PN-ABR-873

FACTORS DETERMINING GROUNDWATER USE FOR IRRIGATION IN PAKISTAN'S PUNJAB

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FACTORS DETERMINING GROUNDWATER USE FOR IRRIGATION IN PAKISTAN'S PUNJAB

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December 1992

ISPAN #51

An Applied Study prepared for the Asia Bureau
of the U.S. Agency for International Development
by the Irrigation Support Project for Asia and the Near East

Irrigation Support Project for Asia and the Near East
Contract No. ANE-0289-C-00-7044-00, Project No. 398-0289
serving the Asia Bureau and the Near East Bureau
U.S. Agency for International Development
Washington, D.C. 20523

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SUMMARY

Increasing demands on limited water supplies pose a serious threat to agricultural production and food supplies of arid and semi-arid regions in South Asia. In Pakistan, agriculture has grown dependent on groundwater pumped from private wells. In areas studied for this research, groundwater contributed almost 60 percent of the water reaching farmers' fields. Groundwater extraction rates already exceed safe yield estimates and available recharge. This deficit will increase as the number of private wells grows.

With South Asian governments divesting themselves of control over public wells, government agencies are losing what little control they once had over groundwater extraction rates. Past attempts to regulate private wells have often failed or produced inequitable results. The results of this research, however, demonstrate how susceptible groundwater use by private well owners is to government energy pricing policies, technology promotion programs, and canal water allocation rules, particularly where there are multiple sources of water.

To aid in the analysis, two original concepts were used—total latent water demand and latent groundwater demand. Together they proved useful in characterizing irrigation water needs for areas such as Pakistan's Punjab Province, where access to water supplies is often constrained, and where water demand depends on many different factors. Of these factors, the two targeted by this research, marginal water costs and average water quality, had a strong impact on both the total latent water demand and latent groundwater demand observed in the study areas. Increasing marginal water costs tended to decrease total latent water demand, while poor water quality tended to increase total latent water demand.

The 14 Lager study watercourse commands demonstrate the impact government policies can have. Because of subsidies for electrical power and taxes on diesel, electric wells cost less than half as much as non-electric wells to operate, and pump twice as much water per acre as non-electric wells. For owners with similar holdings, flat-rate electric wells pumped twice as much water per acre as metered electric wells. Extrapolating from this data, private well development limited to non-electric wells, at current diesel prices, would maintain sustainable latent groundwater demand for Lagar distributary. Conversely, the proliferation of electric wells billed on a flat-rate basis in Lagar's command would quickly result in overexploitation of the underlying aquifer, and a steadily increasing power burden on an already strapped electrical power network.

Government agencies must recognize that their policies can inflict great harm on agricultural systems. In Pakistan's Punjab Province, despite the importance of groundwater to agriculture, the government should begin systematic efforts to

accurately track water table levels and the quality of groundwater over time and across space. In addition, the government can help moderate excessive groundwater demand by reallocating canal water and restructuring pricing of energy used for well pumping.

ACKNOWLEDGMENTS

This study was jointly funded by the USAID Irrigation Support Project for Asia and the Near East (ISPAN) and the International Irrigation Management Institute. Additional support was provided by Herman Miller, Inc.

Special thanks are owed to E.J. Vander Velde, IIMI/Pakistan, who directed IIMI's involvement; Michael Walter, Cornell University; and Sam H. Johnson III who reviewed an earlier draft.

1. INTRODUCTION

Concern about "sustainable agriculture" has gained prominence in the international development community in recent years. This concern arose from the observation that in many parts of the world, increases in agricultural productivity threatened to exhaust the underlying resource base. High yielding varieties (HYV) of rice and wheat greatly increased potential grain output in developing countries. However, they also required more intensive use of fertilizers, pesticides, and other agricultural chemicals. In addition, HYV crops require significantly more water than the traditional varieties they replaced. In many semi-arid and arid regions of the developing world, the switch from traditional crops to HYV crops has required the development of groundwater supplies for irrigation, either by the public or the private sector. Groundwater's inherent scarcity has seldom been considered in its development for agricultural purposes.

In South Asia, groundwater supplies now play a pivotal role in local agricultural production. In Pakistan, the use of groundwater in agriculture was almost nil in 1960. Today groundwater provides an estimated 40 percent of the water reaching farmers' fields. Private wells have helped spur this growth. Beside increasing the total amount of water available to farmers for irrigation purposes, private wells have also eliminated much of the uncertainty associated with public irrigation supplies. Modern HYVs can be very sensitive to interruptions in water supplies, and are hard to sustain using public canal systems in South Asia, which are notoriously unreliable. Unlike water supplied by the vast canal system that serves the region, the timing and amount of groundwater pumped from private wells are controlled by well owners.

Population growth in South Asia continues to exceed 2 percent per year, and Pakistan's growth is closer to 3 percent. Agricultural production has barely managed to keep pace. For this reason, it is imperative that groundwater be developed in the best way possible. In the last decade the governments of India, Pakistan, and Bangladesh have all moved toward divesting themselves of direct responsibility for the extraction and distribution of groundwater supplies. (The reasons for this trend are many. See Johnson [1982] for a comprehensive list of problems with Salinity Control and Reclamation Projects [SCARP] in Pakistan.) However, in relinquishing control of their public wells to the private sector, South Asian governments also lose whatever control they once exercised over groundwater extraction rates. In most, if not all, areas of South Asia, little is known about the extent of private well development for irrigation, whether this development is environmentally sustainable, or what factors influence private well usage.

Overexploitation of groundwater resources can have disastrous results. Overexploitation exists when groundwater use exceeds aquifer recharge rates. The most obvious result is falling water tables. As water tables fall, the cost of lifting water increases. Energy-poor countries such as Pakistan can ill afford to commit a growing proportion of their energy budget to irrigation, while deriving no additional gain in production. Falling water tables also are a clear signal that water extraction rates must eventually be reduced. In short, an agricultural system built on groundwater deficits will eventually suffer a contraction in output. Falling water tables mean that other users of groundwater are robbed of their water supplies. Handpumps and open-pit wells used for animal and domestic water supplies go dry. Perhaps the most insidious result, however, is the loss of a natural cushion against drought that fully recharged aquifers provide. Past research[1] has shown that groundwater's greatest value is as a supplemental water supply in times of drought, not as a primary water source for agricultural production.

This report describes the results of research on groundwater use by farmers in a selected area of Pakistan's Punjab Province. The objectives of the research were to: 1) quantify groundwater extraction rates within a canal command area of the province; 2) relate these rates to the "safe yield" of the underlying aquifer; and 3) determine what factors primarily influenced the groundwater extraction rates of private wells. An important component of the research included defining and applying the concept of "total latent water demand," and its corollary, "latent groundwater demand." Together the two concepts are innovative ways of approaching the question of safe aquifer yields of groundwater used for irrigation.

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[1]See, for example, Burt, 1964a and 1964b, and Tsur, 1990.

2. LATENT GROUNDWATER DEMAND

Total latent water demand is defined as the amount of water per acre that farmers would use, if available, measured at the water's source. In Pakistan's Punjab Province, the source of groundwater is the well discharge pipe, while for canal water it is the watercourse off-take (known as the watercourse *mogha*). Latent groundwater demand is the portion of the total latent water demand that would have to be supplied by groundwater. The term "latent" acknowledges that actual water use is often constrained by limited access. "Demand" reflects the fact that total latent water demand and latent groundwater demand for a given area are not static quantities. They depend on a number of physical and economic factors that may vary both by location within a region (such as groundwater quality) and over time (such as the cost of electricity or the market value of crops grown). While many factors can influence total latent water demand and latent groundwater demand, this paper focuses on two: groundwater quality and marginal water costs.

Studying latent groundwater demand is useful for several reasons. The results help define an upper limit on the total amount of pumping that would take place in a given area. When compared to the "safe yield" of the underlying aquifer, latent groundwater demand signals the potential for overexploitation of groundwater resources. When compared to the actual installed capacity of private wells and their utilization rates, it suggests how much further development of groundwater resources could be expected. Focusing on latent groundwater demand also helps identify hidden constraints to private well development when well installations and/or utilization rates result in a total withdrawal rate that is less than the latent groundwater demand. Finally, when the factors that influence groundwater demand are fully understood, the potential effects of government programs and policies on private groundwater demand, and resulting water table responses, can be evaluated.

There are a variety of approaches for estimating demand for irrigation water. Techniques include using hydrologic models that balance evapotranspiration with crop water requirements, experiments that track water use in agricultural production, simulation models that integrate the first two techniques, and actual water-use data collected from a cross section of agricultural water users. Most irrigation water demand studies rely on one of the first three approaches. However, as Ogg and Gollehon (1989) point out, the first three approaches all fail to capture the latitude farmers' have in determining the amount of water they apply to their crops. Latent water demand estimates for the study area were based on cross-sectional data on farmers' water use.

3. DESCRIPTION OF PROJECT AREA

The sites chosen for data collection were selected watercourse commands from Lagar distributary. Lagar distributary lies near the center of Rechna Doab, about 60 kilometers west-northwest of the city of Lahore. Rechna Doab is the area between the Chenab and Ravi Rivers, in the heart of Pakistan's Punjab Province. Lagar is one of seven distributaries in Farooqabad Sub-Division, Upper Gugera Division, of the Lower Chenab Canal system. The Lower Chenab Canal system is about 100 years old. Lagar distributary has a total length of 62,218 feet and carries approximately 38 ft^3/sec at its off-take from Upper Gugera Branch Canal. Its 29 watercourses serve a total command area of 18,408 acres. Figure 1 shows the location of Lagar's watercourse off-takes along its length. Lagar distributary is small in comparison with the other distributaries fed by the Upper Gugera Branch Canal.

The command area of Lagar distributary falls completely within the SCARP-I project area, begun in the early 1960s. Every watercourse within Lagar's command at one time also received at least a portion of the water pumped by a SCARP-I well to supplement canal water supplies. Over the past 30 years, some of these public wells have been abandoned due to bore failure or water quality problems. Others have been terminated as part of the SCARP Transition Pilot Project. Within Lagar's command area more than 30 public wells are still operational.

The region in which Lagar distributary is contained is flat with very little drainage. Below lies a deep, high-yielding, unconfined aquifer that is relatively homogenous and highly anisotropic. Historically this area suffered from both waterlogging (water tables within five feet of the land's surface) and saline soils. Today the water table in Lagar's command ranges between 8 and 20 feet deep, with a distinct gradient as one moves from the head of the distributary to its tail, and as one moves from its east side to its west. The primary source of recharge to the aquifer in this part of Rechna Doab appears to be seepage from the two large canals that pass along the head and east side of Lagar—Upper Gugera Branch Canal, carrying about 6,000 ft^3/sec at this location, and the Q. B. Link Canal, which carries between 18,000 ft^3/sec and 21,000 ft^3/sec.

Groundwater quality varies significantly within Lagar's command area. Wells yield water of high quality in the head area of the distributary, but water quality dramatically deteriorates as one moves toward its tail. While water from all wells in the head region of the command area would be characterized as fresh and suitable for irrigation purposes, based on the standards used by the Punjab Irrigation Department's Directorate for Land Reclamation (DLR), water quality in the tail areas is decidedly substandard. Figure 2 illustrates the trend in average groundwater quality, as measured by electrical conductivity for private wells from selected Lagar watercourse commands.

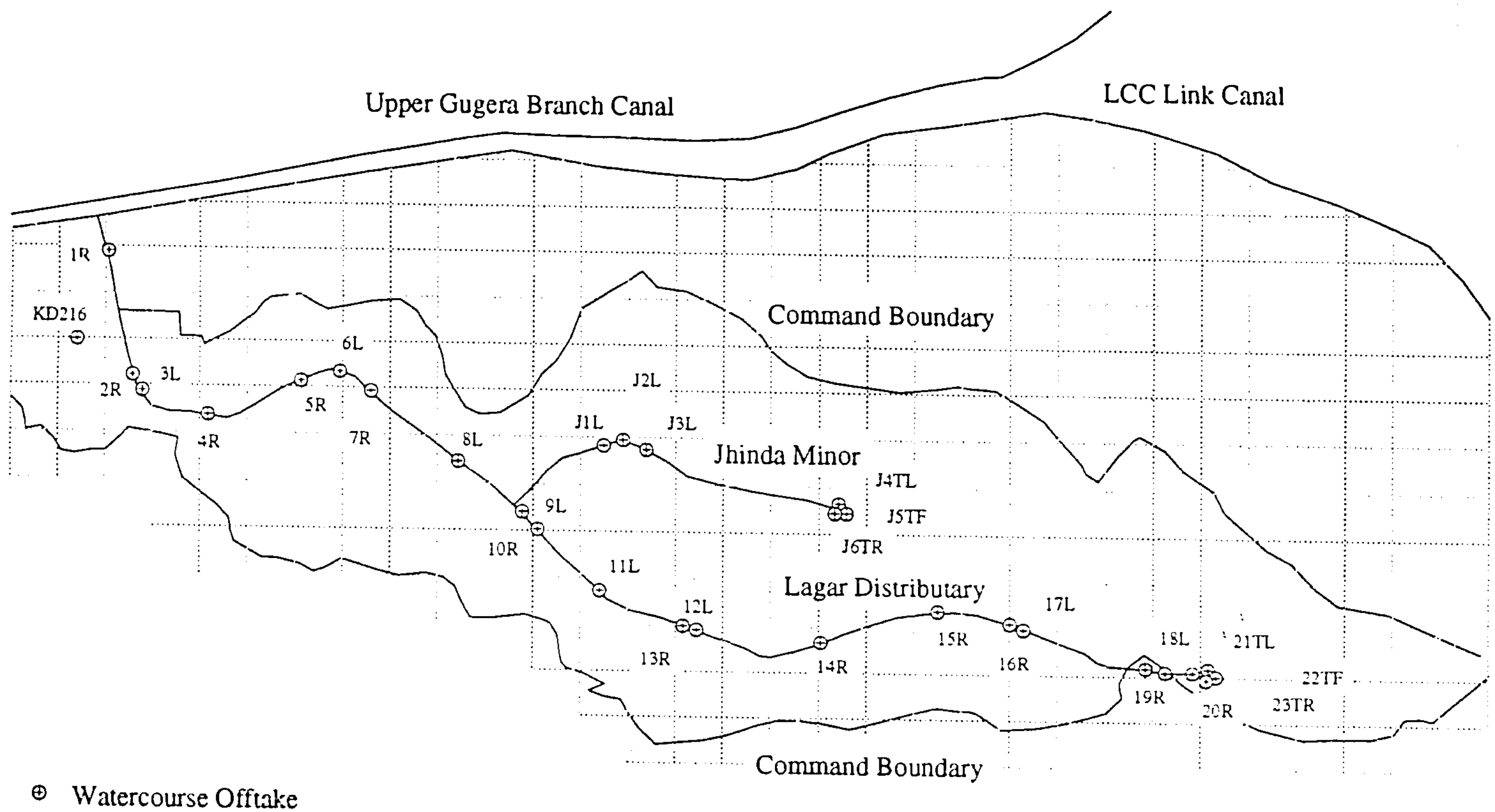

Figure 1

Lagar Distributary with Watercourse Offtakes

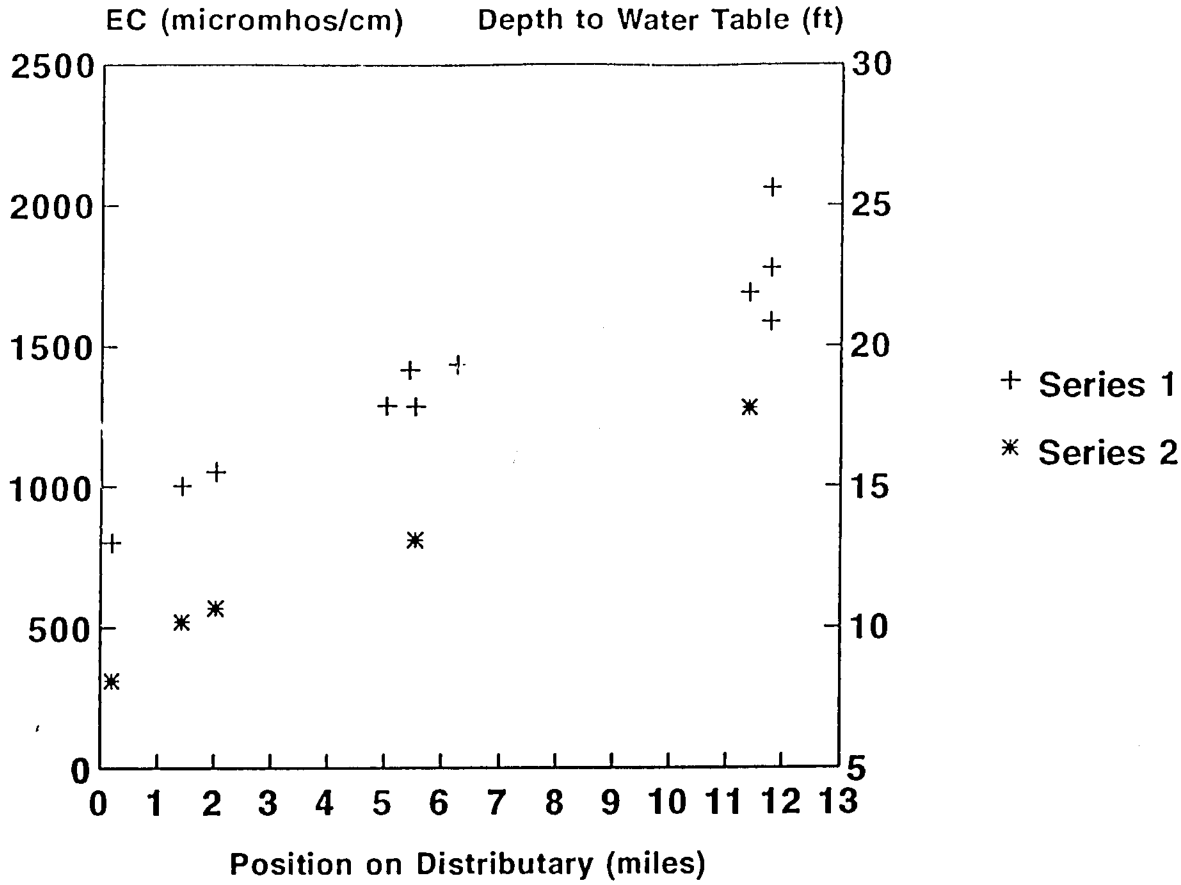

Figure 2

Average Groundwater Quality and Average Depth to Water Table for Private Wells in Selected Lagar Watercourse Commands

The local climate is composed of a hot, rainy cropping season (*kharif*) from May through October, and a cold, dry cropping season (*rabi*) from November through April. Although most precipitation occurs during *kharif*, water is also in shortest supply during this season because of the heat and high evapcration rates. Figure 3 shows the relationship between average monthly rainfall and pan evaporation rates based on data collected between 1982 and 1989 for a weather station adjacent to Lagar distributary. Irrigated agriculture in the study area is conducted under a rainfall/evapotranspiration program and is plagued by shortages and highly variable yearly rainfall.

Lagar's command area falls within Pakistan's rice-wheat agro-ecologic zone. Rice predominates during *kharif*, while wheat is the crop of choice during *rabi*. In addition to these two major crops, sugar cane and fodder are grown all year, and vegetables of various types are grown for cash, with the choice of crop depending on the particular season and the source, quality, and amount of irrigation water available. Holding sizes vary dramatically from just a few acres to more than 50 acres, and may be either consolidated or unconsolidated. Land tenure arrangements include land ownership, land rental, share cropping and contract cropping.

The agricultural production system depends on irrigation; the quantity and reliability of rainfall are insufficient to support the cropping patterns of the study areas. The surface system that supplies the watercourses within Lagar's command area was designed to provide a continuous, year-round supply of water at each watercourse intake. Within watercourses water was to be rotated in a regular manner among farmers; the amount of time each farmer received the full watercourse supply was based on the number of acres he was working. Most of Lagar's watercourses were designed as 50 percent intensity watercourses, receiving one ft^3/sec of water per 528 acres. At the time the system was built, this was thought to be sufficient to fully supply the water needs of half the acreage of a particular watercourse during *rabi*, or to supply half the water requirements if all the land was cropped during *rabi*.

Conditions today are very different from what Lager's designers envisioned. First, farmers plant crops (such as rice and some vegetables) that have much higher water requirements than was expected. Second, the amount of water entering Lagar each year is not as much as the original design. This is due to a variety of reasons, but is primarily because Upper Gugera Branch Canal rarely carries its design flow. Water distribution among watercourses is also not as equitable as intended. In fact, while watercourses near the head of the distributary may actually receive more water than they are allocated, watercourses near the tail often get none at all. Figure 4 shows how the total amount of delivered surface water, expressed as a percent of design, varied by watercourse for Lagar distributary between July 1988 and October 1989.

There is also a great deal of variability in the total amount of water taken in each day at Lagar's head and, consequently, in the amount of water each watercourse receives

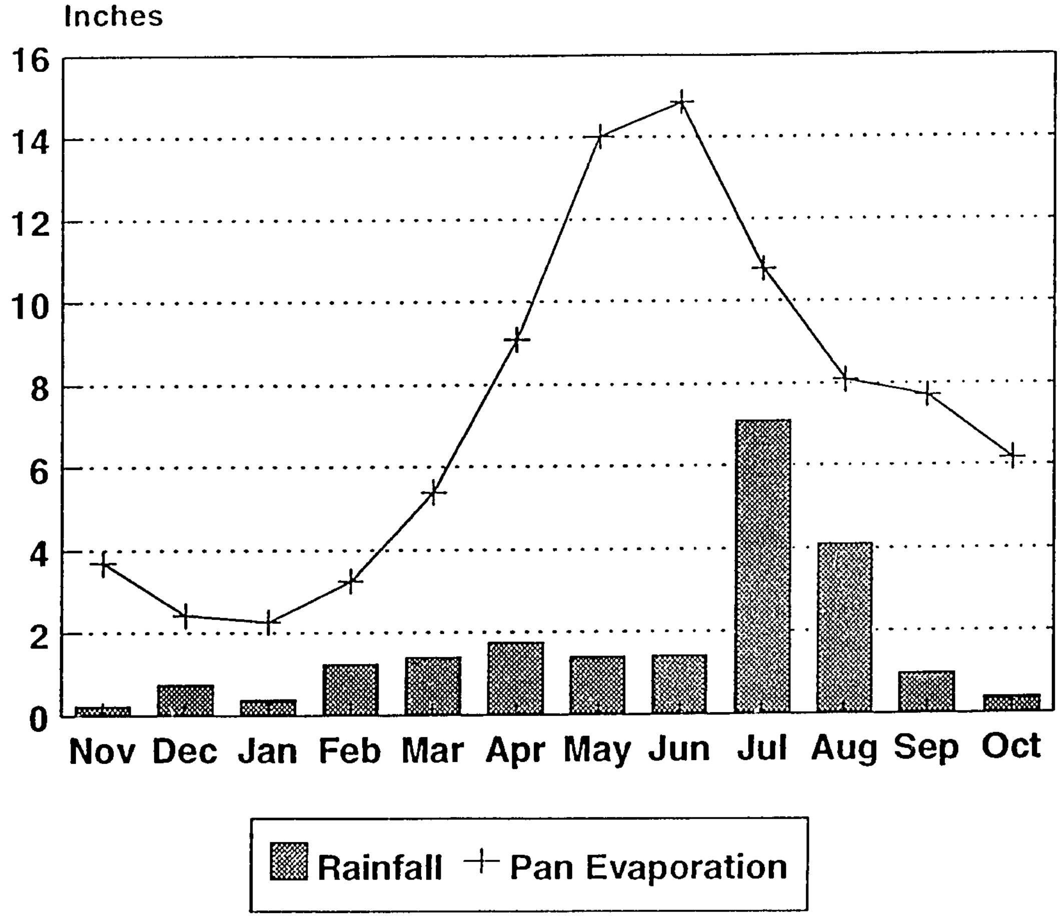

Figure 3

Average Monthly Rainfall and Pan Evaporation Rates for Lagar Distributary

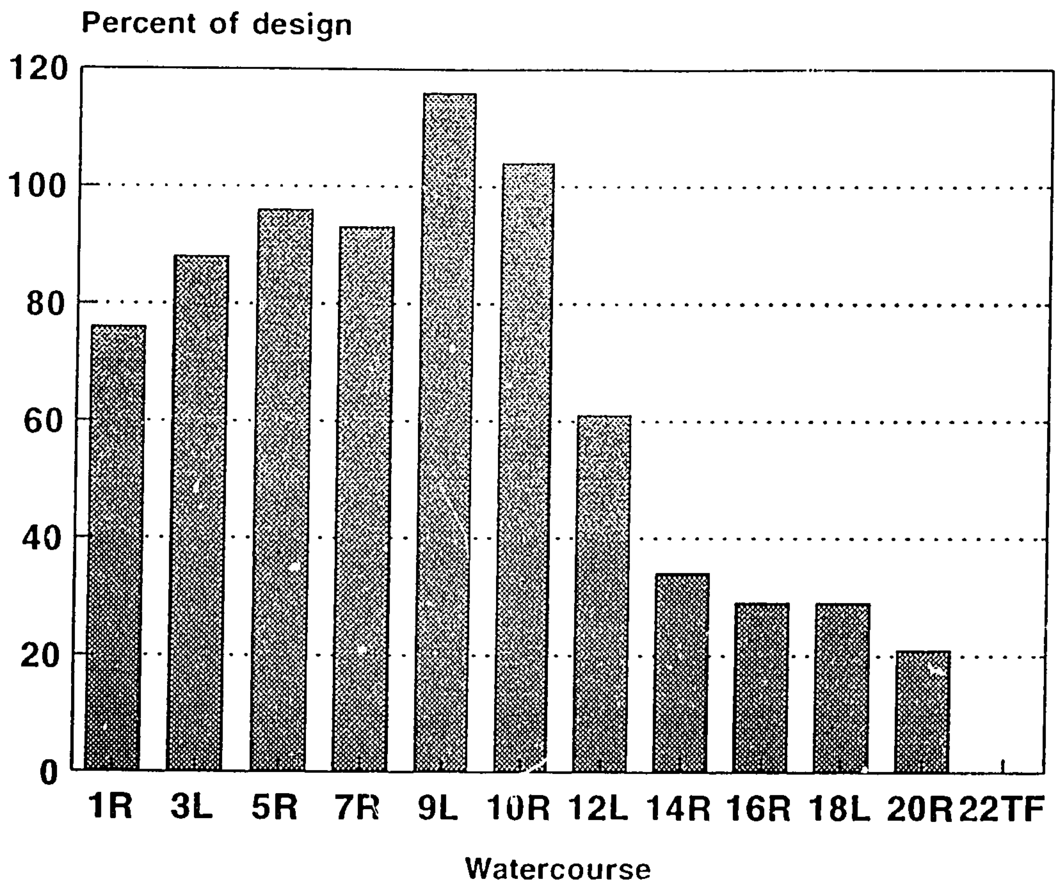

Figure 4

Average Lagar Watercourse Intakes Measured as Percent of Design from day to day. The net result is a cropping system with water demands that far exceed what the surface system can supply, and a great deal of uncertainty at the farm level as to the amount of water a farmer will receive when his turn comes.

Public wells cover some of the irrigation supply shortfall and introduce a greater level of reliability in water delivery for those watercourses served by an operating public well. Public wells are deep (approximately 300 feet) turbine wells driven by electric motors originally designed to deliver between three and four ft^3/sec of water. Because of screen encrustation problems, discharge rates are now considerably below design for the relatively few wells still operating. Public wells pump water directly into surface system watercourses where it mixes with canal water before reaching farmers' fields. SCARP wells are operated by Irrigation Department employees, who are supposed to follow strict, unchanging schedules regardless of the amount of water required by farmers in a particular season. In practice, farmers usually dictate the number of hours SCARP wells operate. While a few public wells operated reliably throughout the study period, many others operated erratically because of frequent equipment and/or bore problems. The relative impact a particular public well has on the total amount of irrigation water available to its watercourse depends on how frequently the well is closed for repairs, its discharge, the size of the watercourse's culturable command area, and the portion of its authorized canal discharge that the watercourse's *mogha* actually draws.

The final source of irrigation water for farmers is private wells. Private wells are generally shallow (about 100 feet deep) bores with centrifugal pumps. Their pumps are driven either by electric motors; by large, slow-speed, domestically-built diesel engines; by small, high-speed, imported diesel engines; or directly via belt/shaft by a tractor. Discharges generally range between one-half and two ft^3/sec, with the average around one ft^3/sec. As of May 1989, 338 private and 31 public wells were installed and operating in the command area of Lagar distributary. This translates into 21.1 private wells per 1,000 acres for Lagar, or 48.4 acres per private well. The number of private wells has been steadily increasing over the past decade, as shown in Figure 5. The total installed capacity of private wells is roughly 362 ft^3/sec. In contrast, the installed capacity for public wells is only 74 ft^3/sec. Taken together, public and private wells have the potential for pumping more than 10 times the amount of canal water Lagar distributary is authorized to deliver to its command. The actual ratio of groundwater to surface water used by farmers in Lagar's command depends, of course, on how much wells are pumped.

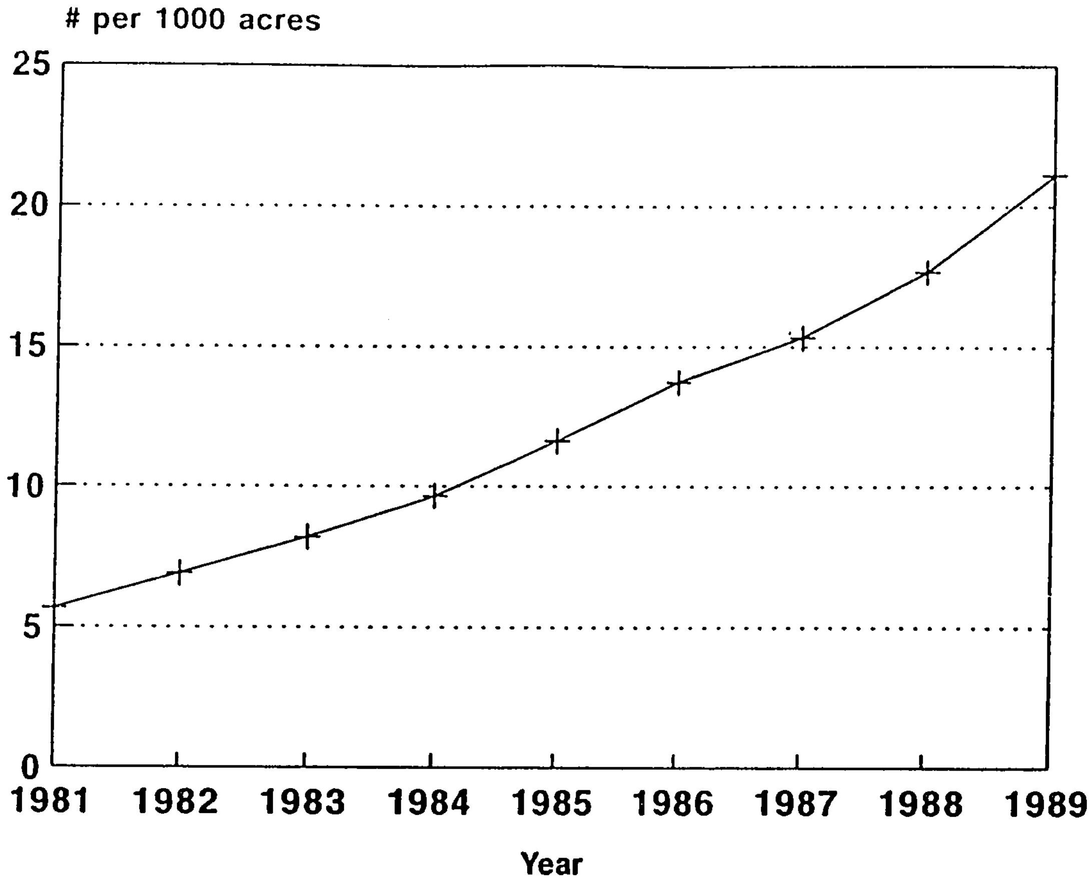

Figure 5

Cumulative Installation of Private Wells in Lagar Distributary

4. FIELD DATA COLLECTION

To explore irrigation water demand in the study areas, a group of private well owners was selected. All the owners were within Lagar distributary's command area and belonged to one of three watercourse clusters: the head area (watercourses 1R, 2R, and the command of KD-216); the middle area (watercourses 8L, 9L, and 11L); or the tail area (watercourses 21TL and 22TF). They all were also part of a larger private well usage sample. These three clusters were used because both water quality and surface water availability varied in a predictable way between the head of Lagar's command and its tail. These two factors are extremely important to the total latent water demand. Choosing head, middle, and tail clusters guaranteed a sample that covered the range of both water quality and surface water availability.

Data collection spanned one full cropping year (*rabi*, 1988-89, and *kharif*, 1989). At the start of each season, approximately 15 well owners were selected from each cluster, with an equal number of electric wells, diesel-engine wells, and tractor-driven wells in each cluster. To be chosen for the study, a well had to 1) have a single owner to prevent demand from outstripping supply, 2) be in reasonable working order, 3) have a cooperative owner, 4) produce sufficient vibration to support a vibration meter[2], and 5) be located where water demand was more than what public sources could supply. In the course of time some owners were dropped because they failed to meet one of the criteria, and others were added to take their place. By the time the study period was completed, 50 well operators had been included for at least a portion of the study.

During the course of the study period, a detailed water budget was maintained for each farmer that recorded total water use, and desegregated water applications by crop type and water source. Groundwater quantity estimates were based on well discharge measurements and well utilization data. Utilization data were obtained either by electric meters (for electric wells with working meters), or by vibration meters installed on well discharge pipes. Public water supply usage was estimated from daily monitoring of the amount of canal water entering study watercourse commands, and the amount of time public wells were operated. In addition to crop surveys and daily water use data, energy consumption tests were run to determine private well operating costs. Seepage loss estimates between water sources and farmers' fields were based on interviews. In addition, several watercourse water loss measurements were conducted to verify farmers' estimates. Also, water quality analyses were performed

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[2]To avoid reliance on farmer interviews for determining well usage, vibration meters were installed on all non-electric wells included in the study. Vibration meters record operating hours by sensing the vibration created by an operating well. Total daily operating hours for electric wells were derived from electric meter readings.

for farmers' well water, as well as for canal water and public well water used by farmers in the sample.

This group of well owners was part of a larger well-usage sample about which less detailed information was collected. More than 200 private wells were selected for well-usage monitoring from 14 watercourses in the command of Lagar distributary. All operational private wells were monitored in each of these 14 watercourses from July 1988 through October 1989. Information about daily pumping hours was collected for all wells in the sample. In addition, details about each well were also noted, including technology type, number of owners, availability of public supplies, total acreage served, whether the owners sold water, approximate watercourse losses, and tariff status for electric wells. Discharge and water quality data were also collected for a significant number of wells.

5. FINDINGS AND IMPLICATIONS

The use of groundwater for irrigation is relatively new in the study area. While the surface system has been in place for more than 100 years, public wells have supplied water for only 30 years. Private wells are an even more recent phenomena. The oldest private well located in the study area was installed just 20 years ago. In the last 15 years, however, the number of private wells has ballooned, doubling every five years. As of the study period, the installed capacity of private wells was almost five times that of public wells. If operated at capacity, Lagar's private wells could have supplied almost ten times as much water as Lagar's surface system was designed to provide. Current installation rates show no signs of decline (see Figure 5), despite the relatively high cost of well installation, an indication of the value farmers place on access to private wells.

The importance of groundwater to agricultural production in the study area was striking. During *rabi* 1988-89 and *kharif* 1989 farmers within the 14 study watercourses applied 19 and 41 inches of water per acre, respectively. Of this total, pumped water accounted for 10 inches during *rabi* and 25 inches during *kharif*. Figure 6 displays the breakdown. Note that these numbers were aggregate values for all farmers within the study's watercourse commands, including both well owners, and farmers without wells. If one considered just the well owners in the detailed study group, the importance of groundwater was even more marked. These well owners during *rabi* applied 23 inches of water per acre, of which more than 16 inches was groundwater. During *kharif*, these same farmers applied, on average, 66 inches of water per acre, of which more than 48 inches was groundwater.

Average groundwater use per acre greatly exceeded the highest safe aquifer yield estimates for the region.[3] Although some of the groundwater applied by farmers undoubtedly finds its way back to the water table, current use of groundwater is clearly greater than the aquifer can support. While there are no good historical records of water table levels for this area, circumstantial evidence indicates that the water table has indeed begun to fall. If private well development and farmers' use of groundwater continue to expand, all farmers could begin using as much water as well owners. If this occurs, the gap between safe yield and extraction rates would be enormous. If nothing else, this suggests that current agricultural use of groundwater is not sustainable over the long term in Lagar distributary, except at increasingly prohibitive groundwater extraction costs.

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[3]Over the course of Rabi 1988-89 and Kharif 1990, farmers within the 14 study watercourses used 35 inches of groundwater per acre. Compare this to the Water and Power Development Authority's 1988 safe yield estimate of 15 inches/acre/year, and the Associated Consulting Engineers' 1985 safe yield estimate of 26 inches/acre/year.

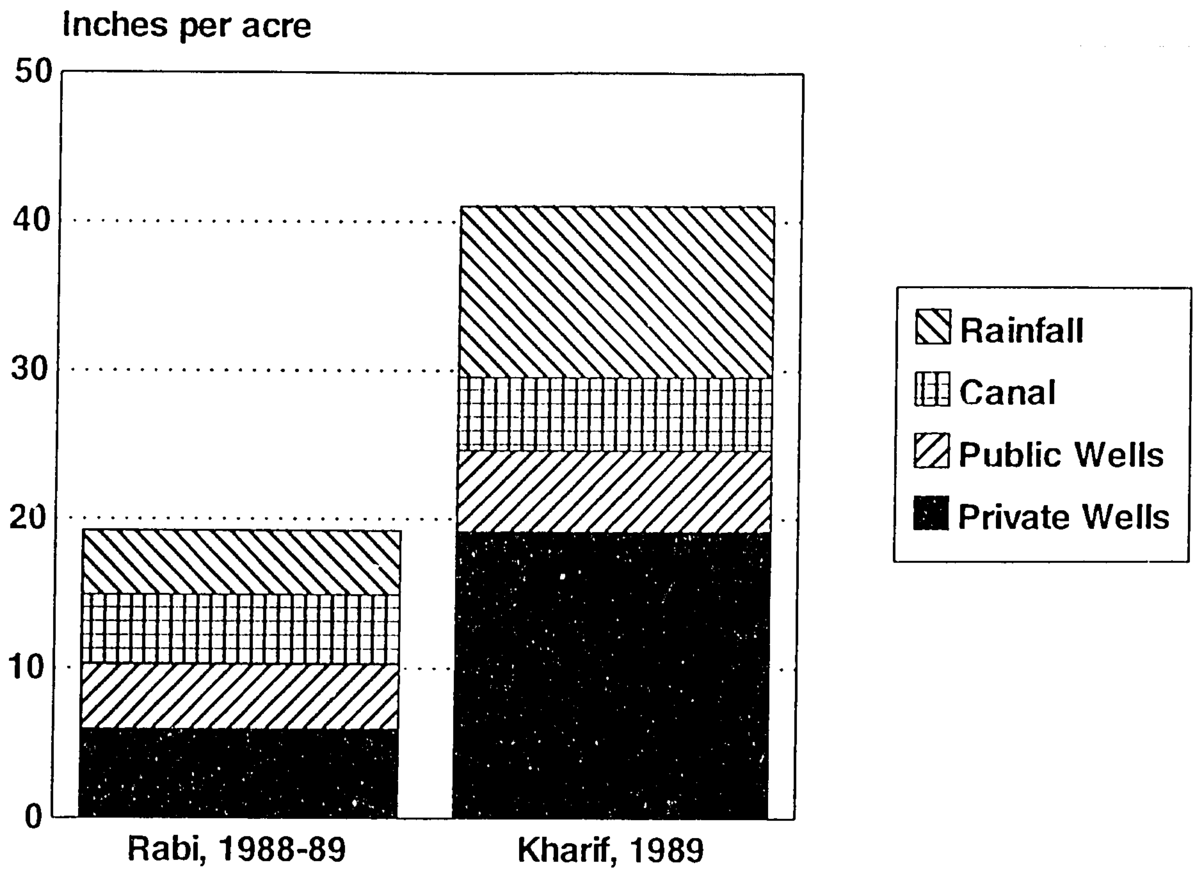

Figure 6

Sources of Irrigation Water Used in 14 Lagar Watercourse Commands

Table 1 shows the average amount of water applied per acre broken down by water use quartiles and season for well owners included in the detailed study. Data in the table also provide the groundwater requirement for each quartile based on the actual amount of canal supplies and rainfall available to the study area during the study period. These data indicate how much groundwater the study area would have required if total water demand across the study area had been proportional to the amount used by each quartile. From this table it is clear that there are significant differences among the total amounts of water demanded by different quartiles and, consequently, among the four estimates of groundwater requirements. Overall, the average groundwater requirement suggests that groundwater extraction is in excess of recharge. However, depending on the quartile, the rate of extraction actually ranges from the safe yield level up to more than seven feet per acre per year above the safe yield level. If it is possible to determine which factors most strongly influence total water use, and hence groundwater consumption, then public agencies might be able to reduce irrigation water demand, or at least avoid policies that exacerbate excessive water demand.

Table 1

Water Applications for Well Owners in Detailed Study Group

	Inches Applied per Acre		Groundwater Requirement	
Quartile	Rabi, 88-89	Kharif, 89	Total	In./Acre
1	14.0	31.7	45.7	19.3
2	18.4	52.8	71.2	44.8
3	24.1	73.6	97.7	71.3
4	35.4	105.4	140.8	114.4
Average:	22.9	65.7	88.6	62.2

The study focused on two primary factors, marginal water costs and average water quality. Marginal water costs, which for well owners translate into pumping costs adjusted for conveyance losses, played a significant role in determining total water use, particularly in *kharif*. There was a strong relationship between increasing marginal water costs and decreasing total latent water demand levels, as Figure 7 illustrates. A more detailed analysis indicated that, over the range of marginal water costs

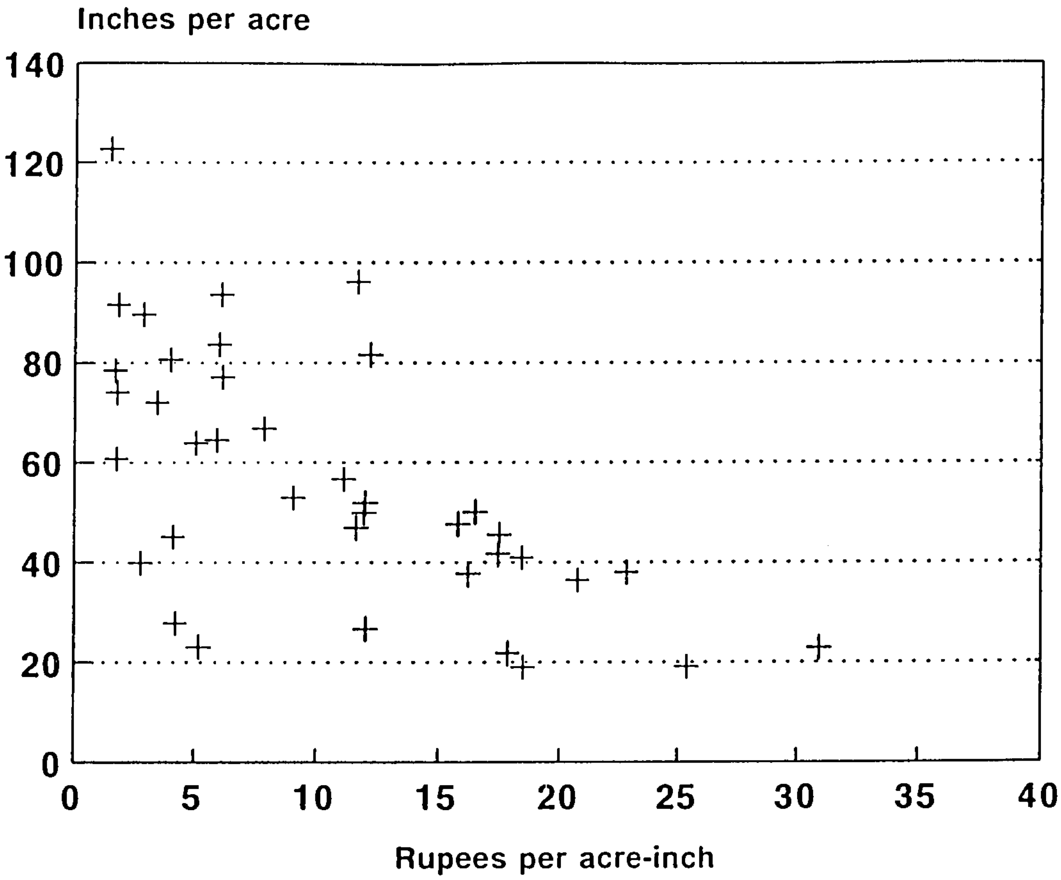

Figure 7

Kharif Water Applications versus Marginal Water Costs for Sampled Well Operators observed for the sampled well owners, farmers primarily responded to changes in marginal water costs by adjusting the amount of water they applied to their crops, not by changing their cropping patterns. For example, based on the field data, for water quality equal to 1,000 micromhos/cm, doubling pumping costs from 5 to 10 Rupees per hour would have cut yearly water consumption by 15 percent.

Changes in average water quality had the opposite effect for well owners in the study group. As water quality deteriorated, water applications increased, again especially during *kharif*, as farmers switched from crops with low salt tolerance to ones with higher salt tolerance, but also higher water requirements. This change was primarily the result of a switch from vegetables to rice as the main cash crop in *kharif*. As an example of the impact of water quality on water use, during *kharif* sample farmers with the poorest quality water used almost twice as much water per acre as their counterparts with good quality water.

The strength of the correlation between water costs and water usage was comparable to that found by various researchers who have studied irrigation in the western U.S.[4] Those studies often concluded that the impact of water pricing on total water use was too small to warrant energy price manipulations as a way of controlling water use. In a conjunctive use environment such as is found in much of South Asia, however, where groundwater is expensive compared to canal water, the effects of changes in energy costs on groundwater consumption can be startling. Because the marginal cost of surface water for the study's farmers was almost zero, wells were only used when surface water supplies were inadequate. For this reason, any impact on total water use brought about by changes in groundwater costs is completely captured by the amount of groundwater used. For example, if groundwater composed 60 percent of the irrigation budget, and an increase in energy costs produced a reduction in total water use of 15 percent, the amount of groundwater used would be cut by 25 percent.

Private farmers in Pakistan can choose between three power sources for their private wells—electric motors, tractors, or diesel engines. Because of energy pricing policies imposed by the Government of Pakistan—in particular, subsidies for electricity and taxes on diesel fuel—electric wells are far less expensive to operate then non-electric wells. Farmers in the study area preferred electric wells when they could obtain them. However, high initial installation costs, bureaucratic obstacles, and connection constraints have limited electric well installations. If one compares electric well usage per acre to that of non-electric wells, the differences are striking. Table 2 compares hourly operating costs for wells monitored in the 14 Lagar watercourse command areas, as well as relative utilization rates adjusted for holding size and well discharge. Electric wells cost less than half as much per hour to operate as their non-electric counterparts. As a result, electric wells pumped, on average, more than twice as much water per acre.

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[4]See, for example, Ogg and Gollehon (1989), or Ayer and Hoyt (1981).

Table 2

Comparison of Operating Costs and Relative Well Use by Technology Type

Technology Type	Average O&M Costs (rupees/hr.)	Relative Pumping Amount
Tractor-Driven	13.8	0.27
Slow-Speed Disel	13.7	0.56
High-Speed Diesel	9.1	0.33
Electric		1.00
Metered	4.5	
Flat Rate	1.7	

Even for owners of electric wells, operating costs varied depending on the way wells were billed for energy consumption. Farmers with electric wells had the option of either metered or flat-rate billings. Those with metered billing paid by the kilowatt-hour used, a number directly tied to the amount of water pumped. Those paying flat rates paid a fixed fee each month, regardless of how much they used their wells. Researchers in India have claimed that flat-rate tariffs have significant social and economic costs. In an arid or semi-arid region such as Pakistan's Punjab Province, flat-rate tariffs on water pumping promote severe overexploitation of groundwater. In the case of Lagar, for farmers with holdings of comparable size, flat-rate electric wells pumped almost twice as much water per acre than their metered counterparts did, and almost four times as much as non-electric wells. Metered tariffs connect the latent groundwater demand to water table levels; as water tables fall, pumping costs per unit of water increase, lowering water demand. Flat-rate tariffs remove this linkage.

Across the subcontinent, the response to unsustainable groundwater extraction rates and/or well interference has been to propose restrictions on installed capacity. Such restrictions include requiring a minimum distance between wells, and requiring sanctioning of new wells. For many reasons, such regulations have not been effective in controlling the installation of private wells. The certification process is open to manipulation by farmers with financial or political resources. Also, most private wells are drilled by the private sector, making it difficult to monitor the installation of new wells. Once installed, private wells are unobtrusive; official surveys invariably grossly underestimate the number of private wells.

Even worse, capacity control tends to formalize existing inequalities governing access to groundwater supplies. Since farmers with large holdings are typically the first to install their own wells, and small farmers or those without permanent holdings of their own the last, installation regulations benefit wealthy farmers with existing wells, while preventing poor farmers from installing their own wells. In the study area, the average holding size of farmers installing wells dropped by half between 1981 and 1989, from 27 acres to 13.

Even if government agencies were capable of monitoring and controlling the installation of private wells, capacity control does not guarantee that extraction will not be excessive. Extraction rates depend on both installed capacity and well utilization rates. Ten wells pumped 80 percent of the time will extract as much groundwater as 100 wells pumped 8 percent of the time. The results of this research showed that while the latent groundwater demand depended on several factors, installed capacity was not one of them. In fact, the study indicated the dramatic impact energy pricing and groundwater quality had on total water demand and groundwater extraction rates.

As noted earlier, groundwater quality for the study watercourses deteriorated significantly as one moved from those closest to Lagar's head down to those near the tail. During the study period, the amount of canal water delivered to watercourses within Lagar's command area was also a function of the relative position of each watercourse along Lagar's length. Watercourses near Lagar's head drew more water than authorized, while several watercourses at Lagar's tail drew virtually none at all. The net result on average water quality was marked. While the average water quality for head-area watercourses was well above the DLR's published irrigation water quality standards, average water quality for the tail areas would have been rated as "unfit" for irrigation based on those same standards. As the results indicated, in response to poorer quality irrigation water, farmers in the tail regions of Lagar were forced to switch to lower value crops and to use more water per acre than their counterparts in the head areas.

While it would require some restructuring of the distributary itself and of watercourse intakes, there is nothing preventing changes in the allocation of canal water among Lagar watercourses. If canal water supplies were allocated so that the worst average water quality among the watercourse commands was minimized, canal water allocations would be significantly different from the original system design, and radically different from the present distribution of surface water supplies among watercourse commands. Table 3 compares current surface water allocations and resulting average irrigation water qualities with canal water allocations, adjusted to improve irrigation water quality and the resulting average irrigation water qualities. In the latter case, canal deliveries would be stopped to head-area commands and focused on the tail area watercourses. Head-area watercourses would be forced to rely solely on groundwater, while the dependence on poor-quality groundwater in the tail region would be greatly lessened. In this scenario, every watercourse command would be

Table 3

Comparison of Canal Water Allocations and Resulting Average Irrigation Water Quality for Selected Lagar Watercourses, Assuming Current Water Allocations and an Adjusted Allocation Rule

	Current Allocation		Adjusted Allocation	
Watercourse	Canal Deliveries (in./acre)	Av WQ (umhos/cm)	Canal Deliveries (in./acre)	Av WQ (umhos/cm)
1R	11.8	482	0	580
2R	8.6	869	0	806
8L	8.3	857	0	930
9L	9.4	926	6.2	991
10R	7.1	1026	1.3	993
11L	7.3	1145	6.0	984
19R	1.6	1535	7.4	994
20R	1.6	1446	12.9	992
21TL	0	1591	6.1	990
22TF	C	1908	19.1	993

provided with irrigation supplies whose average water quality exceeded published standards for Pakistan. An even greater benefit is that this reallocation of canal water would reduce overall groundwater requirements for Lagar's command area by approximately 10 percent.

In Pakistan, government agencies' response to the declining quality of public well water has been to abandon the wells. This approach has also been advocated as the best tactic for contending with private wells with water quality problems. In fact some programs, such as the diesel well subsidy program, have required water quality tests before farmers were allowed to participate. If farmers receive little or no canal water, poor-quality private well water can make the difference between growing some crops and none at all. With groundwater accounting for two-thirds of the total irrigation budget in the study region, the removal of marginal-quality groundwater supplies would have a profound impact on net agricultural production. In the short term, Pakistan's Punjab will be forced to rely on enhanced land and water management practices to minimize the effects of soil and water salinization.

Per-acre use of irrigation water among private well owners was, in general, much greater than their cropping patterns seemed to require. Using crop water requirements published by the Associated Consulting Engineers, Ltd. for this region, along with cropping patterns in place during the study, the amount of water required per acre for the study's farmers should have been on the order of 13 inches per acre during *rabi*, and 24 inches per acre during *kharif*. In contrast, the study's well owners applied an average 23 inches per acre during *rabi* and 66 inches per acre during *kharif*. However, given the relatively high marginal costs for their water, farmers were not applying more water to their fields than necessary. The discrepancy between crop water requirements and actual use may have reflected conveyance losses, runoff from uneven fields, labor shortages, or other inefficiencies. In any case it was real. This points to the danger of relying on mechanistic crop water requirement models for predicting farmers' actual water use.

6. POLICY RECOMMENDATIONS

Several public policy conclusions can be drawn directly from this work. The first applies to energy pricing in the agricultural sector. It is clear that current subsidies for use in the agricultural sector exacerbate the electric power burden on the Punjab's electrical power grid, and result in groundwater demand levels that exceed safe yield estimates for the underlying aquifer. Similarly, flat-rate tariffs for electric wells only compound electric wells' negative impact on water table levels. Flat-rate tariffs reduce marginal water costs to near zero, inflating demand for irrigation water. Flat-rate tariffs also remove all linkages between the falling water tables and well operating costs. Farmers operating flat-rate tariff wells have no incentive to curb water use as water tables drop. For flat-rate wells, the cost of increased energy requirements for lifting water from ever-increasing depths falls squarely on the energy supplier, the Water and Power Development Authority (WAPDA), not on the energy users, the owners of flat-rate tariff electric wells.

The second conclusion concerns policies that affect farmers' choice of pump technology. Policies influencing their choices include taxes on diesel fuel, subsidies for electricity, the availability of flat-rate electrical tariffs, diesel subsidies, WAPDA's electrical connection subsidy, the agricultural department's borehole drilling program, and the SCARP Transition Pilot Project.

Even apart from power pricing policy, government agencies can and do have an immediate impact on farmers pumping technology choice, some for the better and some for the worse. For example, the SCARP Transition Pilot Project (STPP) originally proposed terminating 216 wells in the SCARP-I project area, replacing them with 2,100 private electric wells. The purpose of the additional private wells was to guarantee adequate vertical drainage, and to ensure farmers equitable access to groundwater supplies once public wells were abandoned. As this study found, there was no need for additional vertical drainage in the SCARP-I Transition Pilot Project area. In fact, given current electricity subsidies, such a program would have pushed latent groundwater demand levels even higher than they already are.

Equitable access to groundwater supplies, however, is a valid concern. For the projected cost of upgrading the electrical supply grid to handle greater power demands, and the cost of installing additional private electric wells, the Transition Pilot Project could have installed more than 13,000 diesel-powered pumps and turned them over to farmers. If the STPP had left the acquisition of pumps to participating farmers and just installed bores, almost 20,000 bores could have been drilled, cased, and turned over to farmers. Farmers with only boreholes invariably rely initially at least on tractors as their power source. By promoting the proper technology, the STPP program could have simultaneously reduced latent groundwater demand while also increasing equitable access to groundwater supplies.

Much of the groundwater extracted by private farmers is of questionable quality. The application of this water to farmers' fields can have negative short- and long-term consequences. In the short term, irrigation water of poor quality reduces yields by interfering with seed germination and stressing plants while crops mature. In the long term, depending on the soil type, the use of poor-quality irrigation water can destroy soil structure, rendering fertile land almost unusable. Temporary use of poor-quality water has reversible effects. However, its sustained use produces damage that is much harder to correct.

In Pakistan's Punjab the canal system constantly carries salts into the region, with little opportunity for their removal. This means that for the foreseeable future, the only solution to water quality problems in Pakistan's Punjab is enhanced soil and water management. Unfortunately, the geographic distribution of salinity problems in the Punjab coincides with areas poor in canal water supplies. Farmers in the tail areas of distributaries labor under a twin burden: relatively little surface water and poor quality groundwater. As the example from Lagar distributary illustrates, reworking distributary water allocation rules can provide dramatic improvements in average irrigation water quality across a distributary, while at the same time reducing overall groundwater demand. Simply restoring distributaries to their original design, so that tail areas receive their full allocation of canal water, would substantially benefit the average quality of irrigation water in tail areas. Attempts to regulate farmers' use of marginal quality groundwater have not and will not succeed.

Finally, government agencies cannot develop or implement effective policies and programs without substantiating data. Currently Pakistan has no systematic means of tracking water table and water quality levels across space and over time. In this setting, public policies can only be reactive, responding to problems that have become too pressing to ignore. Environmental degradation, either from falling water tables or soil damage, usually takes place over long periods of time. The positive side of this is that there is often ample time to detect deterioration and to respond, if the appropriate surveillance is underway. Once severe damage has been done, however, it can often be painstakingly slow and difficult to repair.

7. CONCLUSIONS

Increasing demands on limited water supplies pose a serious threat to agricultural production and food supplies of the arid and semi-arid regions of South Asia. In recent years the agricultural production system has grown increasingly dependent on groundwater, particularly, groundwater pumped from private wells. The results of this research indicate that for the area studied in Pakistan, groundwater accounted for almost 60 percent of the total water reaching farmers' fields. Groundwater extraction rates already exceed available recharge. With the number of private wells growing ever larger, this deficit will only increase, and with it the negative effects of falling water tables.

With South Asian governments divesting themselves of control over public wells, government agencies are losing what little control they had over groundwater extraction rates. Past attempts to regulate installed capacity have often failed or produced inequitable results. The results of this research, however, demonstrate how susceptible groundwater use by private well owners is to government energy pricing policies, technology promotion programs, and canal water allocation rules.

To aid in the analysis, two original concepts were used—total latent water demand and latent groundwater demand. Together they proved useful in characterizing irrigation water needs for areas such as Pakistan's Punjab Province, where access to water supplies is often constrained, and where water demand depends on many different factors. Of these factors, marginal water costs and average water quality had a strong impact on the demand for groundwater observed in the study areas. Increasing marginal water costs tended to decrease water demand, while poor water quality tended to increase total water demand.

The 14 Lagar watercourse commands demonstrate the impact government policies can have. Because of subsidies for electrical power and taxes on diesel, electric wells cost less than half as much as non-electric wells to operate, and pump twice as much water per acre as non-electric wells. For owners with similar size holdings, flat-rate electric wells pumped twice as much water as metered electric wells. Extrapolating from this data, private well development limited to non-electric wells at current diesel prices would maintain sustainable latent groundwater demand levels for Lagar distributary. Conversely, the proliferation of electric wells billed on a flat-rate basis in Lagar's command would quickly result in overexploitation of the underlying aquifer and a steadily increasing burden on an already strapped electrical power network.

Because of extensive groundwater development, much of Pakistan's Punjab is no longer threatened by waterlogging. However, the threat of waterlogging has been replaced by two equally menacing possibilities: unsustainable groundwater extractions by private wells and the degradation of soils from the use of marginal-quality groundwater. Past regulatory approaches to managing private groundwater use have failed, as have programs that place pumping facilities in the hands of public agencies. This study illustrates how combinations of government energy pricing policies, technology promotion programs, and canal water allocation rules can dramatically affect the amount of groundwater farmers extract and the overall quality of irrigation water applied to farmers' fields.

Government agencies must recognize that their policies greatly affect the country's agricultural systems. In Pakistan's Punjab Province, the government should increase efforts to accurately track water table levels and the quality of groundwater over time and across space. With this improved monitoring, plus efforts to moderate groundwater demand, Pakistan can help ensure sustainable agriculture and water supplies.

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GLOSSARY

anisotropic	an aquifer whose water moves relatively freely in the horizontal direction, but more slowly in the vertical direction
DLR	Punjab Irrigation Department's Directorate for Land Reclamation
DLR	Directorate for Land Reclamation, Irrigation Department
HYV	high yielding varieties of crops
IIMI	International Irrigation Management Institute
kharif	hot, rainy summer cropping season
mogha	point along a distributary where watercourses draw their water
rabi	cool, dry winter cropping season
SCARP	Salinity Control and Reclamation Projects. This term refers to large installations of deep, public wells installed primarily for vertical drainage, and secondarily as supplemental irrigation water supplies
STPP	SCARP Transition Pilot Project
WAPDA	Water and Power Development Authority