary canal commands. Thus farmers in tail-end locations face a double handicap: they receive much less than their fair share of canal water compared to farmers upstream, and the groundwater supply they therefore must fall back upon is of poorer quality than elsewhere.

In theory, mixing canal water and tubewell water for irrigation is a feasible management alternative for farmers to mitigate and control secondary salinity. Indeed, water even more saline than that found in the command areas of Mananwala and Pir Mahal distributaries can be successfully used for agriculture, as recent examples of the reuse of drainage water for irrigation elsewhere illustrate. But that would certainly *require* greatly increased management skills of farmers, and a likely shift in production to more salt-tolerant crops such as fodders or agroforestry mixtures.

Overall, the problems currently facing farmers and system managers in trying to achieve an appropriate balance in irrigation water quality, at least during crop germination and other sensitive growth stages, are daunting. For example, assuming no significant changes in present cropping patterns, a management intervention that seeks to bring the average EC value of mixed irrigation water in middle and tail watercourse commands below 1 dS/m, seems certain to require greater quantities of canal water than are presently available to the canals in our study.

Since the median EC value of tubewell water in the head reach of the Mananwala Distributary is less than 1 dS/m, in theory, farmers there could rely completely upon tubewell water to meet their irrigation needs without changing their current crop mix or incurring secondary salinity problems. In that hypothetical situation, all canal water then could be made available to middle- and tail-reach watercourses. To produce an average EC water quality value of about 1 dS/m for middle reach farmers, 36 percent of the canal water *now available* would be required for mixing. However the remaining 64 percent of canal supplies, when mixed with available groundwater, would result in an average EC water quality value of only 1.23 dS/m for tail-reach farmers. Thus, redistributing present canal supplies during peak consumption months still would not bring the quality of irrigation water available to farmers within acceptable limits throughout the entire canal command area, even were head-end farmers to use no canal water at all!

Selection of crop varieties for their salinity tolerance and changes in cropping patterns also seem certain to play important roles in sustaining agricultural production with poor quality irrigation water. So far, we are unaware of any systematic research in Pakistan focused on crop or farmers' responses to the effects of poor quality water supplies and secondary salinity. Research results from analog environments in other countries may have fruitful application here. As already noted, field evidence does confirm that many Punjabi farmers are aware of the harmful effects of prolonged irrigation with poor quality tubewell water, and some have responded by changing their cropping patterns.

Present conditions of canal operations also reflect significant failures on the part of existing institutions to observe and enforce long-standing rules and procedures of irrigation system operations. Poorly planned and implemented rotational programs, frequent operation of channels at discharges far below well-established limits, authorizing special water allowances that reduce surface supplies downstream or facilitating other interventions that appropriate water combine with long deferred maintenance and widespread water theft by "influential" farmers to worsen water supply conditions in the tail reaches of distributaries. Indeed, it is now admitted that the tails of at least "40% of the distributaries in Punjab" are dry, notably in kharif season! Clearly, the current situation highlights the critical importance of institutional issues that also must be addressed in developing appropriate system management responses to mitigate salinity impacts on irrigated agriculture.

More and better management of distributary channel maintenance surely could bring improvement in the current pattern of water distribution at the distributary level. And there is clear evidence of both increased farmer participation and farmer willingness to participate in maintaining portions of the distributary system heretofore recognized as the responsibility of the Irrigation Department (ID). In Farooqabad subdivision, for instance, over the past 2-3 years, groups of farmers and agricultural laborers, at times numbering over 100 persons, have regularly carried out substantial desilting, berm cutting and vegetation clearing of the smaller minors of Mananwala and Lagar distributaries and in selected reaches of the larger parent channels. On several occasions, the ID also has provided either limited guidance for this work or nominal sanction for its implementation. Formalizing and expanding such farmer participation in distributary-level maintenance activities, possibly in exchange for an agency operational commitment to improve the quantity and reliability of irrigation service to disadvantaged channel reaches, has significant potential and promise.

Two months ago, the Punjab government launched a province-wide program of accelerated distributary desilting during the annual canal closure utilizing laborers from many government departments to supplement the work of contractors. Simultaneously, farmers, secondary schoolboys and other rural folk have been mobilized by the civil administration in a highly publicized "Self-Help" program to desilt smaller distributary channels and minors. Field observations indicate that the amount of canal desilting and maintenance done so far is unprecedented in recent history. How substantial the positive impact of these activities will be on canal water distribution and how long it can be sustained remains unknown at this juncture. However, perhaps for the first time since the initiation of the Indus Basin Plan in the 1960s, there is in Pakistan a major public program linked to new institutional initiatives with the explicit objective of improving canal system performance.

That is a significant step, hesitant and uncertain though it may be, toward determining whether or not a productive irrigated agriculture can continue to be sustained in the Indus Basin. Admittedly, the potential of these interventions and other management changes to control and mitigate secondary salinity remains a subject requiring further research and assessment. Equally important is monitoring and continued evaluation of several interdependent variables -- aquifer discharge and recharge, groundwater quality, and canal system performance -- to close significant gaps in knowledge and understanding. Collaborative research and development that strengthen the national agricultural research system and other institutional mechanisms for these purposes will continue to be a vital component of IIMI's program in Pakistan.

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