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The Impact of Shallow Tubewells and *Boro* Rice on Food Security in Bangladesh

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Notices

[1] Effective January 2007, the Discussion Paper series within each division and the Director General's Office of IFPRI were merged into one IFPRI–wide Discussion Paper series. The new series begins with number 00689, reflecting the prior publication of 688 discussion papers within the dispersed series. The earlier series are available on IFPRI's website at www.ifpri.org/pubs/otherpubs.htm#dp.

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ABSTRACT

Bangladesh has made notable progress in achieving food security, despite extreme population pressures, limited land resources, and an agrarian structure dominated by small and tenant farmers. After two decades of sluggish performance prior to the late 1980s, the production of rice—the dominant staple food—has increased much faster than the population. The development of minor irrigation, particularly private, investment-based expansion of shallow tubewells, has contributed to this impressive performance, and was an outcome of the government's market liberalization policy for irrigation equipment in the late 1980s. This policy promoted rapid expansion of irrigated "*boro*" rice farming in the dry season. The fast diffusion of boro rice in the rain-fed, low-yielding "*aus*" rice area contributed to accelerated growth in rice productivity, a reduction in the unit cost of production, and a decline in real rice prices. Together, these factors have been a major factor behind attainment of food security and moderately reduced poverty in Bangladesh over the last two decades.

Key words: Millions Fed, Food Security, Minor irrigation, shallow tubewells, tube wells, *boro* rice, agricultural policy, technological progress, and environmental impact, Bangladesh

1. INTRODUCTION

Since its independence in 1971, Bangladesh has more than doubled the production of cereal grains, despite a continuous decline in arable land. Without this impressive growth in the production of staple grains, poverty and food insecurity would have been much worse than it is today. This growth has contributed to an increase in per capita food availability, kept food grain prices low and stable, and has been instrumental in reducing poverty by almost one percent a year (Hossain and Sen 1992; Sen and Ravallion 1997; Ahmed, Haggblade, and Chowdury 2000; Zohir, Shahabuddin, and Hossain 2002; Dorosh 2006; and Narayan and Zaman 2009).

Most of the additional cereal production has come from the diffusion of modern rice technology and improved farming practices. The use of modern variety (MV) seeds has now expanded to three-fourths of the rice-cropped area, which is supported by an expansion of irrigation facilities to two-thirds of the cultivated land. This diffusion of modern rice technology must have surprised many agrarian students in Bangladesh who argued that the small size of farms and exploitative land tenure relationships would seriously impede productivity (Jannuzi and Peach 1980; Van Schundel 1981; and Boyce 1987).

Progress can largely be attributed to the rapid expansion of groundwater irrigation, which was triggered by a change in government policies in favor of liberalization in the procurement and marketing of minor irrigation equipment, such as low-lift power pumps and shallow and deep tubewells. A parastatal, the Bangladesh Agriculture Development Corporation (BADC), had previously controlled access to these resources (Osmani and Quasem 1990; Ahmed 1995; Ahmed, Haggblade, and Chowdury 2000; and Ahmed 2001). The change in policy has radically transformed the production of dry season rice cultivation known as "*boro*" rice. *Boro* rice accounted for only nine percent of the rice production in 1966–67 when the Green Revolution was initiated. By 2008, however, it had contributed 60 percent to total rice production in the country. This paper traces the development of minor irrigation in Bangladesh and its impact on the country's rice production and food security.

2. DEVELOPMENT OF MINOR IRRIGATION IN BANGLADESH

When the government's long-term irrigation policy and water resource development plans were formulated in the 1960s, the general perception among policymakers and civil society was that private investment-based minor irrigation was inappropriate for Bangladesh because of the dominance of small farmers and scattered holdings. Ghulam Mohammad, a noted Pakistani agricultural economist, conducted a survey on the potential of tubewell irrigation in eastern Pakistan (now Bangladesh) in the 1960s and argued that a total of 26,000 private tubewells could be installed if the size of holding was the main criteria (Mohammed 1966). Today, nearly 1.3 million shallow tubewells (STW) and 31,000 deep tubewells (DTW) operate in Bangladesh and account for 3.98 million ha, or about 80 percent of the total irrigated area in the dry season (GOB 2008).

Evolution of Policy Changes on Minor Irrigation

Minor irrigation technologies include small-scale devices such as deep tubewells (DTW), shallow tubewells (STW), hand tubewells (HTW), and low-lift pumps (LLP). Table 1 shows the changes in the policy regimes that have influenced the development of minor irrigation.

Table 1. Time line for changes in the policy regime for the development of minor irrigation in Bangladesh

Year	Public sector	Private sector
1961	Agriculture Development Corporation (BADC) rents LLPs to farmers on an annual basis	Farmers pay the rental fee and fuel at 75 percent subsidy
1962–66	Water Development Board (BWDB) installs and operates 380 DTWs with four-cusec pumps in the northwestern region	Farmers get water from the tubewells free of charge
1972	BADC starts renting STWs to farmers' organizations	Farmers manage operation of the tubewells
1974–75	BADC starts selling STWs to individual farmers with subsidies; Bangladesh Agriculture Development Bank provides credit for the acquisition	
1979	Private sector allowed to import and distribute STWs, with credit facilities from commercial banks	Private sector starts workshops for repair of irrigation equipment
1980	Import duty on STW sets is reduced to 15 percent	Private sector starts manufacturing of pumps
1980	BADC stops renting LLPs and starts selling new and used LLPs to farmers' cooperatives	
1981–82	BADC starts offering rental DTWs for sale at subsidized prices with credit from commercial banks	Workshops and repair facilities for irrigation equipment grow
1984–87	Sale of STWs in the northwestern region and formulation of Groundwater Management Ordinance; the private sector's import of small diesel engines is banned in response to drawdown of aquifer during the 1983 drought	Private sector trade limited to a few standardized engine brands; sales of STWs drop due to restricted installation within specified zones and spacing regulations
1987–89	Private sector bans on small engine imports are removed, import duties are eliminated, standardization requirements for equipment are abolished, and tubewell siting restrictions are withdrawn	Private traders start importing cheaper STWs from China; multiple engine brands and sizes enter the market
1990	BADC starts clearing out its stock of irrigation equipment and stops monitoring siting of equipment	Market for engines, pumps, and spare parts spreads; repair works mushroom all over the country

Sources: International Water Management Institute (IWMI) and Bureau of Socio-Economic Research and Training, Bangladesh Agriculture University (1996); Ahmed, Haggblade, and Chowdury (2000).

Low Lift Pumps (LLP)

Modern minor irrigation started in Bangladesh in 1962–63, with the supply of LLPs of 1–2 cusec discharge capacity to lift water from surface sources to adjoining fields (Ahmed, Haggblade, and Chowdury 2000; Mandal 1987). The Bangladesh Agricultural Development Corporation (BADC) fielded the LLPs in the very low lands (*haor* areas) of Sylhet and Mymensingh regions to reclaim them for dry-season rice farming (locally known as *boro* rice). BADC used to own, operate, and maintain these pumping sets, which supplied water to groups of farms on the basis of a flat charge per unit of land per season. The use of the equipment spread quickly in the depressed basins of northeastern and central Bangladesh where surface water was easily available in the dry season. By the mid-1970s, nearly 35,000 LLPs were fielded and the irrigated area reached nearly 0.57 million ha, or about three-fourths of the total area under modern irrigation at that time. As the operation of a large fleet of LLPs became an unwieldy task, BADC gradually introduced irrigation management groups. BADC later rented the equipment to farmer groups directly and only kept responsibility for maintenance.

Deep Tubewells (DTW)

The Bangladesh Water Development Board (BWDB) initiated groundwater irrigation in the early 1960s with the installation of 380 four-cusec capacity DTWs in Thakurgaon, a northern district. For many years, the project had limited success, despite a 100 percent subsidy provided on irrigation. Managing a large number of farmers in irrigation groups was a major problem. BADC began a groundwater irrigation program with smaller capacity (two cusec) tubewells. Later, the Bangladesh Academy for Rural Development (BARD) in Comilla also successfully experimented with smaller capacity tubewells and formed cooperatives of small and marginal farmers. This approach was found to be more appropriate for the Bangladeshi agrarian structure. The program was replicated throughout the country by the Bangladesh Rural Development Board (BRDB), which also took on the responsibility of developing appropriate management systems for the efficient distribution of water among the cooperative's members. By 1981–82, 12,000 DTWs were under operation and were irrigating 0.32 million ha of land.

Shallow Tubewells (STW) and Hand Tubewells

The most recent addition to the list of minor irrigation equipment was STWs of 0.25 to 0.75 cusec capacity, and hand tubewells of 0.02 cusec capacity. Beginning in 1972, BADC imported this equipment—initially renting and later selling it to individual farmers with loans at soft terms from the nationalized commercial banks. The manually-operated hand tubewells initially spread in areas where groundwater was available at upper aquifers. But, due to the heavy labor needed for their operation, the hand tubewells were found to be uneconomical—even with the low opportunity cost of labor—and were discontinued (Mandal 1993). The privately-owned STWs proved to be the most appropriate technology for irrigation development in Bangladesh and their spread continues today.

Until the late 1970s, the procurement, installation and distribution, and management of irrigation equipment were controlled by parastatals such as BADC, BWDB, and BRDB. These entities provided subsidies for their operation. With the expansion of these operations, however, the subsidies—for agricultural inputs like irrigation, fertilizer and seeds— began to impose heavy burdens on the government's budget. Their management also put a burden on limited administrative resources and skills, and promoted rent-seeking behavior by the government. The farmers' cooperatives that managed the equipment also became inefficient and undisciplined, leading to lower-capacity utilization of the machines.

In 1979, the government decided to change its policy of direct involvement in the input market and to privatize the marketing of irrigation equipment (along with chemical fertilizers). This policy change involved the selling off of existing and new LLPs and DTWs, initially to farmers' cooperatives and later to individual farmers. The equipment was sold through a number of private dealers with credit from commercial banks and Bangladesh Krishi Bank (BKB)—a specialized financial institution set up for

the distribution of agricultural credit. The BKB started its own program of providing credit to facilitate the purchase of STWs through its appointed private farms.

Although the policy of liberalization was introduced in 1979, the process of its implementation was slow due to: (1) the reluctance on the part of civil servants to release control and power and (2) a limited private market for repair and maintenance. Through the early 1980s, there were continued efforts to decrease public-sector involvement in minor irrigation and the momentum grew for private sector activity (IWMI and BAU 1996). Nonetheless, BADC continued to subsidize spare parts and repairs, which created a disincentive to the development of local repair and maintenance facilities. The credit delivery process for the acquisition of equipment also remained cumbersome and involved delays and rent-seeking behavior that encouraged defaults on bank loans. In 1983, Bangladesh experienced a severe drought that led to a drawdown of groundwater in the dry season and there were complaints of shallow tubewells becoming dry in the northern districts (Gill 1983). These incidents led to a setback in the decontrol of the market. The public sector responded with a series of actions in 1984–85 that proved that the policy of market liberalization did not have widespread support within the bureaucracy. The actions included: (1) a ban on the sale of STWs in 22 northern subdistricts: (2) an embargo on the importation of small diesel engines used in STWs; (3) the standardization of engine brands; and (4) the formulation of the Groundwater Management Ordinance, which stipulated spacing requirements for all tubewells. In addition, the supply of agricultural credit was reduced in response to reported irregularities in the loan disbursement process and large defaults in loan repayments. As a result of these measures, the expansion of minor irrigation equipment slowed in 1984, and almost stopped from 1985 to1987.

Policy reform advanced, however, in 1988 when leadership at the agriculture ministry changed. The new secretary of agriculture, Mohammed Abu Sayed, took a direct interest in implementing the liberalization program. He himself visited the diesel engine markets in Dhaka, asked traders about obstacles they faced, directed the formulation of policy changes to remove constraints, and ensured that these changes were approved by the-then government. A study under the sponsorship of UNDP—the Bangladesh Agriculture Sector Review— supported the policy changes (UNDP 1989). In 1988, the government eliminated duties on diesel engines, withdrew standardization requirements, and allowed imports of agricultural machinery without government permits. The import duties were reimposed in the early 1990s, but the rates were much lower than in the mid-1980s.

Policy Impacts on Irrigation Expansion

Privatizing the procurement and marketing of irrigation equipment in Bangladesh contributed to: (1) a mobilization of private savings for irrigation investments; (2) the elimination of delays in equipment installation, repair, and maintenance that were caused by bureaucratic procedures and rent-seeking in the public sector; (3) increased competition in the water market, leading to a decline in water charges; and (4) expansion in capacity-utilization of the machines. With the restrictions removed on private-sector imports, farmers realized lower prices for minor irrigation equipment because they could choose lower-cost sources for pumps and motors, and use plastic pipes in place of metal pipes for installation. By early 1989, the cost of installation of a shallow tubewell to irrigate four to five ha of land had fallen to below USD 600, or about 60 percent of the subsidized price of such equipment through BADC (Gissequist 1992).

With the reduction in prices, farmers of medium- and small-sized farms could afford to invest in small irrigation equipment such as STWs and LLPs. Because the availability of agricultural credit did not expand much since the 1980s—due to large-scale defaults and the incapacity of the BKB to recycle loans—the acquisition of irrigation equipment was financed mostly through farmers' savings.

The expansion in the acquisition of minor irrigation equipment can be seen in Table 2. The number of STWs under operation increased from 93,000 units in 1982–83 to 189,000 in 1987–88, and then expanded exponentially to reach 489,000 units in 1994–95 and 865,000 units in 2000–01. The number has continued to increase until today. The faster growth is observed in years following favorable prices of rice. BADC's latest survey of minor irrigation estimates that there were 1,305,000 STWs

under operation in the 2007–08 dry season, which were irrigating about 3.2 million ha of land out of a total irrigated area of 5.0 million ha (GOB 2008). The number of farmers irrigating land with STWs is estimated at 10.2 million out of 14 million farm households in 2007–08.

Table 2. Operation of minor irrigation equipment, 1976/77–2007/08

Year	Shallow tubewells (000)	Deep tubewells (000)	Low lift power pumps (000)
1976/77	7	4.5	35
1982/83	93	13.8	38
1987/88	189	20.3	51
1989/90	260	22.6	51
1991/92	309	25.5	50
1994/95	489	26.7	57
1998/99	736	26.7	73
2004/05	1129	27.2	99
2006/07	1203	29.2	107
2007/08	1305	31.3	139

Source: Government of Bangladesh, 2008.

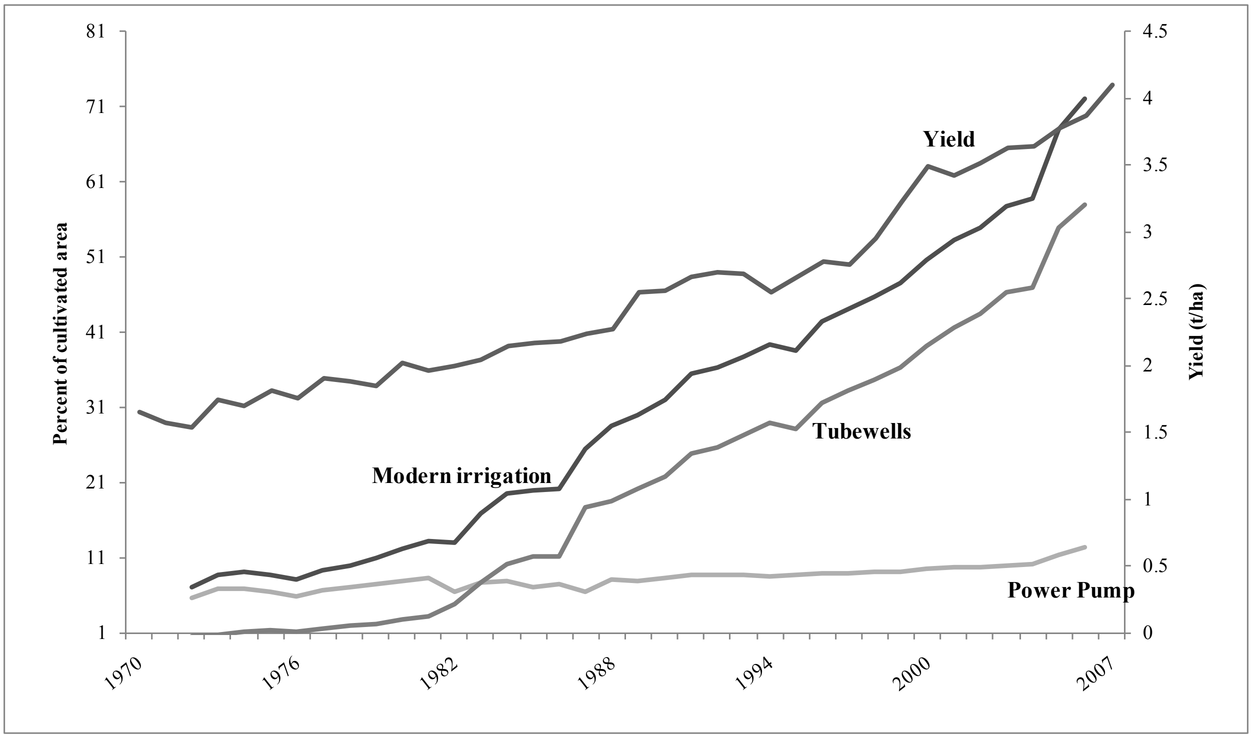
Private investment in the higher-cost deep tubewells (DTWs) has remained sluggish. The deep tubewells acquired earlier by BADC were transferred to the Grameen Bank in the early 1990s, but it could not succeed in operating them efficiently. Recently, the government has set up additional units of DTWs under a special project in the Barind Tract area[1] where the low aquifer cannot be reached by shallow tubewells. The DTWs are supported by subsidies. About 31,000 units are currently in operation, with an estimated irrigated area of 0.8 million ha.

The low-lift power pumps (LLPs), which are used to lift surface water from creeks and canals in the depressed basins and flood-prone areas in the eastern and central regions of Bangladesh, expanded rapidly under the BADC rental program during the 1960s and 1970s. The equipment was sold to the farmers in the 1980s. Since then, expansion has been slow due to full coverage of the potential areas. Only recently, the number of LLPs has increased due to the commissioning of the Tista Barrage Irrigation project, a large public-sector irrigation project that took a long time to complete. Gravity canals from the multipurpose surface water irrigation project and the LLPs now irrigate only 1.04 million ha.

Figure 1 shows the trends in the development of modern irrigation facilities. As shown, the expansion of irrigation was entirely by LLPs until the mid 1970s, but LLP irrigation has not expanded much since then. The area irrigated by tubewells had a slow growth until the mid-1980s, but that growth accelerated from the late 1980s as the shallow tubewell market was liberalized. Since 1990, the expansion of irrigation has been almost exclusively through the exploitation of groundwater by shallow tubewells.

[1] The Barind Tract area is a western, high-elevated, and low-rainfall zone.

Figure 1. Coverage of modern irrigation, 1970–2007



Source: Author, based on data from the Bangladesh Bureau of Statistics, monthly statistical bulletins and statistical yearbooks, various years.

The following linear trend lines were fitted on the time series data on irrigated areas from 1976 to 2008 to assess the degree of acceleration in irrigation that was stimulated by the market privatization of minor irrigation equipment.

Total irrigated area (000 ha) = 540 + 108 Time – 830 Dummy + 59 Time*Dummy
(4.18) (6.68) (3.55) (3.40) R2= 0.98

Tubewell irrigated area (000 ha) = -154 + 87 Time – 612 Dummy + 66 Time* Dummy
(-1.52) (5.89) (-3.73) (4.16) R2=0.99

Where Dummy is a dummy variable to represent the period of privatization that takes a value of 1 for the period 1988 to 2008 when the irrigation market remained fully privatized and a value of 0 for the earlier period when irrigation development was under the control of BADC. The positive and the statistically significant coefficient of the interaction term, Time*Dummy indicates that there has been significant acceleration in the diffusion of modern irrigation since the change in policy in favor of privatization. The value of the coefficients indicates that the irrigated area accelerated from 108,000 ha per year during the pre-liberalization period to 167,000 (108,000+59,000) per ha since liberalization in 1988. In the post-liberalization period, the expansion was entirely due to the use of tubewells. The area irrigated by tubewells increased at a rate of 153,000 (87,000+66,000) ha/year since 1988, which represents a 92 percent expansion of the total irrigated area.

The question remains whether privatization of the irrigation equipment market benefitted the small and marginal farmers in Bangladesh. In the debates of the early 1980s, the general perception was that privatization would create inequitable access to irrigation water and, hence, would worsen the distribution of agricultural income (Quasem 1985; Howes 1985; and Osmani and Quasem 1990). Using

data on ownership of irrigation equipment reported in the Agricultural Census of 1977 and 1983–84, Parthasarathy (1988) argued that larger farmers had greater access to irrigation and that smaller farmers had been losing their differential advantage in farm productivity with the progress in tubewell irrigation. A national-level inventory of shallow tubewells (STWs) conducted in 1987 under a Canadian International Development Agency Project reported, however, that the average landholding size of STW operators had declined, indicating that small farmers' access to STW irrigation had been growing.

The author of the Canadian study generated household level data from a national-level sample survey conducted in 62 villages spread all over Bangladesh. The surveys were conducted during 1987–88, 2000–01, and 2007–08. The objectives of the surveys were to assess the impact of the diffusion of modern technologies on income distribution and poverty (1987–88), the impact of rice research on poverty reduction (2000–01), and to analyze changes in rural livelihoods (Hossain et. al 1994; Hossain et. al 2002; and Hossain et. al 2006). The surveys contained information on ownership of different assets, including irrigation equipment.

The information obtained from the survey on the ownership of STWs by different groups of farmers is reported in Table 3. As noted, only 4.6 percent of the farms owned STWs in 1988, but this grew to 16 percent in 2000, and 22 percent in 2007. Thus, one out of five farmers now own STWs. The data from the survey confirms that the cost of the tubewells has also declined from USD 670 to USD 220 within the last two decades. This decrease is due to the availability of relatively low-cost machines imported from China and the increasing use of second-hand machines. Before liberalization, BADC used to import more durable, but higher-cost engines from Japan.[2] The distribution of ownership of the equipment, however, remains unequal. In 2007, almost 90 percent of farmers operating over 2.0 ha owned STWs, compared to only six percent for marginal farms operating up to 0.4 ha. The latter group constitutes 52 percent of farm households in Bangladesh.

Table 3. Distribution of ownership of STWs in the landownership scale, 1988, 2000, and 2007

Farm size (ha)	Percent of households with own STWs			Average replacement cost of STWs (USD per unit)		
	1988 (n=818)	2000 (n=1,083)	2007 (n=1,131)	1988	2000	2007
Up to 0.4	2.4	2.8	6.8	598	278	194
0.4 to 1.00	2.1	15.6	22.7	692	263	191
1.00 to 2.0	3.9	36.5	60.9	560	280	218
Over 2.0	17.2	81.4	89.7	770	343	273
All farms	4.6	16.1	22.1	671	302	223

Source: Author's estimate from primary data collected through a national-level repeat sample survey by the Bangladesh Institute of Development Studies (BIDS), International Rice Research Institute (IRRI) and Bangladesh Rural Advancement Committee. The methodology of the survey is described in Hossain et al. (1994, 2006).

Although most of the marginal and small farmers in Bangladesh do not own shallow tubewells (STWs), they have access to irrigation equipment installed by other farmers. Due to fragmented and scattered holdings, land parcels located within the command area of a tubewell are usually owned by a number of farmers besides the tubewell owner. So, the tubewell owner has to sell water to operators of adjoining plots for optimum utilization of the capacity of the tubewell. As a result, with the diffusion of STWs, a market for transacting water has emerged.

[2] The average price of Japanese engines (4-8 hp) for STWs in 1986 was Taka 28,000 (USD 1,000), but these prices would last for more than 12 years. In 1991, a Chinese engine with 4-6 hp capacity was imported at Taka 6,300 (USD 160), but it had to be replaced every five years. Still, the cost was within the reach of individual farmers in Bangladesh and they could acquire the equipment with their own savings. The internal rate of return on investment for Chinese-made STWs was estimated at 37 percent, compared to 13 percent for the Japanese-made machines (IWMI and BSRT-BAU 1996).

In the water market, several modes for the payment of water charges are practiced. These include: sharing of one-fourth of the crop with the tubewell owner at the time of harvest; a flat charge per season in cash, which is paid in several installments before harvest; or an hourly charge for renting the machines, with different rates depending on who provides the fuel for operating the machines.

Mandal (1993, 2000) notes that widespread ownership of STWs has helped break monopolistic control over the supply of irrigation water by the landed rich farmers, who were labeled as "water lords" by an influential civil servant in the early 1980s. In the prevailing social and economic setting, several factors—such as topographical limitation on siting, kinship, and personal relationships—have all contributed to increased competition among prospective water sellers and diminished the scope of unilateral pricing of irrigation water. If, within a command area, a landowner is not interested in renting water, the owner of the STW may opt for renting the land for tenancy cultivation. The growth of partnerships in the irrigation business by small farmers has been another development. Some nongovernmental organizations (NGOs) have organized the landless to invest in STWs with microcredit and to sell water to farmers (Wood 1988).

In summary, the expansion of STWs has contributed to the development of rural entrepreneurship, which has led to the growth of other agribusiness services (Mandal 2000). Competition in many areas has reduced the water charge. Over time, arrangements for water sharing in the market have moved from share payments (high cost) to seasonal cash payments (relatively low-cost), to an hourly rental system. The latter promotes incentives to economize water use and, overall, there is a trend toward more efficient operation of irrigation services in the market.

3. IMPACT ON GROWTH IN RICE PRODUCTION

Diffusion of *Boro* Rice

In Bangladesh, rice is grown in three overlapping seasons. The monsoon rice, “aman,” is harvested from late October to December and was the predominant rice crop in the 1960s when the Green Revolution was initiated. In the medium-low to medium-high elevations, the aman crop is transplanted; in the low-lying lands, it is broadcast-seeded (aka deepwater aman). The early monsoon rice known as “aus” is dry direct seeded in April when occasional mild rains moisten the soil. The plant survives under mild drought conditions in May, matures with the early monsoon rains in June, and is harvested in July and August. This low-yielding crop is grown in relatively high lands where cultivation of the rainfed transplanted aman crop is not possible. The dry season irrigated rice, “boro,” used to be grown in extreme low-lying lands in depressed basins. It was not possible to cultivate the deep water aman rice in these basins because of flooding during the monsoon season. The land is usually kept fallow during the period of high floods from June to October. Boro is transplanted in knee-deepwater from November to December when the floods recede, and is harvested from April to May. The yield of boro rice is the highest among the three seasonal traditional rice varieties (TVs). The development of irrigation infrastructure has contributed to the expansion of boro rice in both the traditional aus and the deepwater aman areas.

The adoption of modern rice varieties (MVs) was initiated in the *boro* season in 1967 when the Bangladesh Rural Development Academy in Comilla imported seeds of IR8 from the International Rice Research Institute (IRRI) in the Philippines. It distributed these seeds to farmers through cooperatives and provided them with support for irrigation (Bose 1974). Later, IR20 was introduced in the *aman* season. With support from IRRI, Bangladesh was able to develop an active rice research system through the establishment of the Bangladesh Rice Research Institute (BRRI).[3] To date, BRRI has developed 47 modern varieties (MVs) to suit the agroecological conditions of all three rice growing seasons. The development of these MVs is based on parent materials received from IRRI under a program called the International Genetic Evaluation of Rice Germplasm (Hossain et. al 2003).

With the availability of MVs and the spread of minor irrigation, irrigated rice farming during the dry season began to spread rapidly. The traditional *boro* has also given way to modern *boro* as improved varieties for the irrigated ecosystem have been adopted. Initially, the expansion was limited to low-lying lands in the depressed basins of eastern and central Bangladesh where surface water could be exploited with low lift pumps. Later, *boro* cultivation was diffused to medium and high lands with groundwater irrigation through tubewells, where surface water was not available. *Boro* has mostly encroached on *aus* land and, partially, to deepwater *aman* areas.[4] The area under *aus* cultivation has declined from 3.24 million ha in 1969–71 to 0.96 million ha in 2006–08. The area under deepwater *ama*n has declined from 2.08 million ha to 0.54 million over the same period. In contrast, the area under *boro* rice has increased from 0.89 million ha during 1969–71 to 4.4 million ha during 2007–08. Since MV *boro* is substantially higher-yielding compared to traditional *aus* and the deepwater *aman*, the average rice yield has continuously increased with its diffusion (Table 4).

Wherever irrigation facilities are available, the farmer now grows *boro* with improved varieties in the dry season, except in parcels with dominant light soil that requires more irrigation. On these types of land, farmers grow wheat, potatoes, and recently introduced vegetables and maize, which have comparative advantages over *boro* because of the unusually high cost of irrigating *boro*. Socioeconomic

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[3] The Bangladesh Rice Research Institute was established in 1972 and was nurtured by an IRRI-managed collaborative project that was funded by a number of donors until 1992. The project financed the development of laboratory facilities and regional stations for adaptive research, degree training of Bangladeshi scientists, and the evaluation of international genetic materials—distributed by IRRI under the International Network for Genetic Evaluation of Rice—for suitability under different agroecological conditions in Bangladesh. It is estimated that almost 70 percent of improved varieties adopted in Bangladesh are based on genetic materials developed at IRRI (Hossain 1996; and Hossain et. al 2006).

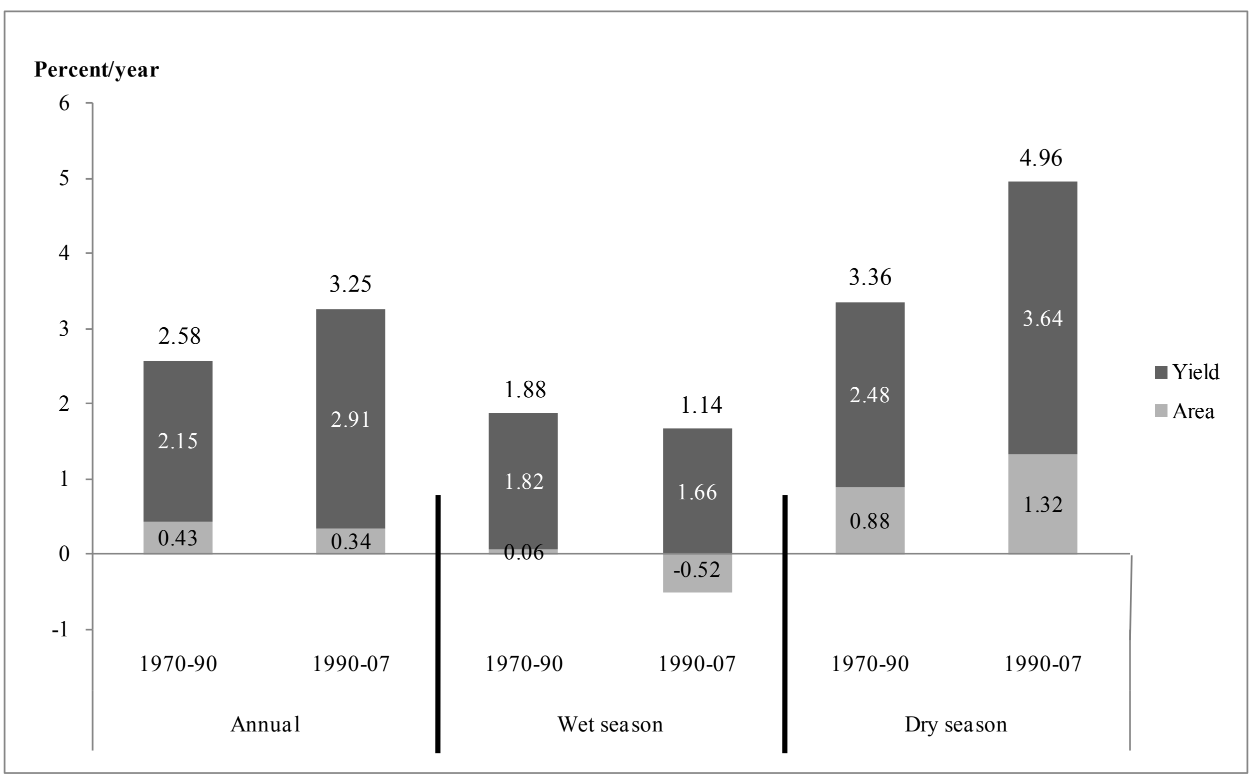
[4] Instead of growing the deepwater *aman*, which is often destroyed by floods, the farmer now keeps the low-lying parcels fallow during the monsoon season and *grows boro* rice in the dry season with full irrigation.

factors, such as small and fragmented holdings, tenancy farming, and lack of credit facilities have not constrained the diffusion of modern *boro* varieties which have been adopted equally by all categories of farmers (Hossain 1989; Hossain et. al 1994; Hossain, Bose, and Mustafi 2006; and Ahmed 2001). The sample surveys mentioned earlier estimated that the number of farmers cultivating *boro* rice increased from 34 percent in 1988 to 69 percent in 2000. The latter figure has since remained constant. The preliminary Agricultural Census undertaken in 2008 estimates that there are 14.6 million farm households. Thus, boro rice is grown by 9.8 million households in Bangladesh.

Bangladesh's rice economy has made respectable progress (Hossain 1989; Ahmed 2001; Zohir, Shahabuddin, and Hossain 2002; and Dorosh 2006). Bangladesh has an agrarian structure dominated by marginal farmers and share tenants who operate land in scattered, tiny holdings. Many scholars predicted that such a structure would constrain the productive development of agriculture (Jannuzi and Peach 1980; and Boyce 1987). But modern agricultural technologies have spread rapidly in Bangladesh. Improved varieties are now used in three-fourths of the land under rice cultivation and their adoption has followed the development of the country's irrigation infrastructure.

Over the last four decades, the rice-harvested area has increased only marginally from 10.1 to 10.5 million ha, but rice production has more than doubled from 17.1 to 41.4 million tons. The rate of production growth has been about 2.5 percent per year, or much faster than the population growth. The average rice yield has reached 3.91 t/ha in 2006–08 from a meager 1.69 t/ha during 1969–71, or a growth of 2.4 percent per year. The growth in both production and yield was relatively slow during the first two decades after independence, but has accelerated since the late 1980s (Figure 2). The increase in the average yield for all rice crops was only partly due to the increased yield of individual seasonal varieties arising from the adoption of improved germplasm and better management of crops (Hossain, Bose, and Mustafi 2006). The yield increase was mostly due to changes in crop composition that resulted from shifting land from lower-yielding to higher-yielding seasonal varieties.

Figure 2. Growth in rice production in Bangladesh by season, 1970–90 and 1990–2007



Source: Bangladesh Bureau of Statistics, monthly statistical bulletins and statistical yearbooks, various years.

Table 4 provides information on trends in the production of *boro* rice compared with rice grown in other seasons. The growth in *boro* production and yield was relatively slow in the 1970s and picked up in the 1980s. The increase has been most rapid, however, since 1988 when the area under shallow tubewells grew. As mentioned earlier, the expansion of *boro* areas has been at the expense of the decline in the area under *aus* rice cultivation. The extreme low-lying *aman* areas where deepwater rice used to be grown have also been converted to *boro* rice.[5]

Table 4. Trends in rice area, production, and yield in different seasons, 1969–2008

Year	Boro rice (summer)			Aus rice (pre-monsoon)			Aman rice (monsoon)		
	Area (000 ha)	Production (000 tons)	Yield (t/ha)	Area (000 ha)	Production (000 tons)	Yield (t/ha)	Area (000 ha)	Production (000 tons)	Yield (t/ha)
1969–71	894	2,853	3.19	3,242	4,254	1.31	5,860	9,866	1.68
1979–81	1,127	3,648	3.23	3,127	4,692	1.50	5,937	11,348	1.91
1989–91	2,183	9,111	4.17	2,348	3,796	1.62	5,689	13,012	2.29
1999–01	3,646	16,750	4.59	1,367	2,634	1.93	5,740	15,202	2.65
2006–08	4,315	23,346	5.41	952	2,382	2.50	5,367	15,657	2.92

Sources: Bangladesh Bureau of Statistics, monthly statistical bulletins and statistical yearbooks, various years.

The contribution of *boro* to overall increases in rice production can be assessed from Table 5. The share of *boro* in incremental rice production was 34 percent during 1950–70, a period that roughly predates the Green Revolution in Bangladesh. The share increased to 62 percent during 1971–88 during the pre-liberalization period. Since 1988, over 90 percent of the increase in rice production can be attributed to *boro* rice.

Table 5. Contribution of *boro* rice to growth in total rice production, 1950–2008

Period	Increase in total rice production (000 t/yr)	Increase in boro rice production (000 t/yr)	Contribution of boro to incremental rice production (percent)
1950–52 to 1969–71	333	114	34
1969–71 to 1989–91	500	312	62
1989–91 to 1999–01	867	764	88
1999–01 to 2006–08	971	942	97

Sources: Bangladesh Bureau of Statistics, monthly statistical bulletins and statistical yearbooks, various years.

To assess the impact of the increase in tubewell irrigation in the post liberation period, a linear trend line was fitted on the time series data on rice production, area, and yield for the 1976 to 2008 period. The estimated lines are as follows:

Production (000 ton) = 17,769 +424 Time – 7325 Dummy +503 Time* Dummy
(15.74) (2.55) (-4.01) (2.83) R^2=0.94

Area (000 ha) = 10,777 +35.7 Time – 114 Dummy – 16.5 Time* Dummy R^2=0.16
(66.6) (1.60) (-0.47) (-0.69)

[5] In earlier years, such land used to be single-cropped with *boro* rice grown in the dry season and then left fallow during the monsoon season. Recently, such land has been converted into shallow ponds for aquaculture during the monsoon season and for rice production during the dry season.

$$\text{Yield (t/ha)} = \underset{(23.17)}{1.77} + \underset{(3.07)}{0.035}\ \text{Time} - \underset{(-5.09)}{0.627}\ \text{Dummy} + \underset{(4.03)}{0.048}\ \text{Time* Dummy} \quad R^2=0.97$$

Figures within parentheses are estimated t-values. The "Dummy" variable assumes a value of 1 for the post-liberalization period, 1988–2008. The coefficients of the interaction term "Time*Dummy" are statistically significant in production and yield equations, but not in the equation for rice area. The results indicate acceleration in yield and production in the post liberalization period.

The estimated value of the coefficient for the yield function indicates that the rice yield has increased at a rate of 35 kg per year during 1976–88, the pre-liberalization period. The coefficient of the variable "Time*Dummy" indicates that the yield growth has increased by an additional 48 kg per year over the 1988–89 to 2007–08 period. The coefficient is statistically significant. We may thus conclude that the policy changes contributed to an additional 0.96 t/ha increase in rice yield over the last two decades, which is about 58 percent of the incremental rice yield during this period.

Rice production has increased from 424,000 tons per year during 1976–88 to 927,000 tons per year during 1988–2008. In the latter period, the rice-cropped area has increased by a mere 19,000 ha per year. Thus, the acceleration in the growth of production was almost entirely due to the acceleration in yield rates. Assuming that 500 gm of milled rice is required to feed a person per day, the 503,000 tons of incremental production per year will feed an additional 1.84 million people per year. The population of Bangladesh is increasing at almost a similar rate.[6] From 1988 to 2008, the incremental rice production due to the liberalization policy has, thus, helped to feed nearly 37 million people.

For a rigorous estimate of the impact of policy changes, Ahmed (1995, 2000) estimated input demand and rice production functions using the Seemingly Unrelated Regression Model with time series data for 1975–76 to 1996–97. This approach helped to establish counterfactuals, i.e. what would have happened without the policy reforms. He concludes that the gross effect of the liberalization of agricultural equipment market is large—about 2 million tons, while the indirect effect of the expansion of irrigated rice (*boro*) on rainfed rice (*aus*) via the change in crop composition is both large and negative. The net effect of irrigation-related changes, notes Ahmed, is about 1.3 million additional tons of rice (from 1988–89 to 1996–97). This means that rice production during the post-liberalization period would have been 1.3 million tons less had the market reforms not been undertaken. The net effect is 38 percent of total incremental production (Ahmed 2000, p.67). The incremental rice production between 1988 and 2008 was 15.5 million tons. Therefore, using Ahmed's parameters, we estimate that 5.9 million tons could be attributed to policy changes. With the current level of per capita consumption, this amount of rice would feed nearly 22 million people.

Socioeconomic Impacts of *Boro* Rice Production

Despite clear food-production benefits, how has the diffusion of modern varieties in the *boro* season affected the costs of food production, employment, and farmers' income? To shed some light on this issue, the costs and returns data collected from the repeat surveys mentioned earlier were processed. The findings are reported in Table 6. Since *boro* rice has expanded mostly at the expense of the *aus* rice, the effect of the diffusion can be assessed by comparing the numbers of these two seasonal varieties. Since paddy prices were abnormally low in 2000, we use the numbers for 1988 and 2007 for assessing the effects.

The paid-out costs of production (including seed, fertilizer, pesticides, irrigation charges, and machinery rental) in the cultivation of *boro* rice (MVs) was almost three times that of traditional varieties (TVs) grown under rainfed conditions (*aus* rice) in 1988, and almost double that of TVs in 2007. These higher costs indicate the input- intensive nature of irrigated rice farming. The total cost of production per hectare was about 1.4 times higher in *boro* cultivation in 1987, and 70 percent in 2007. But the increase in

[6] The population of Bangladesh has increased from 70 million in 1971 to about 145 million at present. The growth rate has declined from 2.5 percent to 1.4 percent per year over this period. The population is still growing by two million every year. The country needs to produce an additional 0.5 million tons of rice to feed the incremental population.

production from the adoption of MVs was much higher than the increase in cost. Hence, the cost per unit of output went down with the adoption of MVs. The unit cost of production was 22 percent lower in the cultivation of boro compared to aus in 1987–88, and 17 percent lower in 2000–01. The unit cost of production has declined over time. Faster technological progress has also contributed to a reduction in the unit cost of production, which has helped maintain rice prices at a low level—a major factor behind improving access to food for low income households.

Table 6. Costs and returns in the cultivation of *boro* and *aus* varieties, 1988 to 2007 (per ha of land)

Elements	Boro rice			Aus rice		
	1987/88	1999/00	2006/07	1988	2000	2007
Gross value of production (US$)	747	731	867	274	313	483
Paid-out cost (US$)	380	426	429	129	179	202
Net income (US$)	367	305	438	145	134	281
Total cost of production (US$)	486	445	568	204	282	333
Operating surplus (US$)	261	286	299	70	31	150
Yield (ton/ha)	4.46	4.98	5.36	1.48	2.03	2.63
Unit cost (US$/ton of paddy)	109	89	106	138	139	127
Harvest price (US$/ton of paddy)	159	141	152	164	145	171
Labor use (days/ha)	206	131	120	142	112	98
Labor productivity (US$/day)	2.20	1.88	2.92	1.37	1.48	1.61
Wage rate (US$/day)	0.95	1.31	1.81	0.90	1.22	1.56

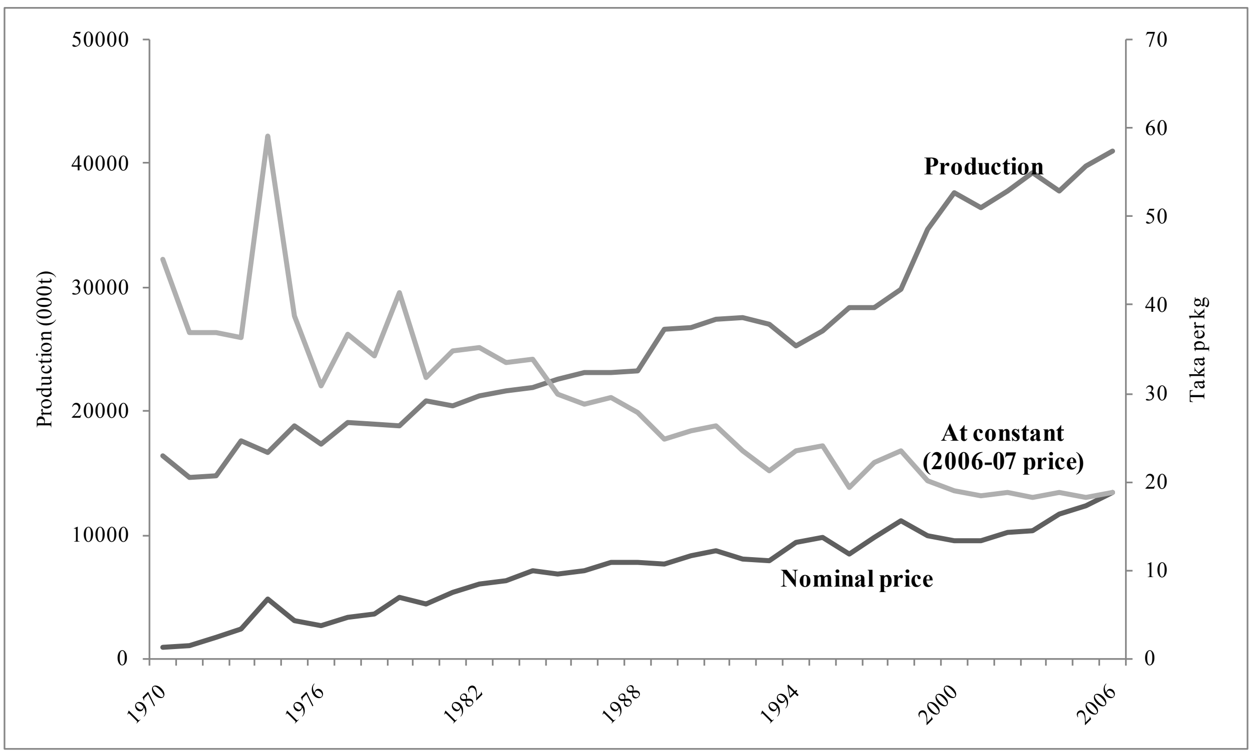
Source: Author's estimate from primary data collected through a national-level repeat sample survey by the Bangladesh Institute of Development Studies (BIDS), International Rice Research Institute (IRRI) and Bangladesh Rural Advancement Committee. The methodology of the survey is described in Hossain et al. (1994, 2006).
Notes: The gross value of production includes the value of paddy straw, which is used as cattle feed. The paid-out cost includes the out-of-pocket expenses on seeds, fertilizers, pesticides, irrigation charges, machinery rental, and wage bills for hired labor. Total cost includes the cost of family-supplied inputs, including family labor. The total costs include the imputed interest charge on working capital, but excludes the depreciation of farm equipment and imputed land rent. The land rent is a real cost for rented land for tenant farmers. Nearly 22 percent of the land in 1988 and 38 percent in 1987 were tenant-operated. The rent is about 30 percent of the gross produce. Thus, the net returns to the tenant farmer would be much less than the numbers shown in the table.

The MVs are also more labor-intensive than the TVs. So, the expansion of the area under MVs has contributed to increasing labor demand, which has helped to generate additional employment for labor-selling, low-income households. The labor use in MVs compared to the TVs was higher by about 64 days per ha in 1987–88 (Table 6). The *boro* area has increased by about 2.2 million ha over the 1988–2008 period; most of this increase has come from the decline in area under traditional varieties. This change would have generated additional employment of 141 million person days of labor. The actual impact has, however, been much less because farmers have resorted to mechanization of agricultural operations in response to increasing wages and costs of feeding animals. The land preparation is now almost entirely mechanized, and mechanization in threshing operations is progressing fast. The labor use in *boro* cultivation had declined consistently from 206 days per ha in 1987–88 to 131 days/ha in 2000, to 120 days/ha in 2007. Despite the spread of labor-saving mechanization, the labor use in the cultivation of *boro* rice was about 28 days higher than in that in the cultivation of *aus* rice. If we use the recent number, which is the conservative estimate of the effect of the diffusion of boro cultivation on employment, it would be 62 million person days, or about 238,000 full-time equivalent jobs.

As noted earlier, *boro* rice farming is highly input-intensive compared to the traditional *aus* farming and entails higher costs associated with irrigation and use of chemical fertilizers.[7] *Aus* farming, in contrast, is entirely dependent on rainfall. The farmers also use fertilizer in low amounts due to the cultivation of traditional varieties and the high risk of occasional drought. In 1988, for example, the farmers hardly used any fertilizer in the cultivation of *aus* rice, and in 2007, the fertilizer used was one-fourth of that used in the cultivation of *boro* rice. Despite the capital-intensive nature of *boro* farming, the family income from *boro* rice cultivation (gross value of production minus paid out cost) was substantially higher than that from *aus* (Table 6). The net income gains from the shift of land from *aus* to *boro* was US$ 222 per ha in 1988, US$ 171 per hectare in 2000, and US$ 157 in 2007. The reduction in the unit cost of production—facilitated by technological progress—has helped keep rice prices within affordable limits for the rural landless and the urban poor.

The trend in the nominal and real price of rice and its association with the growth in rice production can be seen from Figure 3. The real prices showed a consistent downward trend over the entire period. Until the late 1980s, the prices had been fluctuating and the rate of decline was relatively slow. The downward trend in price was more pronounced from the mid-1980s to the end of the last century. The decline in price has been more moderate in the current decade. The downward trend in rice prices has been a major factor behind the moderate reduction in poverty that Bangladesh has experienced since the mid-1980s.

Figure 3. Trends in the price of rice and production, 1970–2006



Source: Author, based on data from the Bangladesh Bureau of Statistics, monthly statistical bulletins and statistical yearbooks, various years.

7 In many areas, shallow tube well owners take one-fourth of the harvest for supplying water to the farmers. In 2007, irrigation charges were estimated at 26 percent of the total cost of production and 16 percent of the value of gross produce. The cost on account of chemical fertilizers was 16 percent of the total cost of production and 7 percent of the gross value of production.

The following linear trend in the price of rice (adjusted for the wholesale price index) is obtained from the time series data for 1976–2007.

Rice Price (Taka/kg) = 37.18 – 0.42 Time – 2.62 Dummy – 0.13 Time*Dummy
(26.25) (2.02) (-1.14) (-0.58) R^2= 0.90

The value of the parameters indicate that the price of rice declined by 0.42 Taka per kg per year during 1976–88 and by Taka 0.55 per kg per year during 1988–2007. The acceleration in the downward trend in prices in this recent analysis was found to be statistically significant.

The lower price of rice—following higher rice production and lower unit cost of production—went to keep the vast number of low-income urban consumers and the rural landless and marginal farmers on a stable financial footing. Since the poor spent nearly 50 percent of their budget on rice (30 percent for all consumers), the downward trend in rice prices has been a major factor behind the moderate reduction in poverty that Bangladesh has experienced since the mid-1980s. The incidence of poverty had declined by 1 percent per year during the 1980s and 1990s. The progress was more rapid (at 2 percent per year) during 2000–2005 (Ravallion and Sen 1996; Narayan and Zaman 2009).

4. ENVIRONMENTAL IMPACTS

The expansion of minor irrigation-led boro cultivation has, however, not been without its critics. In recent years, the government has been de-emphasizing the cultivation of boro in favor of aman rice due to some perceived negative environmental effects. The adverse effects mentioned are: (1) pushing out major non-cereal crops—such as pulses and oilseeds—that were important sources of protein and micronutrients for the poor; (2) decline in soil fertility due to raising two MV rice crops, which are heavy users of soil nutrients; (3) heavy use of pesticides, which have led to adverse impacts on the quality of surface water and fish habitats; (4) over-exploitation of groundwater resources leading to adverse impacts on the supply of drinking water; and (5) the arsenic contamination of groundwater that is widely prevalent in Bangladesh (Harvey et. al 2002, Brammer 2009). In this section, we shall touch briefly on these alleged negative effects of the expansion of boro rice and on the basis of the findings of the repeat sample household survey mentioned earlier and other available information.

The expansion of irrigation infrastructure and the *boro* cultivation gave farmers the opportunity to grow two modern rice varieties on the same parcel of land. But such double-cropping of rice is still not widely prevalent in Bangladesh. The parcel-level data from the 2000–01 sample survey indicates that *boro* rice is single-cropped on about 20 percent of the land, which is mostly in the low-lying areas in the flood-prone ecosystem. *Boro* is double-cropped with MV *aman* rice in 18 percent of the land; traditional *aman* is in another nine percent of the area. For parcels that are double- cropped with MV *boro* and MV *aman*, yields were not lower than single-cropped systems of either *boro* or *aman*. Also, the yield for both crops has increased over time. Thus, the validity of the hypothesis that the expansion of *boro* has led to a decline in soil fertility is yet to be confirmed.

The area under pulses and oilseeds has, indeed, declined over time. But, whether it is entirely due to the expansion of *boro* cultivation is again a debatable issue. We have already noted that the major area for the expansion of *boro* has come from the reduction in area under *aus* rice and deepwater *aman*. Only a small fraction of this area has come from other crops and the seasonally fallow land. In fact, it is the expansion of wheat cultivation that has displaced these minor crops more than *boro* rice.

It can be noted from Table 7 that the incidence of pesticide use is indeed very high with *boro* cultivation compared to other rice varieties, and the use of pesticides has grown over time. In 2007, more than 80 percent of the farmers used pesticides in the cultivation of modern *boro* compared to only 9 percent for wheat, 16 percent for traditional *aman*, 37 percent for Jute, and 50 percent for MV *aman*. The rate of the use of pesticides in *boro* is many times higher compared to competing cereal crops, but still substantially lower than other high-value crops such as sugarcane, potatoes, and vegetables. The expansion of *boro* rice has, indeed, contributed to the increased use of harmful agrochemicals.

Table 7. Use of pesticides in the cultivation of different crops, 1988 and 2007

Crops	Percent of farmers using pesticides			Cost on account of pesticides (US$/ha)		
	1987/88	2000/01	2007	1987/88	2000/01	2007
Rice crop variety:						
Aus TV	21	13	33	2.8	0.89	4.41
Aman TV	12	17	16	1.4	1.48	1.92
Aman MV	43	62	50	7.2	7.42	6.40
Boro MV	86	80	82	12.1	3.01	12.7
Other crops:						
Wheat	16	12	9	2.09	1.04	0.78
Jute	24	12	37	4.70	1.53	5.70
Potato	28	94	96	6.20	48.2	63.4

Source: Data from national-level repeat sample survey conducted by the Bangladesh Institute of Development Studies (BIDS), International Rice Research Institute (IRRI) and Bangladesh Rural Advancement Committee. See Table 6.

It was reported earlier that the expansion of dry season irrigated rice farming was heavily dependent on the exploitation of groundwater through shallow tubewells (STWs). Pitman (1993) estimated that by late 1980s 0.77 million ha of land were irrigated with groundwater resources and an additional 1.2 million ha could be irrigated with deep set tubewells. The National Commission on Agriculture estimated that the available potential recharge of the aquifer that could be extracted by STWs had almost been exploited by 1996 (Table 8). Since then, use of STWs has expanded, which suggests that groundwater resources have already been over-exploited. However, the water pumped from the groundwater each year is replaced by the recharge in the wet season. If farmers pump out much more, the recharge will refill the aquifer. Farmers have introduced adjustments in the technology to extend the reach of their STWs, such as digging holes, placing pumps lower in the ground, installing pipes in several places, and moving pumps from one place to another. Recently, they are delaying the planting of *boro* so that they can take advantage of early monsoon rains and reduce their water use. This practice also helps them raise a highly profitable non-rice crop (potatoes, or vegetables) during the winter season from November to February. Farmers have also started using shorter-maturity modern varieties for the *boro* and *aman* seasons.

Table 8. Utilization of groundwater resources through small scale irrigation equipment, 1996 (million cubic meters)

Indicators	Regions				
	North-west	North-east	South-east	South-central	South-west
Available recharge	12,100	23,100	9,800	3,500	5,600
Maximum extractable through DTWs	11,900	14,500	4,700	2,500	4,900
Maximum extractable through STWs	9,900	5,000	1,200	1,000	3,200
Already extracted by tubewells	8,151	4,154	948	524	2,520
Amount required for household & industrial use	185	333	169	79	135
Estimated additional recharge that can be extracted by STWs	1,564	523	83	397	545

Source: Report of the National Agriculture Commission (unpublished report), Ministry of Agriculture, Bangladesh, 1999.

It is now established that the arsenic contamination of groundwater is a serious problem for Bangladesh (Kiniberg and Smedley 2001; Harvey et. al 2002; van Geen et. al 2003; Hossain 2005; and Brammer 2009). But its link with the exploitation of groundwater for *boro* cultivation is yet to be firmly established. It is suggested that arsenic may have recently been released through sulfide oxidation reactions induced by massive increases in the dry season pumping of groundwater. A large-scale study conducted by the British Geological Survey and the Bangladesh Department of Public Health Engineering (Kiniberg and Smedley 2001) concludes, "There is no evidence to support the proposition that the ground water arsenic problem is caused by the recent seasonal drawdown of [the] water table due to [the] recent increase in irrigation abstraction." The study covered samples from 3534 tubewells from 61 of the 64 districts of Bangladesh and from 433 of the 496 *upazilas* (subdistricts). The greatest concentration of arsenic contamination was found in the south and southeast of the country where the coverage of groundwater irrigation is very low. The arsenic contamination was found to be very low in the northwest of the country where groundwater irrigation through shallow tubewells has spread most. However, it has recently become apparent that arsenic-contaminated groundwater that is used for irrigation is seeping into soils and rice in several countries of South and Southeast Asia, thus posing a serious threat to sustainable agricultural production and to the health and livelihoods of the affected people in these countries (Brammer 2009). Since groundwater-dependent *boro* rice now accounts for nearly 60 percent of the annual rice production, the risk is very high for Bangladesh.

5. SUMMARY AND CONCLUSIONS

The rice economy of Bangladesh has made good progress during the past four decades. The rice-cropped area has remained almost stagnant at 10.5 million ha, but rice production has increased from 17 to 41 million tons, almost entirely due to the increase in yield. This yield growth was propelled by the diffusion of dry season irrigated rice farming, locally known as boro rice. The boro rice cultivation—initially limited to the depressed basins in the country—has gradually expanded from very low-lying lands to medium-low and medium-high elevations. The area under cultivation for modern variety boro rice has increased from 0.3 million ha in 1970–71 to 4.4 million ha in 2007–08, and the production ha increased from 1.5 to 26 million tons of paddy rice (17.8 million tons of milled rice). Boro now accounts for 44 percent of the rice harvested area and 60 percent of total rice production. The contribution of boro to overall increases in rice production grew from one-third in the pre-independence period to over 90 percent during 1989–2008.

The expansion of *boro* cultivation has proceeded in full force since the late 1980s, when markets were deregulated for minor irrigation equipment. With unrestricted private-sector imports of agricultural equipment and the lowering of prices, private investment in shallow tubewells for extraction of groundwater has expanded rapidly, as has the area under *boro* cultivation. The process was helped by farmers' own savings and the agrarian structure dominated by small farmers and tenants did not stand in the way of the dissemination of modern agricultural technology.

Nearly 22 percent of farm households now own 1.3 million shallow tubewells that provide irrigation service to 10.2 million of 15 million farm households. The policy of market liberalization may have contributed to an increase in rice yield by 0.96 t/ha, or 58 percent of the increase in average rice yield over 1989–2008. It contributed to an incremental rice production of 5.9 million tons per year, which would feed about 22 million people. The adoption of improved technology in *boro* rice farming has helped reduce the unit cost of rice production and, thereby, keeps rice prices affordable for the poor. The unit cost of production of *boro* rice was lower by 20 percent in 1988 and 17 percent in 2007, compared to rainfed *aus* rice. Since *boro* cultivation is more labor-intensive than *aus*, the change in variety composition also generated an additional 52 million person days of employment, equivalent to 238,000 full-time jobs. The income gains were estimated at US$ 222 per ha in1988, and US$ 157 in 2008. The expansion of *boro* farming using shallow tubewells has, however, led to some adverse environmental effects, such as the increased use of harmful agrochemicals (pesticides) and the over-exploitation of groundwater resources.

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