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MANAGEMENT OF PRIVATE TUBEWELLS IN A CONJUNCTIVE USE ENVIRONMENT:

A Case Study
in the Mananwala Distributary Command Area,
Punjab, Pakistan

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Abstract

The present paper is a follow-up of IIMI Working Paper No. 21 by Vander Velde and Johnson (1992). It analyzes the tubewell data collected by IIMI-Pakistan over a period of 4 years. While the main emphasis remains on the operation of private tubewells, public tubewell and canal water supplies are included in the analysis to give a more comprehensive picture of the conjunctive use environment, a characteristic of most of the irrigated areas of the Punjab, Pakistan.

The analysis of the data for two channels, Mananwala Distributary and Karkan Minor, confirms the importance of groundwater use in irrigated agriculture in the Punjab. Private tubewells increase the irrigation water supply available to farmers and also play a stabilization role to mitigate the (unpredictable) fluctuations of the canal water supply. The specially high dependance on groundwater supplies at the tail of the system increases problems associated with secondary salinization in these areas.

The impact of technical and economic factors on private tubewell operation is analyzed. The costs of tubewell operation, directly related to the source of power, is the major factor influencing the operation of private tubewells. The relative importance of electric tubewells, with lower operation and maintenance (O&M) costs, explains most of the differences in groundwater use between watercourses. The level of canal water supply and the quality of the groundwater influence groundwater pumpages only marginally.

Non-tubewell owners, mainly small farmers who cannot afford the purchase of a private tubewell, have access to the groundwater resource via a market for groundwater. Most of the time, the price of tubewell water in this market is solely determined by the O&M costs of the tubewell of the seller. Water from electric tubewells, which have low O&M costs, is sold most in this groundwater market.

The concluding chapter highlights the importance of the dissemination of research results and of a proper monitoring of the conjunctive use environment. It also discusses relevant issues for further research on the management of the conjunctive use environment in Pakistan.

Introduction

Agriculture in Pakistan is directly dependant on the Indus Basin Irrigation System. Sixteen million hectares are irrigated by a huge network of canals and distributaries dating back to the British times, along with more traditional systems as the ones found in Baluchistan or North-West Frontier Province. Groundwater is also extensively used for irrigation, within or outside the surface water distribution system.

Despite favorable resources (land and water), the Indus Basin Agricultural System does not perform as expected. Yields have been far below their potential and stagnant over the past 20 years for three of the four major crops grown in Pakistan: wheat, rice and sugarcane (Siddiq 1991). Reasons of disappointing performances of the irrigated-agriculture system are numerous and complex. The "twin menace" of waterlogging and salinity, however, is often cited as a major constraint for the agricultural production.

In 1989, the International Irrigation Management Institute (IIMI) started a project in Pakistan titled ***Managing Irrigation Systems to Minimize Waterlogging and Salinity Problems*** and funded by the Government of the Netherlands. The overall objective of this five-year project is:

to devise plans for the management of irrigation systems which are expected to lead to the mitigation of problems related to salinity and high water tables.

A further objective of the project is to field-test these management interventions, to monitor their impact, to evaluate their benefits and identify costs and opportunities for implementation on a wider scale.

Analysis of data collected during the first years of the project has confirmed the importance of problems associated with the inequitable distribution of canal irrigation water: watercourses at the head of distributaries draw a larger amount of water than their design shares whereas watercourses at the tail of the distributaries receive a very low canal water supply. Moreover, the unreliability of the canal water supply increases as one moves from the head to the tail of the distributaries and the watercourses command areas.

To overcome the problem in part, farmers have invested in tubewells to tap groundwater resources and to increase their irrigation water supply as well as their control over this supply. However, new problems have appeared due to the rapid increase in the number of tubewells in most of the canal command areas. IIMI research has shown that part of the salinity constraining agricultural production in the irrigation system is related to the use of groundwater of doubtful quality. This secondary salinity represents a more recent (and increasing) phenomenon than salinity related to waterlogging.

The present study focuses on the operation of tubewells within a conjunctive environment and addresses issues related to the following three questions:

1. How do farmers currently manage the groundwater resources (mainly via private tubewell operation) ?

11. What are the main factors influencing the management/operation of private tubewells ?

iii. What is/would be the impact of the current management of groundwater resources on agricultural sustainability ?

The impact of the distribution of canal water and of groundwater characteristics (mainly water quality) on tubewell characteristics, density and operation, will be the major aspects of the study, based on data collected in Mananwala Distributary Command Area (channel offtaking from Upper Gugera Branch of the Lower Chenab Canal). Socioeconomic aspects are included as well in our analysis. The management of tubewells by farmers and their participation in water markets will be the last point considered in this study. Finally, proposals for a better management of the groundwater resources within a conjunctive environment will be presented and discussed.

Research Setting

PRESENTATION OF THE IRRIGATION **SYSTEM**

The Lower Chenab Canal, a century-old canal offtaking from the Chenab River at Khanki Head Works, has a design capacity of 307 curnecs. It is bifurcated at Sagar Head into two branch canals, the Upper Gugera Branch Canal and the Main Line Branch Canal. The design discharge of the Upper Gugera Branch Canal is 170 cumecs. On the left side of this canal, a link canal, Qadirabad-Baloki (QB) Link Canal with a design discharge of 510 cumecs, runs parallel to the Upper Gugera Canal for 45 km. On the right side of Upper Gugera Canal, 8 distributaries of different sizes (with a design discharge ranging from 0.23 cumecs to 5.1 cumecs) takeoff up to its 37th km and supply canal water to the area of the Farooqabad Subdivision of the Upper Gugera Division.

Mananwala Distributary is the largest of these **8** distributaries. It takes off at 27.9 km from Sagar head (RD91) and has a length of 45 km. With a design discharge of 5.1 cumecs, it irrigates a Culturable Command Area (CCA) of ***26,800*** ha through 121 outlets (see map in Appendix I). Three minors, namely Karkan Minor, Mitu Minor and Litan Minor, offtake from Mananwala Distributary. Mitu and Litan minors are both relatively small channels with a design discharge of 0.28 curnecs and 0.17 curnecs, respectively. Karkan Minor has a higher design discharge (2.01 cumecs) and includes a Subminor named Kotla Subminor. Karkan Minor offtakes at 23.2 km (RD.76) from the head **of** Mananwala Distributary and has a total length of 25.7 km. It has 39 outlets which serve 9,400 ha of CCA, with an additional area of 859 ha supplied by Kotla Subminor. The whole distribution system is being built with earthen nonlined channels.

A gated structure controls the water flows entering the Mananwala Distributary. The head of Karkan Minor, located at a trifurcation point of Mananwala (RD.76), is a proportional distribution structure. It has not been provided with a gate. **A** permanent Head Gauge Reader (gate keeper) is employed to regulate the surface water flows at Mananwala head. Under the orders of the Sub-Divisional Officer (SDO), Farooqabad, he adjusts the gates to increase or decrease the discharge into the distributary to cope with the changes in water levels in the main canals or to take into account downstream conditions (like breaches along the distributary or problems of tail supplies).

For the Provincial Irrigation Department operating and maintaining the system, the operational objective is to run the distributaries and minors at 100 percent of their authorized discharge in order to provide an adequate supply to the tail parts of the irrigation system. The discharge at the head of the distributary (or minor) should not be less than 70 percent of the design discharge to avoid siltation in the channel and its long-term negative effect on the canal water supply. The outlets of a specific distributary or minor have been designed to receive (at least in theory) the same quantity of water per hectare of CCA. Below the outlet, canal water is shared among farmers following a predefined rotation (of a 7- or 10-day period) of water turns called *warabandi*. The designed yearly cropping intensities for Mananwala Distributary and Karkan Minor are 50 percent and 70 percent, respectively.

The analysis of the current operation of the irrigation system has shown, however, that the discrepancies between the design and the current situation of canal water supply are quite high. The inequity in the distribution of canal water along Mananwala Distributary and Karkan Minor, head outlets being favored against tail outlets, has now been well documented by IIMI-Pakistan research (see, for example, Vander Velde 1990; Kijne and Vander Velde 1990 or Van Waijjen 1992) and appears to be a lastingphenomenon (see Van Waijjen 1992).

Moreover, farmers located in tail watercourse command areas face a highly variable and unreliable canal water supply. Poor maintenance resulting in silt accumulation and the importance of illegal imgation along the head reaches of the canal are the main reasons to explain the poor performance of these two channels. The performance at the tail of Karkan Minor is comparatively better than at Mananwala tail, certainly due to the better physical condition of this minor and its higher water duties (see Van Waijjen 1992).

It is interesting to compare design cropping intensities with the actual ones for the sampled areas. With cropping intensities[1] for the Kharif and the Rabi seasons of 55 percent and 69 percent, respectively, for Mananwala Distributary and 54 percent and 73 percent for Karkan Minor, the area shows a much higher land-use intensity than designed (yearly values of 50 percent and 70 percent respectively). The main reason of the discrepancy between design and actual figures lies in the fact that surface irrigation supplies are supplemented by groundwater pumped by public and private tubewells in all the watercourses offtaking from Mananwala Distributary and Karkan Minor.

Falling into the Salinity Control and Reclamation Project 1 (SCARP 1) area, public tubewells have been installed in most of the watercourses of the command area of Mananwala Distributary and Karkan Minor, 20 to 30 years ago. A few commands, however, do not have public tubewells anymore (see Appendix 11, characteristics of sample watercourses) due mainly to the recent SCARP Transition Pilot Project (STPP). In the context of this pilot project, public tubewells (sometimes only the bore) have been transferred to farmers/group of farmers or simply closed down.

AGRICULTURE AND FARMING SYSTEMS

Mananwala command area is located in the wheat-rice ecological zone of Punjab. Within the most frequent rotation of wheat and rice, other crops like sugarcane, fodder, vegetables and pulses have been included in the cropping pattern leading to an average yearly cropping intensity of 120-130 percent for the area. Cotton is sometimes present as well, mostly in the middle watercourse command areas of Mananwala Distributary. Although fodder and vegetables do not cover a large part of the land cultivated, their economic importance in the farming systems has been fully recognized. Moreover, these crops represent a real interest for the irrigators, using part of the inter-seasonal water supplied by canals.

The average farm size in the area is around 3 - 4 ha and this has been decreasing over the past years, following a general trend observed for the whole Province. The impact of this land fragmentation on irrigation water use efficiency has not been well-documented. However, while the number of small holdings increases, farmers without any possibility to invest in private tubewells are also becoming more and more numerous. Alternative sources for these small farmers to complement their public supplies would be more and more needed.

Differences between large and small farms are quite important in terms of use of inputs and access to various resources. Large farms will use comparatively more hired permanent and casual labor, more improved inputs (weedicides, pesticides, seeds) and will have a better access to institutionalized credit. No significant difference, however, seems to exist between large and small farms in their access to different sources of irrigation water (see Khan et al. 1990).

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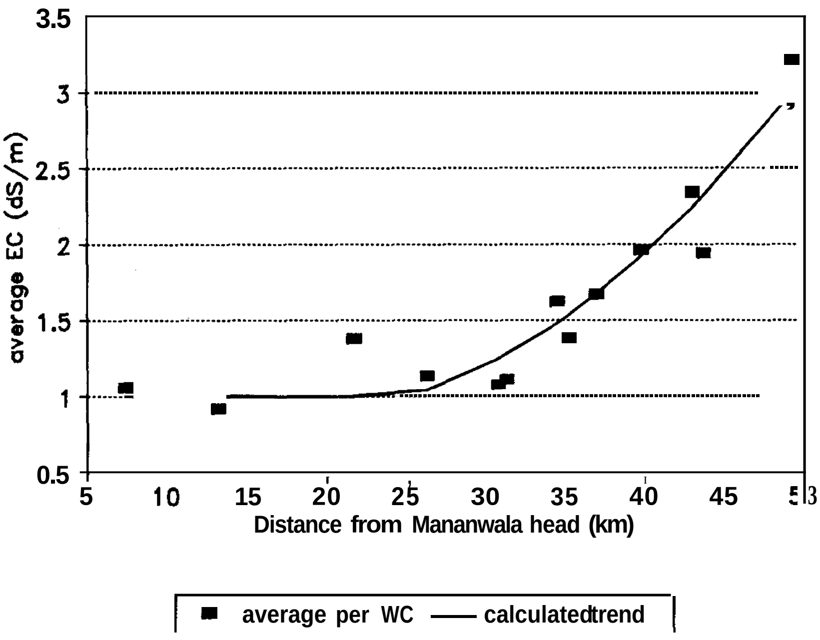
[1] Data provided by the Provincial Irrigation Department, Sheikhupura Division.

Waterlogging and its associated salinity have long been major problems in the area. Farmers reported a flood about 30 years ago as a major reason for waterlogging. With the introduction of public tubewells and the development of private tubewells, water tables have been significantly lowered. Salinity, however, is still a major constraint faced by farmers and related now to the use of poor quality tubewell water (see Kijne and Vander Velde 1990).

The problem is particularly acute in the tail ares of the distributary as presented in Figure 1 giving the average ***electrical conductivity***[2] (EC) of the groundwater pumped as a function of the distance between the head of Mananwala Distributary and the outlet of sample watercourses from Mananwala Distributary and Karkan Minor.

Figure I. Groundwater quality versus distance from the head of Mananwala Distributary.



To cope with salinity, farmers have adapted new farming practices, including specific salt tolerant crops ***(Kalar Grass*** especially in Karkan Minor Command Area and/or ***Jantar)*** in their cropping pattern, favoring appropriate crop rotations, using chemicals to reclaim soil, changing the management of their irrigation water, etc. The availability of good-quality irrigation water and/or the financial capacity of the farm or its access to short-term credit are, however, key aspects to be taken into account in evaluating the potential of the farmers to reclaim saline soils with a given reclamation practice (see Strosser 1990).

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[2] The ***electrical conductivity*** (EC) is used in this study as a parameter for expressing groundwater quality. Other criteria as the ***residual sodium carbonate content*** (RSC) and the ***sodium absorption ratio (SAR)*** have not been included in this analysis. The trend is however similar for these two criteria as for the EC values showing a decreasing groundwater quality from the head to the tail of the distributary command area.

METHODOLOGY AND DATA COLLECTION

Seven watercourses in Mananwala Command Area and 7 watercourses in Karkan Minor Area have been selected by IIMI for the collection of data on surface water and groundwater and form our basic sample. The sampled area is equal to approximately 1,770 ha (12 percent of the area) for Mananwala Distributary and 1,410 ha (15% of the area) for Karkan Minor. At some points of the analysis, data collected for other watercourses have been included to gain a more complete picture of the situation.

Private tubewells of sample watercourses have been monitored since 1989 for different periods of time. Hours of operation, hours sold or given to other farmers, discharge and groundwater qualities form the main data set which will be used for this study. Emphasis will be given to two seasons, Kharif (summer season) 1990 and Rabi (winter season) 1990-91. The characteristics of the tubewells (location, source of power, type of pump, etc.) have been collected through a private-tubewell census of whole watercourse command areas. This information was complemented during the Rabi 1992 season by interviews of tubewell owners to understand their management and their participation in groundwater markets. Some of the methods used to collect private tubewell information are described and discussed in Appendix III.

Data on surface water have been collected at distributary and watercourse levels. Crop surveys for a few sample watercourses have been conducted as well in order to estimate the impact of the current pattern in water supply on the agricultural production. In 1992, 100 farmers of 30 watercourses were interviewed to gain a better understanding of the farming system in the area and of the constraints faced by farmers for their agricultural production.

Secondary data used in this study have been provided by the Irrigation Department (characteristics of the irrigation system, cropping intensities at watercourse and distributary levels, operation of the public tubewells) and by WAPDA (characteristics of public tubewells and groundwater qualities).

The next chapter will give a picture of the tubewells in the area and this looks first at the development and operation of public tubewells before focusing on the private tubewells which are far the most important both in terms of number of tubewells and in terms of quantity of water supplied to farmers for irrigation purposes.

Tubewell Development and Operation

PUBLIC TUBEWELLS: HISTORY AND CURRENT OPERATION

In 1959, the Government of Pakistan, with financial and technical assistance from the United States, began an ambitious program to alleviate waterlogging and salinity problems under the Salinity Control and Reclamation Projects (SCARPs). The main objective of this program -- via the installation of large deep public tubewells -- was to control waterlogging and salinity by providing vertical drainage. Increasing cropping intensities and agricultural production, capitalizing on the economies of scale in pumping technology and reducing the inequity in access to groundwater were other aspects considered in the projects.

Mananwala Distributary and Karkan Minor fall within the area of the first Salinity Control and Reclamation Project Large and deep public tubewells were installed here in the early sixties at the head of the watercourse command areas. The water pumped by the public tubewells, operated by the Provincial Irrigation Department staff, is mostly mixed with canal water. The turns for the use of public tubewell water are the same as defined by the canal water warabandi.

All the public tubewells are electric tubewells, with an average bore depth of 90 meters (or 300 feet) and an average discharge of 55 l/s (or 1.9 cusecs). The main difference between public tubewells is their water quality, ranging from 0.9 dS/m to 2.42 dS/m for public tubewells located in Mananwala commands and from 0.9 dS/m to 4.1 dS/m for the ones located at the head of Karkan watercourses. For both channels, public tubewell water quality is decreasing from the head to the tail of the canals, following the general trend presented in the second section of the previous chapter for the average EC calculated for sample watercourses.

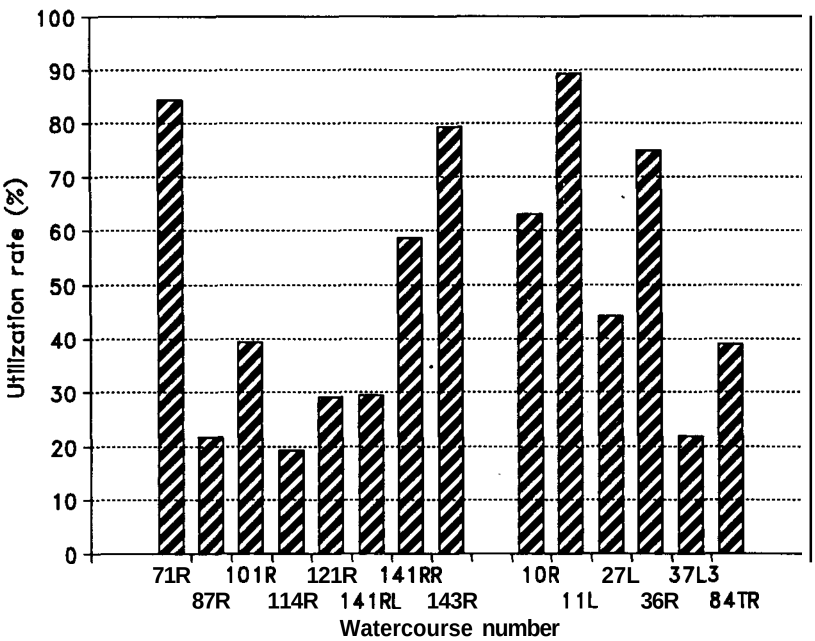
The performance of these public tubewells was good at the beginning of the project, adding a significant amount of irrigation water to the already short canal water supply. The life of most of these public tubewells, however, has been much shorter than expected and their performance rather low. The low level of maintenance and management of these public tubewells (despite the huge amount of money allocated by the Government of Pakistan to their Operation and Maintenance. See Anson 1983) is the main factor explaining the decreasing performance of SCARP tubewells. Data collected by the Tubewell Wing of the Provincial Irrigation Department for the whole SCARP-I area, for example, show that the average utilization rate[3] for SCARP-I public tubewells has decreased from 70 percent in 1960 to less than 45 percent in 1985. Because of this, the Government of Pakistan has decided to disengage from groundwater resources exploitation and transfer that responsibility to the private sectors through a SCARP Transition Project.

[3] The utilization rate is the ratio of the average daily hours of operation for a given period divided by 20 hours. Twenty hours (giving a utilization rate of 100%) are assumed to be the maximum a tubewell can be operated per day, with the 4 remaining hours required for maintenance, repairs, etc.

Data on public tubewell operations collected in the sample area confirm that the utilization rate for public tubewells is rather low and close to 50 percent. The deterioration of the discharge of the public tubewells is the second factor to be considered in their decreasing performance. On average, the design discharge of a public tubewell was 70 **l/s** or **150** percent more than the design discharge of the surface water outlets. Now, with an average of ***55*** l/s, public tubewells supply 20 percent less water than originally designed for a given number of hours of operation. The lowering of the water table is certainly one factor explaining the decrease in the public tubewell discharges.

The variability within the public tubewell population is however large as presented in Figure 2, the utilization rate varying from 20 percent only (Mananwala Watercourse **114R)** to slightly less than 90 percent (Karkan Watercourse 11L)

Figure 2. Utilization rate of public tubewells (sample watercourses).



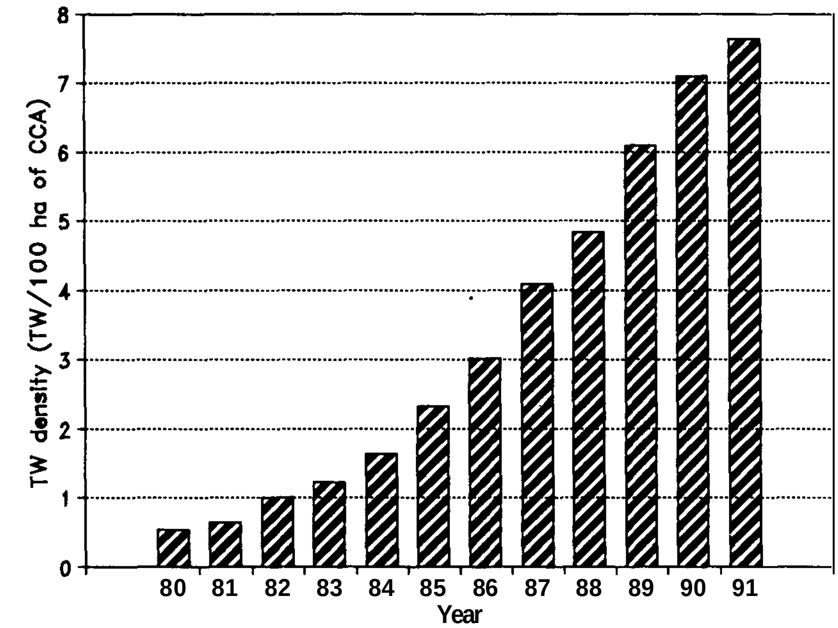
The performance of the public tubewells is slightly better in Karkan area ***(55%)*** than in Mananwala area **(45%)** for the whole year and also for most of the months of 1990-1991. The difference between the public tubewells of the two channels is particularly significant during Kharif. The variability over time, however, is higher for Karkan public tubewells. While Mananwala public tubewells have a lower performance in terms of utilization rate (and quantity of water supplied), the reliability of their water supply seems to be better than for Karkan ones. No clear explanation has been found for the difference in operation of public tubewells of the two areas .

No correlation was found between the quantity of canal water supplied to the sample watercourses or the water quality of the public tubewells and the utilization rates (used as a proxy of performance). Cooperation among farmers within a watercourse and relations between operator and farmers would be important aspects to be considered in an in-depth analysis of the performance of public tubewells.

PRIVATE TUBEWELL DEVELOPMENT..

The decreasing performance of the public tubewells, that currently supply only **40** percent of the quantity of water they were designed for, is certainly one of the factors that had a positive impact on the development of private tubewells in the area. This development started in the mid-sixties in Mananwala and Karkan commands, well before the start of the **SCARP** Transition Pilot Project. The private tubewell development remained slow for the first **15** years. The average number of private tubewells per watercourse command area was lower than **2** until **1980. A** dramatic increase took place during the eighties (see Figure **3).** There were **75** private tubewells in **1985 (2.2** tubewells/100 ha of **CCA)** and **225** in **1990** (or **7** tubewells/100 ha of **CCA)** in the sample area of 14 watercourses of Mananwala Distributary and Karkan Minor. The highest increases in the number of private tubewells have taken place in **1987** and **1989,** with **40 (+30%)** and **32 (+20%)** private tubewells, respectively, installed during these years.

Figure 3. Private tubewell development in Mananwala Distributary and Karkan Minor Area.



Private tubewell development, however, has not been homogenous in the sampled area. Differences exist among watercourses. Development has been more important first in the head and tail watercourses, reaching a threshold in **1987 - 1988.** For watercourses from the middle reach of the distributary, the main phase of private tubewell development has been delayed by **4 - 5** years and is still under way.

The similar development for head and tail watercourses is an interesting one because they face a completely different canal water supply in terms of quantity and reliability. The comparison between the reaches of the sample watercourses themselves, however, did not show any significant difference between the development of private tubewell in head, middle and tail reaches of the watercourses.

It is interesting to note that the installation of private tubewells is mainly undertaken during Kharif when crop water requirements are at their peak (more than 50% of the tubewells have been installed during the months of May, June and July). Unexpected shortages of water, most likely to appear during this period, could be the factor pushing farmers to invest in tubewells at this time of the year.

About 50 percent of the tubewells are driven by diesel engines, both high and slow speed. Thirteen percent of the tubewells are electric and **37** percent are Power-Take-Off (PTO) tubewells operated by tractors. The average bore-depth calculated for each source of power does not show any significant difference among power sources[4] (see Table 1). PTO tubewells have, on average, a higher discharge than electric and diesel tubewells. But this difference was not found to be significant either.

Table 1. Bore-depth and discharge of private tubewells per source of power.

Power source	Bore-depth (m)	Discharge (l/s)
Electric	29	25
Diesel	31	23
PTO	32	31
Average	31	26

The decision to purchase a tubewell with a specific source of power is influenced by the investment capacity of the purchaser, his potential tubewell water use (related to his cropping pattern and the supply of irrigation water from other sources), the presence of electric lines in the neighborhood, tractor ownership, etc. Electric tubewalls are found in only 8 of our sample watercourses, at the head and at the tail of Mananwala Distributary and at the head of Karkan Minor.

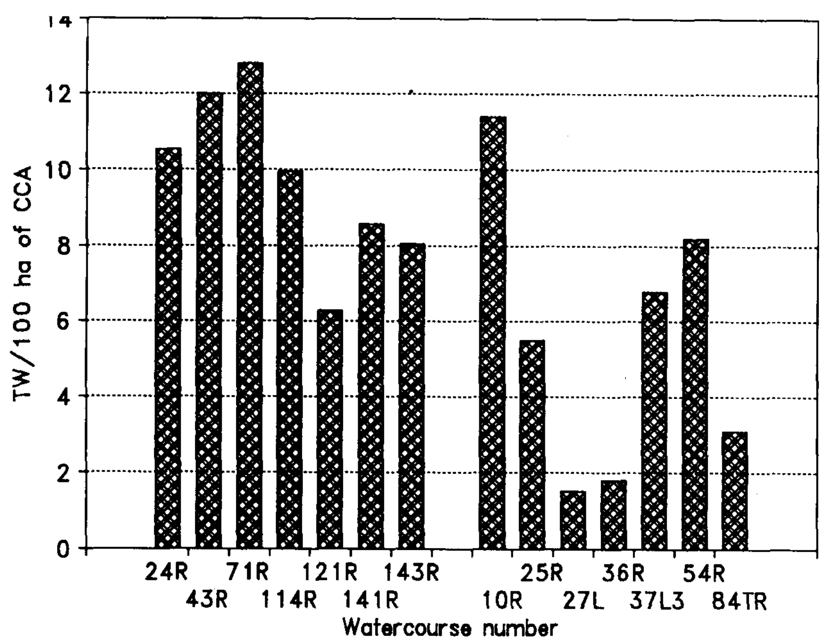
Farmers with large landholdings, for example, choose electric tubewells with comparatively high investment costs but with low operation costs while medium-size farmers would opt for a diesel tubewell. Tractor owners prefer generally PTO tubewells (with the lowest investment costs) but consider it as a temporary arrangement in order to stage investment costs. They often convert their tubewells into diesel or electric tubewells to avoid the competition between tractor use for tubewell operation and for other farm activities, and to decrease their tubewell operation costs.

[4] The analysis of the bore-depth location-wise has shown that there is no trend in bore-depth from the head to the tail of the canals.

The aggregated tubewell density is equal to 7.6 tubewells per 100 ha (1992) for the sampled areas of the two channels.' Private tubewell density is on average higher for Mananwala watercourses than for Karkan watercourses, with 9.7 and 5.2 tubewells, respectively, per 100 ha of CCA for the two channels. Canal water allocations, higher for Karkan Minor than for Mananwala Distributary, could explain this difference. However, comparisons between the current canal water supply of the two canals show that, although Karkan Minor is better off than the equivalent tail of Mananwala Distributary, there is no significant difference between the canal water supplied to Mananwala Distributary and Karkan Minor. Differences in cropping pattern (a lower percentage of the area under rice crop in Karkan Command Area) could be one factor explaining differences in tubewell density. However, the relationship between cropping pattern and tubewell density is rather complex. It is not clear whether crops and their expected economic returns influence the decision of farmers to invest in private tubewells or whether the installation of private tubewells provides further opportunities to grow crops like rice which not only have high water requirements but would in turn impact on the cropping pattern. It is expected that in the present dynamic economic and physical environment faced by farmers, the two causal relationships coexist.

Differences in tubewell density among watercourses are relatively high, ranging from 1.5 tubewells/100 ha for Karkan 56R watercourse to nearly 14 tubewells/100 ha for Mananwala Watercourse 71R as presented in Figure 4. Figure 4 does not show any clear correlation between tubewell density and position along the distributary (used as a proxy of the canal water supply). Several environmental (water table depth, groundwater quality) and economic factors influence the installation of private tubewells by farmers, sometimes in opposite directions.

Figure 4. Private tubewell density in sample watercourses.



5 A tubewell census has been undertaken in the 26,800-ha of Mananwala Command Area at the end of 1992. The average tubewell density for the whole area is equal to 6.9 private tubewells for 100 ha of CCA, quite similar to the average intensity calculated for the 14 watercourses.

A simple regression analysis was performed to correlate tubewell density at a watercourse level with the average groundwater quality and the average Delivery Performance Ratio (DPR)[6] calculated for each season or for the year. The best linear relation was found between tubewell density and the average EC as given below.[7]

$$TW = 14.6 - 3.3 * EC$$

where TW = watercourse tubewell density (tubewells/100ha)
EC = average groundwater electrical conductivity (dS/m)

($R^2 = 0.64$; No. of observations = 12; degrees of freedom = 10; both coefficients significant at a **5** percent probability level).

This relation shows the negative impact of groundwater quality on the tubewell density for the sample watercourses. The analysis also showed the negative relationship between average DPR and tubewell density as would be expected: with a higher DPR (thus a better canal water supply), farmers have less incentives to invest in private tubewells. However, this correlation was not significant at a 10 percent probability level. The absence of a significant relationship between the density of private tubewells and the supply of canal water has also been highlighted by Murray-Rust and Vander Velde (1992). They did not find any apparent relation between the installation of private tubewells and the location along the distributary, used in their paper as a proxy for the level of the canal water supply.

The negative impact of both average EC and average DPR would explain why no real trend in tubewell density is found from the head to the tail of Mananwala Distributary for example. The increasing EC values and the decreasing DPR play opposite roles, their marginal impacts on the tubewell density compensating each other. At this stage, the analysis with a larger number of watercourses with their tubewell densities and average EC would be needed to further substantiate there results.

PRIVATE TUBEWELL OWNERSHIP

Sixty-five percent of the private tubewells are owned by individuals. Out of the 35 percent of tubewells owned by shareholders, the majority is the property of several members of the same family (usually brothers). The information available on the ownership status of tubewells for Karkan Minor shows that there are more tubewells on a share basis in the middle and tail command areas than at the head end. The Mananwala data set, however, did not confirm this trend. Although the percentage of single owners is lower for diesel tubewells (see Table 2),[8] the difference was not statistically significant (Chi2 test).

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6 The average DPR is used as a proxy for the exact quality of canal water supplied to a specific watercourse. It is expected to be a better proxy than the position along the distributary or the RD number of the watercourse.

7 Two recent watercourses (25R and 27L) from Karkan Minor were excluded from the analysis.

8 Percentages calculated for 143 out of a total of 223 private tubewells.

Table 2. Ownership status and tubewell power source (in %).

Ownership status	Electric	Diesel	PTO
Single	73	56	67
Multiple	27	44	33

A few tubewells are abandoned every year. In the sample areas of Karkan Minor, for example, seven tubewells have been abandoned. The main reasons reported by farmers and observed in the field are physical or technical (bore failure, unsuitable water, improper tubewell location, etc.). However, social and economic factors have to be considered as well. Conflicts among shareholders of a single tubewell, for example, can lead to the abandonment of the tubewell. The problem of credit and cash availability for buying expensive spare parts is another reason for private tubewells to be abandoned.

OPERATION OF PRIVATE TUBEWELLS

The highest utilization rate for the 12-month period considered has been recorded for an electric tubewell located in Mananwala 24R watercourse command area: this tubewell has been operated 5,500 hours equivalent to a utilization rate of 77 percent. However, it can be considered as an exception, the average utilization rate calculated for the 223 private tubewells of the sample watercourses being less than 10 percent (9.4%) ! 124 tubewells (or 55% of the sample) have a utilization rate lower than 5 percent and 52 tubewells (or 23% of the sample) between 5 percent and 10 percent. The frequency distribution of utilization rates per source of power highlights that while most of the PTO and diesel tubewells have utilization rates lower than 10 percent, electric tubewells show a more homogenous frequency distribution between 10 percent and 70 percent (see Figure 5).

With a less skewed frequency distribution, electric tubewells have, on average, a much higher yearly utilization rate (40%) than diesel (6%) and PTO tubewells (3% only). The utilization rate is also higher for tubewells with multiple ownership than for tubewells with one single owner. A regression analysis for 143 private tubewells gives us the relation between the number of hours of operation for the 12-month period as a dependant variable and the source of power and the ownership status as independent variables. The linear relation found is given below.

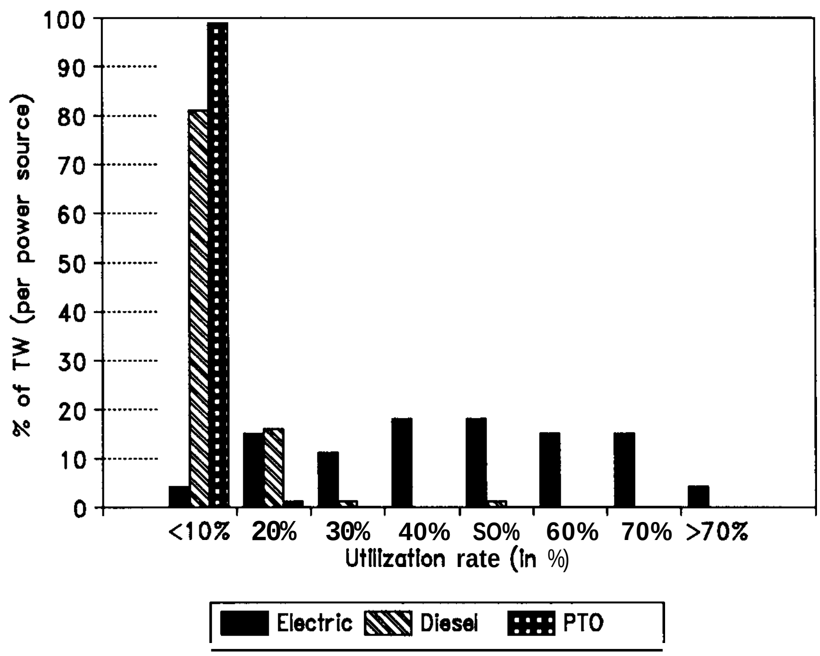
$$\text{Hours} = 540 + 1{,}675 * \text{Power} - 248 * \text{Owner}$$

Where Hours : hours of operation for the 12-month period.
Power : dummy variable, equal to 1 for electric tubewells and equal to 0 otherwise.
Owner : dummy variable, equal to 1 if single owner and equal to 0 otherwise.

(R^2: 0.53; number of observation = 143; degrees of freedom = 140; all coefficients significant at 5% probability level)

The estimated coefficients explain that, on average, electric tubewells will be operated 1,675 hours more than diesel and PTO tubewells. The higher utilization rate of electric tubewells was expected (but perhaps not with this amplitude), due to their lower O&M costs (see for example, Kuper and Strosser 1992).

Figure 5. Utilization rate of private tubewells: Frequency distribution per source of power.



Tubewells belonging to shareholders will be operated 200 hours more than tubewells belonging to a single owner. The difference remains, however, quite small. Although the number of users is much higher for the former, the number of hours of operation remains quite low, certainly due to the fact that the size of the landholdings of the shareholders is smaller than that of single tubewell owners. The difference between the operation of tubewells belonging to single owners and shareholders is more significant for diesel tubewells than for electric and PTO tubewells.

The period of the year is an important factor influencing the operation of private tubewells. Private tubewells operate more during Kharif, when crop water requirements are high. Differences between months are important, from less than 20 hours in April (equivalent to a utilization rate of 3%) to nearly 120 hours in August (utilization rate of 20 percent). The comparison between locations shows that, on average, tubewells are operated more in Mananwala Command than in Karkan Command. This trend is valid for every month but November as presented in Figure 6.

Differences between the two areas could be related to the higher percentage of electric tubewells, the higher percentage of rice and the lower public tubewell utilization rate in Mananwala command area than in Karkan area. However, the canal water supply, similar for Mananwala Distributary and Karkan Minor, does not explain differences in the operation of the private tubewells from the two areas.

Large differences in tubewell operation exist from one watercourse to the other. For Mananwala Distributary (see Figure 7), tubewells located within head and tail reaches of the distributary are operated more than those located at the middle reach of the distributary. Watercourse 24R, with more than 2,500 hours of operation per tubewell per year represents a real exception in our watercourse sample. On the other side of the scale, tubewells located within 114R watercourse command are operated less than 200 hours per year. A similar but less clear trend is found for Karkan sample watercourses from the head to the tail.

Figure 6. Average monthly operation for private tubewells: Mananwala Distributary versus Karkan Minor.

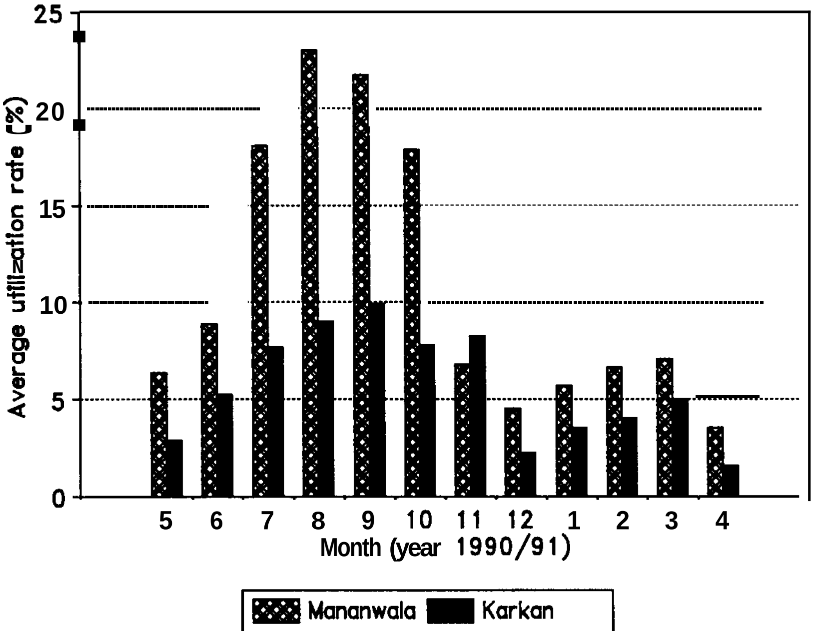
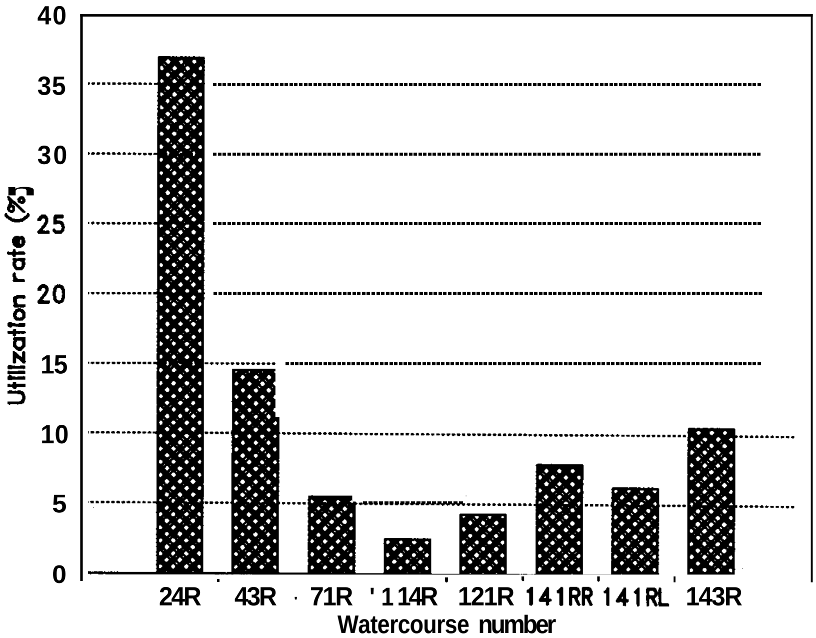


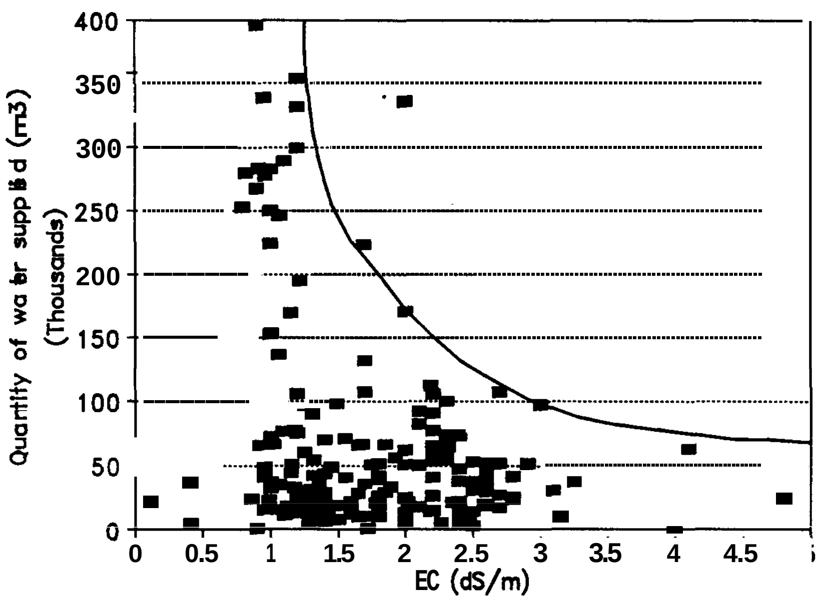
Figure 7. Location along Mananwala Distributary and private tubewell operation.



As for the tubewell density, it is difficult to explain differences between watercourses by differences in canal water supplies. It appears, however, that the lower utilization rate of private tubewells in the middle reach is related to the higher percentage of PTO tubewells with very high operating costs while electric tubewells with low operating costs and a higher utilization rate are located in head and tail watercourses. There is a strong correlation between the percentage of tubewells from different power sources and the average operation of tubewells. In our sample, **85** percent of the variation in average tubewell operation per watercourse is explained by different percentages of electric tubewells in the sample watercourse command areas.

Regression analysis showed that there was an inverse (but nonsignificant) relationship between operation and groundwater quality of a specific tubewell. As shown in Figure 8, the quality of tubewell (EC **as** a proxy) water plays the role of a constraint limiting the operation of private tubewells. When the groundwater quality is low (high EC values), tubewells do not operate for more than a certain limit, this limit decreasing when EC values increase. When the groundwater quality is high (low EC values), tubewell owners do not consider it **as** a constraint and other factors explain differences in tubewell operation. A similar but stronger trend is observed when considering only Karkan Minor tubewells with average lower groundwater qualities. For tail watercourses of Karkan Minor, a significant and inverse relationship exists between water quality and tubewell operation, explaining more than **25** percent of the differences recorded in the operation of private tubewells.

Figure 8. Tubewell operation versus groundwater quality (187 private tubewells, Mananwala Area).



Canal water supplies have an impact on the operation of private tubewells in the different watercourses. However, the main factors explaining differences in private tubewell operation are the source of power of the tubewells and the cropping pattern (thus the crop water requirements) of a specific area. The correlation between these two variables (source of power and cropping pattern) is recognized but its nature (which one influence the other ?) is not yet clear.

The conjunctive use of canal water and tubewell water is considered in the next chater, by aggregating surface water and groundwater supplies at watercourse level. To be able to analyze the conjunctive use at a micro-level (farm or area served by a specific tubewell), a more in-depth analysis would be needed, which goes beyond the scope of this present study and the available data set. Tubewell location and source of power, localized cropping pattern and tubewell density, and supply of canal water considering water losses within watercourse command areas, would be important factors to be taken into account.

Management of Groundwater Resources

CONJUNCTIVE USE OF SURFACE WATER AND GROUNDWATER

Canal irrigation has become insufficient to meet the present-day water requirements of increased cropping intensities. Therefore, farmers are left with no choice but to supplement the surface supplies with groundwater. The growth of groundwater utilization which started, some 3 decades back, at a very slow rate, has now become an overwhelming part of the total irrigation water.

For the sample command areas of Mananwala and Karkan the share of groundwater was more than 60 percent of the total irrigation supplies during Kharif 90 and Rabi 90/91 seasons. While the groundwater supplies for Kharif are 65 percent higher than for Rabi, it is interesting to note that the ratio of groundwater to surface water supplies remained the same for the two seasons. Differences exist between the two channels, Mananwala Distributary and Karkan Minor, and between watercourses supplied by these two canals.

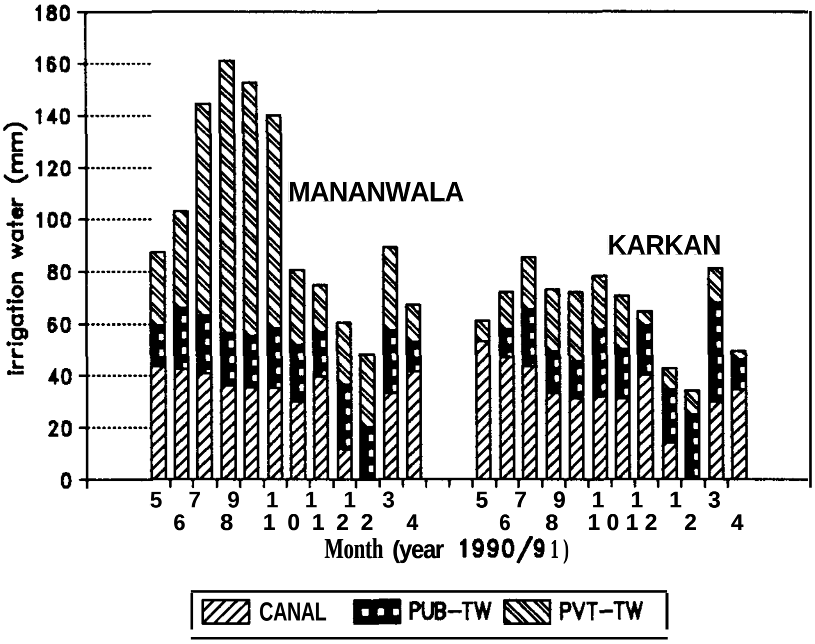
First, the total quantity of irrigation water allocated to the CCA is higher in Mananwala area than in Karkan area (see Figure 9). With similar cropping intensities for the two areas, the main explanations for this difference would be a higher percentage of rice crop in Mananwala area and the lower groundwater quality in Karkan area limiting private tubewell operation.

Second, with a rather regular canal water supply over time,[9] the main changes in the total quantity of water supplied to the two areas are related to the operation of tubewells. When looking at the percentage of irrigation water coming from the different sources the same trend over time is found for the two channels. August and September, the period of the year with the highest crop water requirements due to the rice crop, are the months with the highest share of groundwater supply (around 80% and 60% of the total supply for Mananwala and Karkan) and private tubewell supply (65% and 40% of the total supply for Mananwala and Karkan). April, harvesting time for wheat crop, is the month with the lower share of groundwater and lower private tubewell supply.

Third, private tubewell water supplies and groundwater supplies have a greater importance in terms of percentage of the total irrigation water supplies in Mananwala Distributary than Karkan Minor Area. The difference is particularly significant for Kharif, with groundwater supplies amounting to 70 percent of the total supply in Mananwala Command versus only 45 percent in Karkan Command. The lower average groundwater quality in the earlier area would be one reason why farmers in the Mananwala Area use their groundwater resources more intensively.

[9] The significantly lower canal water supply of the January-February period is due to the closure of the canal irrigation system for its annual maintenance by the Provincial Irrigation Department.

Figure 9. Monthly irrigation water supply: Mananwala Distributary and Karkan Minor.



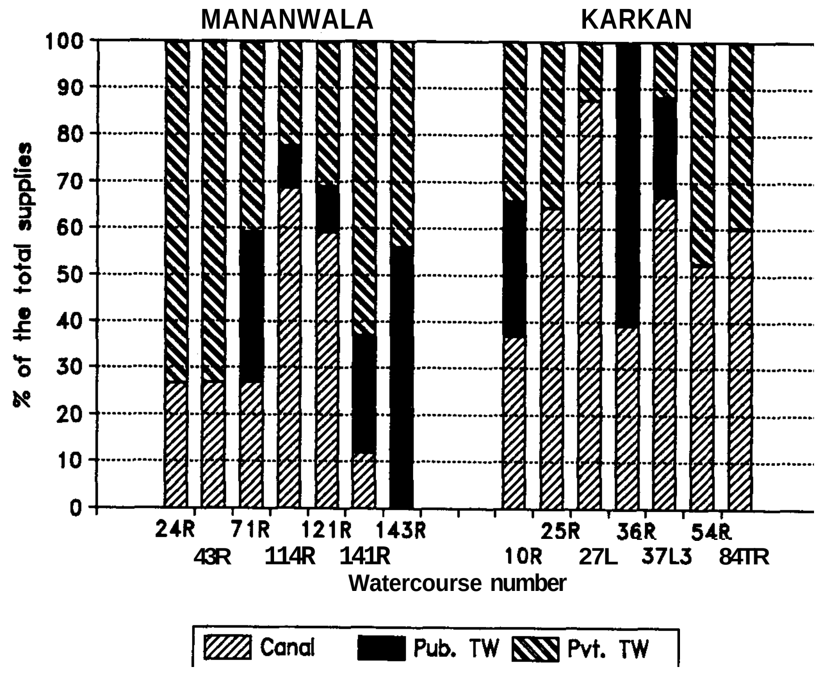
The variation between watercourses is relatively high, in terms of total quantity of irrigation water used by farmers as well as in terms of relative share from the three different sources, particularly for Kharif. Differences in cropping intensity and in percentages of cropped area under rice and orchards partially explain differences among watercourses.

It is difficult to find a significant trend in the quantity of irrigation water supplied by the three sources from the head to the tail of the channels. For example, the quantity supplied to Mananwala 143R is higher than that supplied to Mananwala 43R of the head reach of the canal. Differences between watercourses are mainly related to differences in cropping pattern and in the source of power of private tubewells (as explained in the previous section).

The relative importance of private tubewell supplies decreases from the head reach to the middle reach of the two channels and then increases again towards the tail area as shown in Figure 10 for Kharif 1990.[10] There is no trend for the aggregated groundwater supply (public and private tubewells) mainly due to the high variability of the public tubewell performance from one location to the other.

[10] A similar trend but with a lower percentage for private tubewells is observed for Rabi as well.

Figure 10. Sources of irrigation water supply for.sample watercourses (Kharif 1990).



The high percentage of groundwater use at the head is related to the higher utilization rates of private electric tubewells, while at the tail, it is related to both the presence of electric tubewells and the extremely low canal supply. Mananwala **143R** is an extreme case where the total irrigation water is supplied by tubewells during Kharif.[11] Watercourses at the tail of Karkan have a relatively high percentage of their supplies coming from canal water, due to a better performance of Karkan tail compared to Mananwala tail as reported by Van Waijjen **(1992).** Another extreme situation is Karkan **36R** watercourse where private tubewells (all PTO) have not supplied any water during the two seasons considered. The relatively good performance of the public tubewells of this area could explain that tubewell owners did not need to supply their crop with expensive private tubewell water.

Irrigation water supply data collected by IIMI for **4** Mananwala watercourses and for **5** consecutive seasons (from Kharif **89** to Kharif **91)** are presented in Appendix **4.** For Mananwala **121R,** with a very low area under rice crop during Kharif and **a** relatively good canal water supply, private tubewells are mostly used to mitigate undesirable fluctuations in the public (canal and public tubewells) irrigation water supply and thus to play a stabilization role. In the other watercourses with a higher discrepancy between crop water requirements (more rice) and the public water supplies, the primary role of private tubewells is to increase the total quantity of irrigation water (it is specially clear for Mananwala **24R** and Mananwala **143R),** the stabilization process taking a secondary role.

[11] During the Rabi season, canal water performs slightly better for this watercourse with **4** percent of the total irrigation water supply.

The share of groundwater supplies in Mananwala 24R has been constant for the Kharif seasons (close to 75%) while an increase (from 52% in 89/90 to about 70% in 90/91) has been reported for the Rabi seasons. With similar rainfall for these seasons, changes in the relative profitability of crops with different crop water requirements could explain changes in groundwater use. For Mananwala 121R, the share of groundwater has decreased, from 52 percent of the total in Kharif 89 to 42 percent for the next two seasons. The Rabi seasons have seen the opposite trend, the percentage of the groundwater increasing from 15 percent to 42 percent of the total irrigation water supply. The growing importance of vegetables in this part could be the main reason for these changes but several seasons would be needed to further assess this trend. For the whole period, the tail command area (Mananwala 143R) has received more than 95 percent of its imgation water from groundwater resources.

IRRIGATION WATER MANAGEMENT AND SALINITY-RELATED ISSUES

As described in the previous section, groundwater quality has an impact on the tubewell intensity and the operation of private tubewells. In the context of the sustainability of the agriculture in the area, however, not only the quality of one specific source (in this case private tubewells) but also the average quality of irrigation water applied by the farmers to their crops" has to be considered.

The average EC values have been calculated for the sample watercourses and aggregated for the two canal areas. The average EC values for Kharif and Rabi seasons are respectively 1.11 dS/m and 1.07 dS/m for Mananwala and 0.89 dS/m and 1.14 dS/m for Karkan. Differences from one season to the other follow changes in the percentage of groundwater out of the total quantity of imgation supplied to the two canals. At this aggregated level, values calculated are all lower than (but close to) the 1.15 **dS/m**[13] limit which is used as an acceptable limit for the irrigation water supply.

The comparison between values calculated at watercourse level for the two seasons shows that average EC values are higher during Kharif than during Rabi for all but one of the Mananwala watercourses, Watercourse 121R (see Figure 11). For Karkan Minor, half of the watercourses follow the same trend. A higher EC value for Kharif is found for watercourses that record a high percentage of the area under rice. The highest EC values, much higher than the acceptable 1.15 dS/m, are found for the three tail watercourses of the two channels. With 2.09 dS/m and 2.02 dS/m for Kharif and Rabi, respectively, Mananwala Watercourse 141R has the worst position regarding irrigation water quality.

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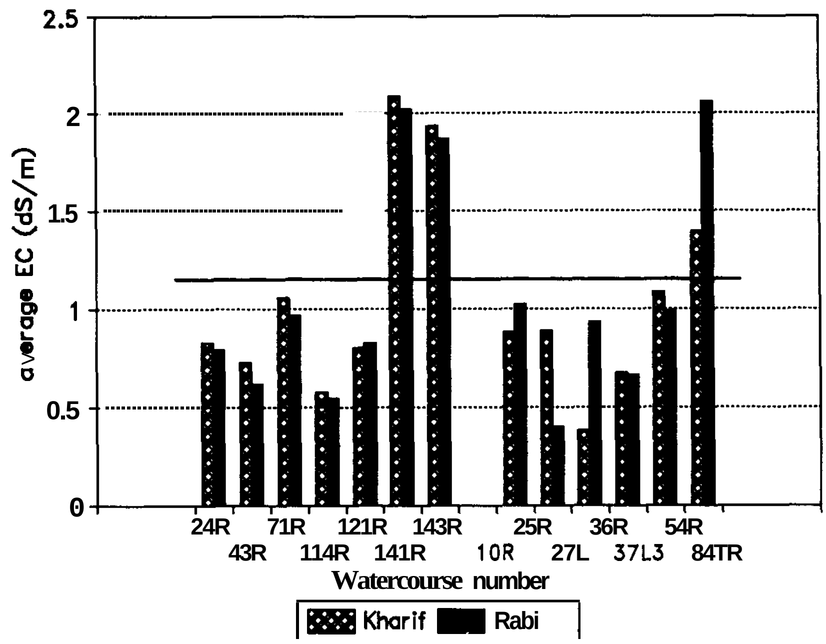
12 The timing of the application of water of different qualities at different critical growth stages of the crops would also be an important aspect to be included in the analysis. It has not, however, been included in the present study.

13 1.15 dS/m is the limit value adopted by the Punjab Agriculture Department. However, more conservative values for this limit are used by the Directorate of Land Reclamation of the Punjab Irrigation Department (1.0 dS/m) and by the Food and Agriculture Organization (0.7 dS/m).

Figure 11. Average EC values of irrigation water (Mananwala Distributary and Karkan Minor watercourses).



With higher losses to be accounted for canal water than for tubewell water, the average EC values of the irrigation water available at the root zone of the crops are expected to be even higher than the values calculated at a watercourse level and presented in this paper. Moreover, if the 0.7 dS/m value proposed by the Food and Agriculture Organization is used instead of the 1.15 dS/m adopted by the Punjab Agriculture Department, the average irrigation water quality (EC in our case) is problematic for as many as 11 watercourses out of a total of 14 !

The comparison between watercourses highlights that where canal water supplies are comparatively better (watercourses from the head and middle reaches of the canals), farmers are in a position to maintain their average irrigation water quality within an acceptable range. When surface water is not available anymore, farmers have to pump tubewell water, whatever its quality, in sufficient quantities to irrigate their crops and to be able to live with their farming activities. An interesting aspect is the EC values for the first head watercourse of Mananwala Distributary 24R, higher than what could be expected. Although this watercourse has a good canal water supply, farmers use their electric tubewells intensively leading to an EC value of 0.8 dS/m for their irrigation water.

The mixing of canal and tubewell water is of particular importance in view of the potential hazard of soil salinization resulting from marginal groundwater quality. Most of the tubewell owners from the head reach of the distributary did not report a need to mix the two types of water. At the tail watercourses, however, where farmers would need to mix their tubewell water of poor quality with a certain amount of canal water, farmers use their tubewell water alone most of the time because canal water is not available in appropriate quantities or not available at all. Problems of secondary salinization and their negative impact of agricultural production are expected to be much more acute in these tail areas.

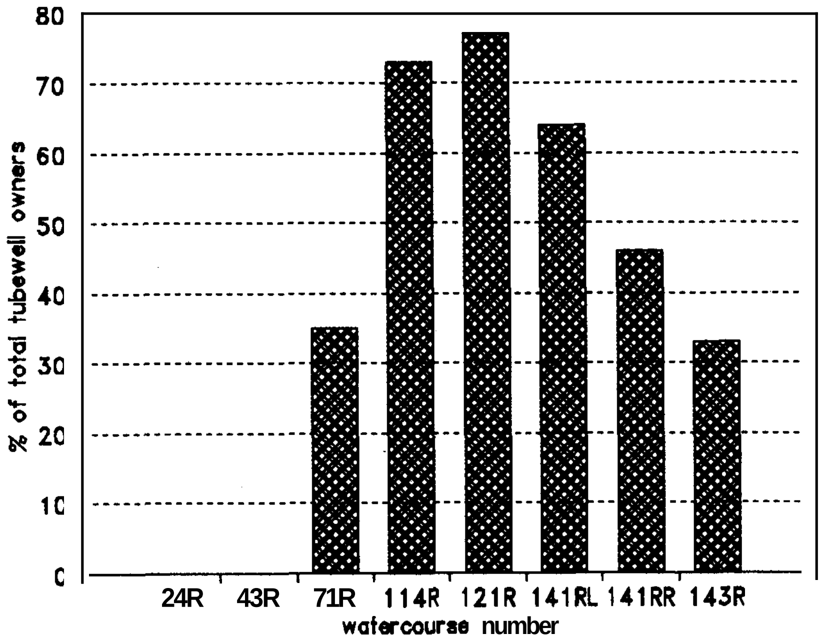
The problem of the quality of the groundwater does not only concern tubewell owners in Mananwala Distributary and Karkan Minor areas. Beside using tubewell water on their own land, tubewell owners sell water to other farmers in our sample watercourse command areas.

WATER MARKETS[14]

Most of the tubewell owners are not heavily involved in water sale and still use the bulk of the pumped water on their own fields. When asked whether they would supply tubewell water to their crops or sell it to needing farmers, nearly all of the tubewell water sellers reply that the first priority would be given to their own fields. However, the low number of purchasers per tubewell and the usually low utilization rate of the private tubewells allow most of the tubewell owners to sell water when demanded.

The percentage of tubewell owners selling water is higher for the middle watercourses than for the head and tail watercourses as illustrated in Figure 12. What is interesting is that the percentage of tubewell owners selling water is inversely related to the quantity of tubewell water supplied to the different watercourses. Tubewell owners, who operate their tubewells intensively to irrigate their own crops, would have less opportunities to sell water to potential purchasers.

Figure 12. Percentage of tubewell owners participating in water sales (Mananwala Distributary).



The number of hours sold per tubewell is influenced by the source of power. Electric tubewell owners participating in water sales sell, on average, more water than diesel and PTO tubewell owners. Differences in prices between the three sources of power mainly explain these differences (see price analysis below). However, it is not clear yet whether the higher level of water sales benefits a higher number of farmer-purchasers or not.

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[14] Data analyzed to answer issues related to water markets have only been collected in Mananwala sample watercourses.

Most of the water sales are paid for in cash in the area, at the time of the use of water or at the end of the season after the harvest of the crops. Only one case of sharecropping, involving a payment in kind, has been found in our sample of tubewell water transactions. What is interesting is that this sharecropping arrangement was used only for rice, much more dependant on irrigation, whereas tubewell water sold for irrigation of other crops (mainly wheat and cotton), was paid for in cash.

Prices of tubewell water are highly variable from one tubewell to the other. Over time, for a given season or even a year, however, prices remain constant. Relative changes of the water scarcity over a season (due to changes in crop water requirements and the variability of water supply from public sources) are not translated into changes in tubewell water price. The lower transaction costs could be one factor explaining a fixed price over time. Few tubewell owners reported differences in prices from one buyer to the other. Most of the time, these differences are related to blood or landlord-tenant relationships.

Tubewell owners rarely include investment costs in fixing the price of water but, contrary to the expectation, they seem to do it mainly when public irrigation water is more abundant (a larger set of data would be needed, however, to assess the significance of this statement). Differences in prices from one tubewell to the other are mainly explained by differences in O&M costs. The presence of electric tubewells selling water at a comparatively lower price seems to have an influence on the price of water sold by owners of adjacent PTO and diesel tubewells.

Tubewell discharge and source of power have been used as a proxy of the O&M costs and correlated with the price of tubewell water sold. The relation between these variables has been estimated for 75 tubewells selling water and is presented below.

$$P = 17 + 11 * Q - 10 * PS$$

with P = price of tubewell water (rupees/hour),
Q = discharge of the tubewell (cusecs), and
PS = dummy variable, equal to 1 for electric tubewells, 0 otherwise.

(R^2 = 0.33; No. of observations = 75; Degrees of freedom = 72; all coefficients significant at **5** percent probability level)

The positive correlation between price and discharge of the tubewell is according to what one could expect. Those owning tubewells with high discharges supply a higher quantity of groundwater per hour of operation and thus can ask a higher price from their purchasers. The negative sign of the estimated coefficient before the dummy PS translates the lower price charged by electric tubewell owners, due to their lower costs of O&M (Rs. 10 less on average than for diesel and PTO aggregated).

Some farmers of Mananwala Distributary Command Area report that groundwater salinity has an impact on the price of tubewell water. However, the quality (EC) of the groundwater did not prove to have a significant impact on the price of tubewell water.

Other factors (competition between tubewell owners related to a localized tubewell density, lining of watercourse increasing the number of potential purchasers, canal water supply along the watercourse, etc.) influence the price of water as well (it has to be noted that the R^2 of the above equation is only equal to 0.33).

Research undertaken by IIMI in another location in South Punjab (Strosser and Kuper 1993), for example, shows that the local density of private tubewells and the delay in paying the purchased water (equivalent to a short-term credit) are factors considered while setting the price of water. Meinzen-Dick and Sullins (1993) report an additional fee of Rs. **4** to Rs. 6 per hour in Faisalabad Area as a normal practice to cover the wear and tear on the engine. New data would be needed to further understand how farmers set their water prices in Mananwala Distributary Command Area.

Conclusions and Recommendations

Analysis of data collected in Mananwala Distributary and Karkan Minor Area has confirmed the importance of groundwater in the current irrigation environment of Pakistan. Public tubewells are no longer in a position to supply an adequate and reliable groundwater supply and most of the groundwater is provided by private tubewells. The role of the groundwater pumped by private tubewells for irrigation purposes is particularly important where farmers grow crops with high water requirements (such as rice) and where tubewell owners have installed electric tubewells with comparatively low operation costs.

The supply of groundwater by private tubewells has in fact two roles: first, to increase the imgation water supply and second to mitigate unpredictable fluctuations in the surface water supply. The second role seems to be predominant in the case of tubewells with high operation costs (PTO tubewells) and relatively good canal water supply as is the case for the middle watercourses of Mananwala Distributary. When canal water supplies are large and costs of operation of tubewells low (as in Mananwala 24R), the predominant role of the tubewells is to increase the irrigation water supply, and the role of tubewells for stabilizing the imgation water supply becomes secondary. For the tail watercourses, with hardly any canal water supply, tubewells are operated to provide imgation water as needed by the farmers for their farming system.

In the context of the unreliability of the canal water'supply and the stabilization role of the groundwater supplied by private tubewells, the relative overinvestment in private extraction devices as well as the low utilization rate of private tubewells have a certain rationale. Private tubewells are not operated as a separate unit but are included within the decision-making process of a farmer for his entire farming system. The stabilization role of the tubewells is a very important one, private tubewells being the equivalent of an insurance taken by the farmers to reduce their risk related to the unreliable canal (or public) water supply.

The dependance on groundwater supplies, especially at the tail of the canal irrigation system, increases problems related to secondary salinization in these areas. Tail watercourses have, on average, a lower irrigation water quality than head and middle watercourses, due to a poorer surface water supply as well as to a lower groundwater quality.[15] For three watercourses out of 14, the irrigation water EC calculated at a watercourse level was higher than the limit of 1.15 dS/m adopted by the Punjab Agriculture Department. Using the EC threshold (0.7 dS/m) proposed by the Food and Agriculture Organization, the irrigation water quality is problematic in 11 sample watercourses.

Farmers of these watercourses are under a serious threat for the sustainability of their agriculture. Although groundwater quality has a negative impact on tubewell density and constrains tubewell operation, farmers at the tail of the system do not have any choice apart from pumping brackish water to irrigate their crops and cultivate their land. In other watercourses, average EC values close to 1 suggest that secondary salinization could be avoided but only with an appropriate conjunctive management (over space and over time) of the different sources of irrigation water.

15 IIMI's research work in other areas has shown that the decreasing head-to-tail trend in groundwater quality could not be generalized to all secondary canals.

Of course, individual farmers are worse off than one would expect on the basis of the average figures. In fact, farmers face a variable environment within watercourses, with different canal water supply and variable qualities of tubewell water.

Results reported by Murray-Rust and Vander Velde (1992) suggest that farmers, operating relatively close to a Relative Water Supply[16] of 1, manage their water with some precision, adjusting their tubewell water supply to the canal and public tubewell supplies. With these values of Relative Water Supply and the problem of groundwater quality, the authors conclude, however, that ***it is not surprising then that secondary salinity is building up rapidly*** in tail areas with no water allocated by farmers for leaching of salts. Long-term monitoring of the irrigation practices of sample farmers, however, would be needed to establish the trend in secondary salinity related to the use of irrigation water of different qualities.

Another important issue which has not been addressed in this paper is related to the water table depth and the sustainability of groundwater extraction. Data collected by IIMI since 1989 at two reaches of Mananwala Distributary show that lowering of the water table seems to be a regular phenomenon over time.[17] In the long run, a decline in the groundwater level would increase pumping costs (especially for the tail farmers where depletion of the aquifer seems to be slightly faster) thus decreasing the demand for groundwater over time. This process would continue until the system reaches a steady state. The impact of this process, however, could be severe for small tubewell owners and small farmers and would have an impact on the agricultural production as well. The slower private tubewell development observed in the area for the last few years could have its origin in the depletion phenomenon of the water table.[18]

Problems of groundwater quality and water table depletion not only concern tubewell owners but nearly every farmer who purchases tubewell water. Water markets give access to groundwater resources to non-tubewell owners (mainly smaller farmers) and thus improve the equity in groundwater supply.[19] The supply of canal water (and its impact on the demand for extra irrigation water ?) and the tubewell power source have an impact on the development of water transactions among farmers. Prices paid by farmers are much higher than prices paid for canal water through the water rates or ***abiana*** suggesting that there could be a potential for increase in canal water charges, if canal water supply is made more reliable.

Three important aspects have now to be considered by researchers, line agencies staff, policymakers and funding agencies: the use and dissemination of research results, the monitoring of the conjunctive use environment and a new research agenda on conjunctive use in Pakistan.

IIMI's knowledge of the O&M of private tubewells has now to be used by public agencies and research institutes in their planning and project preparation. Several examples highlight this need.

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16 Defined as the ratio of the water supply to the demand.

17 A similar conclusion is found in the study on private tubewells undertaken by NESPAWSGI for the Government of Pakistan (Government of Pakistan 1991a). According to their data, the groundwater resources have already been overmined in Sheikhupura District where Mananwala Command Area is located.

18 The exceptionally high rainfall which has affected the country in 1992, has, however, partly recharged the aquifer as shown by more recent IIMI data, highlighting the importance of water table monitoring over a long period of time.

19 Khan et al. (1990) report that 48 percent to 60 percent of the farmers of the project and non-project areas were purchasing private tubewell water.

i) The "without project" situation of the SCARP Transition Pilot Project (STPP) (Government of Pakistan 1985) was based on a 3 percent yearly increase in the number of private tubewells for the period 1985-1988. The trend in tubewell development before 1985 presented in this paper for Mananwala Area suggests that much higher figures for the annual tubewell growth rate could have been used at the project appraisal stage. Most of the private tubewell development would have happened anyway without the STPP. Thus, the use of the 3-percent figure has led to an over-estimation of the economic indicators calculated for the STPP.

ii) The actual tubewell density used in the second SCARP transition project (Government of Pakistan 1991a) is 2.1 private tubewells per 100 ha of CCA, much lower than the average 7.6 value for 14 watercourses or the 6.9 value calculated **for** the 26,800 ha of Mananwala Command Area. Thus, figures related to the current pumpage by private tubewells have been under-estimated by at least 50 percent. If the expected target of 10 new private tubewells per public tubewell abandoned is reached, it will accelerate groundwater depletion in the area.

iii) Groundwater depletion has already been reported in the area in the study undertaken by NESPAK for the Government **of** Pakistan (Government of Pakistan 1991b). In their study, however, no PTO tubewell has been included. Thus, the problem of groundwater depletion in the area has been underestimated by 25 percent and would be even more acute than presented in this study.

Although water table and salinity are not directly related anymore as it was in the past (they were usually named the *twin* ***menaces),*** they are variables from the same conjunctive use environment and thus need to be monitored. With the importance of secondary salinization and the decline in water tables, a serious monitoring of the conjunctive use environment has to be included in the agenda in the context **of** a sustainable agriculture. Although important variables are already monitored by several institutions in Pakistan, the lack of coordination among institutions and their narrow approach of the conjunctive use environment are serious constraints for an efficient monitoring (Murray-Rust and Vander Velde 1992). Moreover, in the present situation, private tubewell data are not collected by any public agency.

Murray-Rust and Vander Velde (1992) propose three items for further research on conjunctive use, i.e., to determine realistic critical limits for surface water/groundwater ratios at different water qualities; to develop a model to predict salinity changes over time; to analyze factors other than water quality and location that affect farmer cropping choices in a conjunctive-based irrigated agriculture.

With 85 percent of the variation in tubewell operation explained by the percentage of electric tubewells (with lower O&M costs) in a specific command area, the present study suggests that economic variables (O&M costs, landholding size, etc.) have to be included in further work on tubewell O&M on farmer cropping choices and on environmental issues (water-table depletion, secondary salinization) directly related to tubewell operation and conjunctive use. It suggests also that a farm (or tubewell owner) level analysis would be required (and perhaps more appropriate) to further understand conjunctive use management by farmers and its impact on secondary salinization.

The impact of water markets on the agricultural production and on the environment (especially secondary salinization and water table depth) would have to be assessed as well. More research is needed to compare water markets and their impact on the quality of irrigation services offered to farmers (in terms of quantity, equity, reliability) with other ways of water allocation (as public tubewells or tubewells with multiple ownership).

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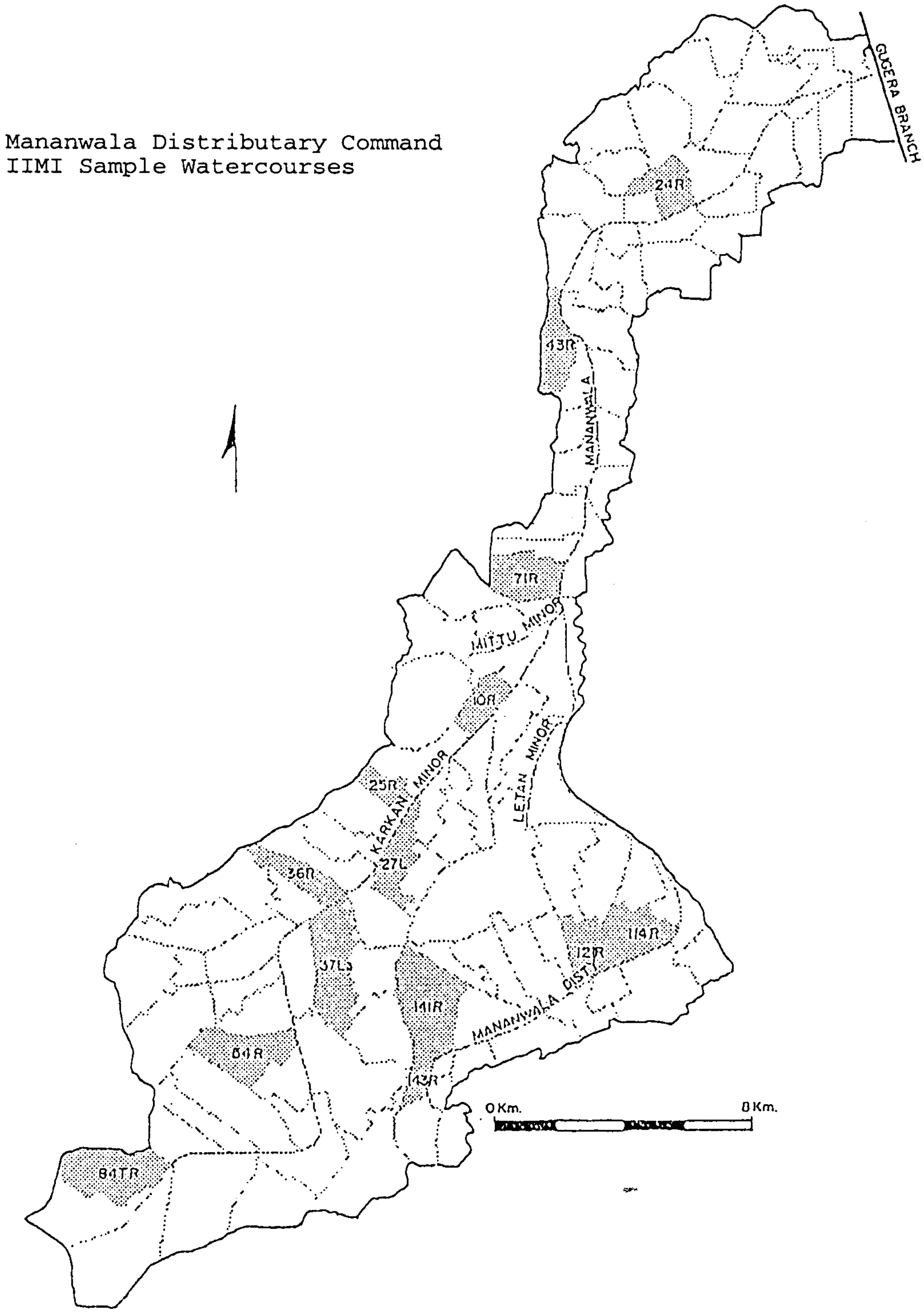
Appendix I

Map of the Research Area



Appendix II

Characteristics of Sample Watercourses

Mananwala Distributary

Watercourse number	Distance from head (km)	Design discharge (l/s)	CCA (ha)	Public tubewell	Private tubewell density (TW/100ha)
24R	7.4	24	171	No	10.5
43R	13.2	30	225	No	12.0
71R	21.7	38	289	Yes	12.8
114R	34.8	31	231	Yes	10.0
121R	37.0	34	255	Yes	6.3
141R	43.0	68	514	Yes (2)	8.6
143R	43.7	12	87	Yes	8.0

Karkan Minor

Watercourse number	Distance from head (km)	Design discharge (l/s)	CCA (ha)	Public tubewell	Private tubewell density (TW/100ha)
10R	3.2	31	158	Yes	11.4
25R	7.7	18	91	No	5.5
27L	8.2	35	200	Yes	1.5
36R	11.1	33	167	Yes	1.8
37L3	11.4	35	177	Yes	6.8
54R	16.7	46	232	No	8.2
84TR	25.7	77	388	Yes	3.1

Appendix III

Private Tubewell Data Collection

After *5* years of intensive research, IIMI-Pakistan has gained a good experience in the collection of data related to the management of private tubewells within a conjunctive use environment. The main objective of this short appendix is to describe the methods used by IIMI-Pakistan to collect primary data directly related to private tubewells and analyzed in the present study. Methods to collect data related to other aspects of the irrigation system (surface water or crop data for example) and used in this study will not be described here.

Data collection methods of IIMI-Pakistan field staff can be classified into three broad categories: (i) observation, (ii) measurement and (iii) interview. Most of the time, several methods are used to complement one another and improve the accuracy of the information collected. Direct measurements will have the first preference whenever possible. The following Table presents the three approaches used for the main variables describing the private tubewell environment in Mananwala Area.

Information	Data collection method
Basic characteristics	
. Location	Observation
. Power source	Observation and interview
. Technology	Observation and interview
. Investments costs	Interview
Tubewell water supply	
. Discharge	Measurement
. Operation	Measurement and interview
Tubewell management	
. Use of water at farm	Observation and interview
. O&M costs	Interview
. Water sales	Interview
Environmental variables	
. Groundwater quality	Measurement and interview
. Water table depth	Measurement and interview

The first step in the collection of tubewell data is a tubewell census of the sample watercourse command areas selected as basic sample units. Basic tubewell characteristics are collected through field visits and interviewing tubewell owners. The use of maps (canal ***patwaries*** or ***chukbandi*** maps) facilitates a clear identification and location of the private tubewells. Owner's name, location of the tubewell (distributary name, watercourse, square and ***kilu*** [field] numbers. Vander Velde and Johnson 1992. Appendix A.), date of tubewell installation and investment costs, bore depth, source of power, etc., are the main characteristics collected during the tubewell census.

Several methods exist to measure tubewell discharges. The quickest one is the trajectory method, giving a good estimate of the discharge when the tubewell delivery pipe is strictly horizontal and pipes are fully filled by the flow of water. An L-stick with a fixed Y-axis length gives an X-axis value directly proportional to the discharge. Flumes (earthen watercourse) and current meters (lined watercourses) can also be used to measure discharges. Comparisons between fluming and trajectory methods have shown that differences are not significant and that the less time-consuming trajectory method can be confidently used.

The source of power influences the choice of the method used to collect private tubewell operation.

(i) For electric tubewells with WAPDA electric meters in working conditions, a calibration of the meter (number of electric units for one hour of operation) gives the possibility to convert the reading of electric units into number of hours of operation. A regular calibration of the meter is however needed (at least once a month or after any major change in the motor size or suction pump setting).

(ii) For diesel tubewells, a vibration meter (small device recording the period of vibration) can be installed on the delivery pipe or preferably on some parts of the engine. The use of this device with other sources of power has been found less successful.

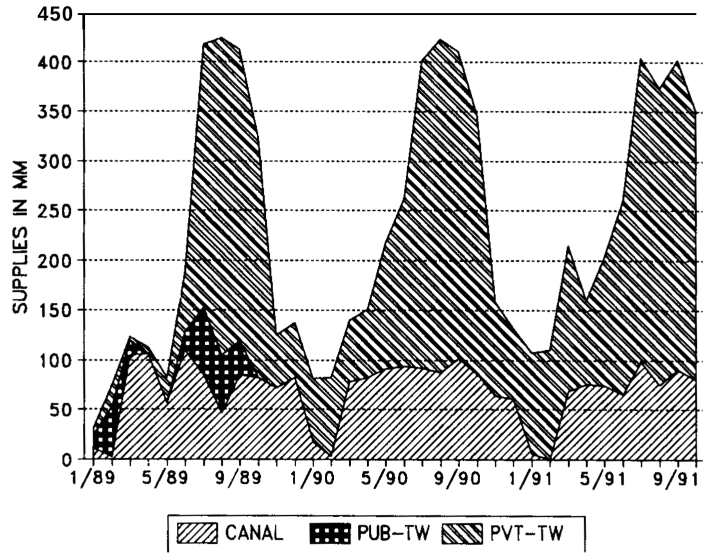
(iii) Interviews of tubewell owners have been used to collect the number of hours of operation for two types of tubewells : PTO tubewells, and electric tubewells with WAPDA electric meters in poor working conditions.

Tubewell owners and key informants (*numberdar* or village head-man, WAPDA officials, etc.) are interviewed to gain a better understanding on the management of private tubewells. Regular interviews of the tubewell owners (for the number of hours sold or their O&M costs) are complemented by specific topic-oriented interviews to answer particular questions (for example their strategy regarding water sales) pertaining to groundwater management.

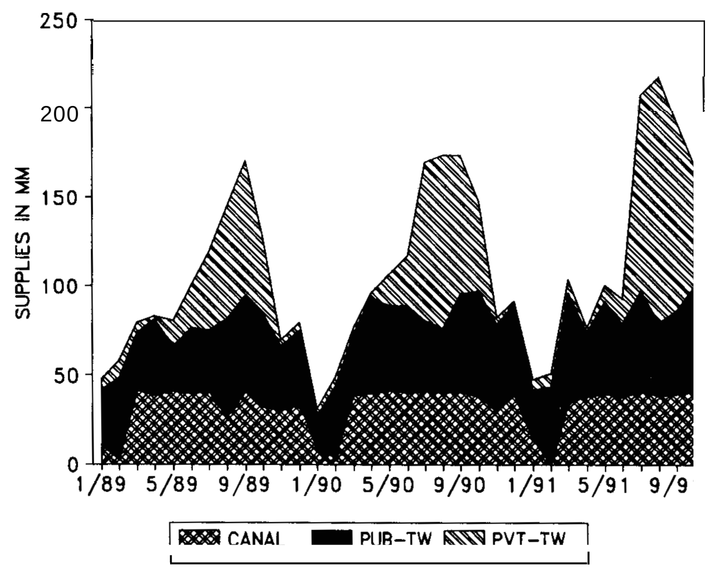
Piezometers have been installed in specific locations for a regular monitoring (monthly measurements) of changes in the water table depth. For the quality of the groundwater, two methods have been used: a complete analysis of groundwater samples in certified laboratories (Directorate of Land Reclamation, Irrigation Department, Lahore, for example) or a direct measurement in the field using an EC meter. The second method has the advantage of being rapid and gives instantaneous results.

Appendix IV

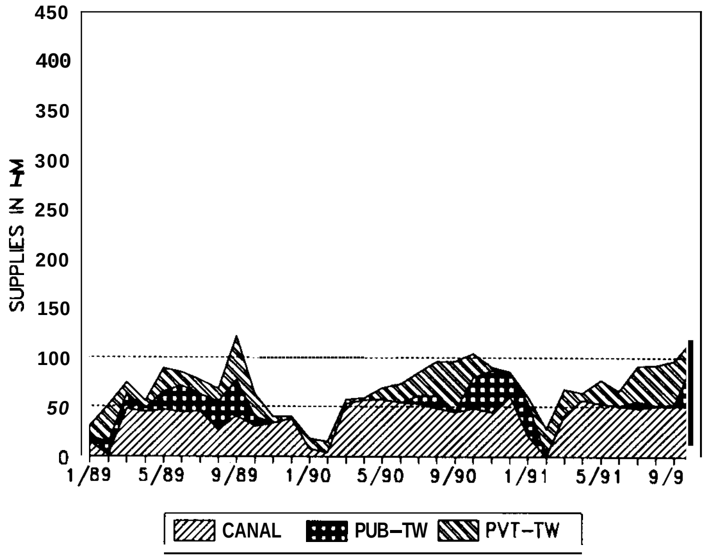
Irrigation Water Supply for 4 Mananwala Watercourses
January 1989 - December 1991



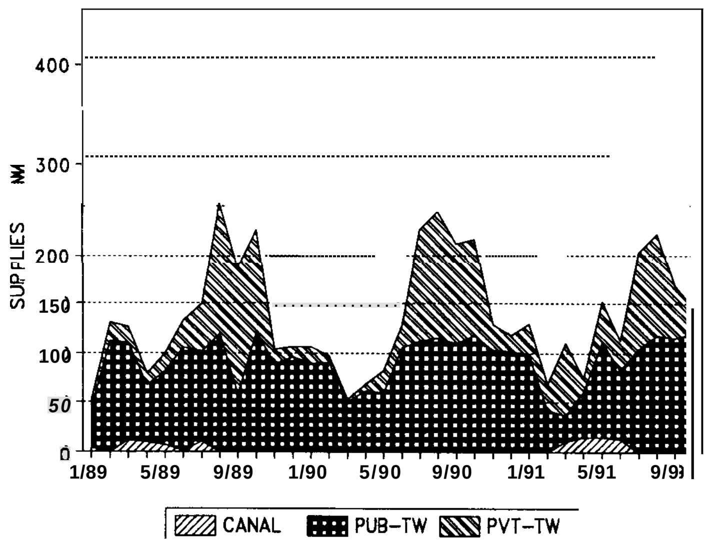
Watercourse 24R – Mananwala Distributary



Watercourse 71R – Mananwala Distributary



Watercourse 121R – Mananwala Distributary



Watercourse 143R – Mananwala Distributary