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Research Report No. 2

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Executive Summary

Increased groundwater accessibility resulting from the expansion of deep and shallow tube wells helped Bangladesh attain near self-sufficiency in rice, with national output increasing over 15 million tons in the last two decades. Available evidence suggests that the policy focus so far has been largely on "*resource development*", and not on "*resource management*". This has resulted in serious problems, most notably excessive drawdown in intensively irrigated areas, and the deterioration of groundwater quality. Increasing energy prices are also threatening the sustainability of Bangladesh's groundwater irrigated economy. The forefront challenge, therefore, is to take the necessary corrective measures before the problem becomes either insolvable or too costly to remediate. We suggest that attention must be given to the development and management of surface water resources to ease pressure on groundwater. In addition to supply-side solutions, water demand will also need to be curtailed by increasing water use efficiency through the adoption of water conserving management practices, for example reduced tillage and raised bed planting, and the right choice of appropriate crops. Decreasing water availability both in terms of quantity and quality suggest that the unchecked expansion of dry season *boro* rice cultivation is probably not a long-term option for Bangladesh. Therefore cropping patterns need to be rationalized – starting with the promotion of feasible alternatives to *boro* – considering water availability and the sustainability of aquifers. In the absence of proper institutional arrangements, evaluation of strategic options and monitoring the implementation of national policies for the public water sector will remain a challenge. At present, seven different agencies are responsible for the management of groundwater. In addition to technical solutions, we therefore conclude that strong linkages and improved communications between different organizations involved in the management of groundwater resources, and alignment of objectives, will be required.

Key Messages

1. Currently, 35,322 deep tubewells, 1,523,322 shallow tubewells and 170,570 low lift pumps are working in Bangladesh to provide water for irrigation. About 79% of the total cultivated area in Bangladesh is irrigated by groundwater, whereas the remaining is irrigated by surface water.

2. More than 90% of the pumps within Bangladesh are run by diesel engines. The remaining 10% use electricity. Despite subsidies on electricity, diesel pumps are preferred by farmers due to low capital cost and mobility ease within small and fragmented farm lands.

3. Each year, on average, about 980 million kwh of electricity is used by electric tubewells with an estimated subsidized cost of USD 50 million. The annual diesel consumption for groundwater extraction is of the order of 4.6 billion liters, costing USD 4.0 billion in aggregate.

4. The Arsenic contamination in groundwater is increasing at an alarming rate. Today, in Bangladesh, an estimated 35–77 million people have been chronically exposed to Arsenic via drinking water. An estimated 25% of the wells exceed Arsenic levels according to the Bangladesh standard.

5. Improving water use efficiencies through the adoption of resource conserving crop management practices such as alternate wetting and drying (AWD), direct-seeded rice, and bed planting could help in reducing groundwater demand for agriculture. Fixed-irrigation rates, non-availability of water on needed schedules, and lack of technical understanding are the major constraints in the wide scale adoption of AWD in Bangladesh.

6. (Ground) water demand for irrigation can also be reduced by rationalizing cropping patterns. Decreasing water availability both in terms of quantity and quality suggest that the unchecked expansion of dry season rice cultivation is probably not a long-term option for Bangladesh.

7. For sustainable groundwater management, involvement of water users, investments in improved water and agricultural technologies, charging water on a volumetric basis or crop specific pricing, fixing quotas for groundwater extraction, facilitate markets for non-rice crops, promotion of alternative cropping patterns, and extra support for farmers making transition to less water demanding crops is needed.

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1. Introduction

Groundwater is an important resource for livelihoods and the food security of billions of people, and especially in booming Asia's agricultural economies. Globally, groundwater provides approximately 50% of current potable water supplies, 40% of the industrial water demand, and 20% of the water used for irrigation (UNESCO 2003; Molden 2007). In Asia and the Pacific, on average, about 32% of the population uses groundwater as a drinking water source (Morris et al. 2003). However, there are regions where dependence on groundwater for drinking purposes is much larger. For example, 60% of the rural population in Cambodia relies on groundwater (ADB 2007a) and 76% of people who do not have access to piped system depend on tube wells in Bangladesh (ADB 2007b; ADB 2007c).

Groundwater provides approximately 50% of current potable water supplies, 40% of the industrial water demand, and 20% of the water used for irrigation.

Due to shortage and inconsistencies in surface water supplies, groundwater acts as the mainstay for agriculture in India, Northern Sri Lanka, the Pakistani Punjab, Bangladesh, and the Northern China Plain. In India, groundwater provides about 60% of the total agricultural water use, accounting more than 50% of the total irrigated area (Shah et al. 2003). In the North China plains, groundwater extraction accounts for 65%, 70%, 50% and 50% for the total agricultural water supply for the provinces of Beijing, Hebei, Nanan and Shandog, respectively (Li 2001). Tube well irrigation has helped India and China to move towards food security for their massive population and to improve the livelihoods of the rural poor. In Pakistan, groundwater contributes more than 50% to the total crop water requirements in the Punjab, which produces 90% of the national grain output (Qureshi et al. 2008; Qureshi et al. 2010).

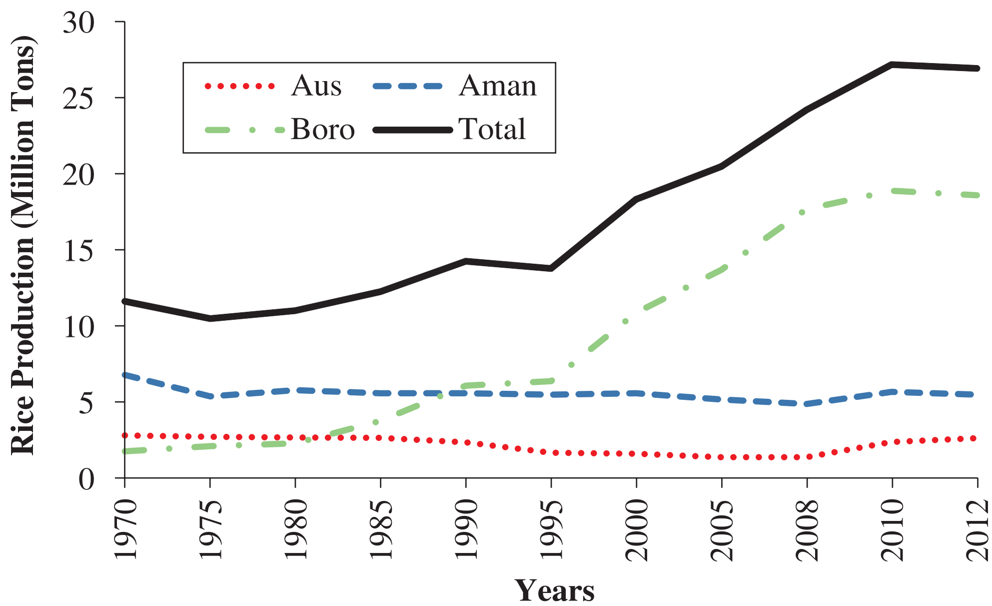


FIGURE 1.

Production of *aus, aman* and *boro* rice in Bangladesh (BBS 2013).

Agriculture is the major user of water in Bangladesh, with rice cultivation as the single most important economic activity. Rice is the staple food in the country, and is grown on 75% of the total cultivated land, constituting 90% of the total food grain production (BADC 2013). There are three main seasonal types of rice grown in Bangladesh i.e. *aus, aman and boro. Aus is rainfed, pre-monsoon rice, and is typically low yielding. Aman rice is grown during the monsoon (rainy) season and is also lower yielding*, whereas *boro* is irrigated and high yielding rice production grown during the dry winter season (January through June). Due to its comparatively higher yield potential (3.4 tons ha^{-1}) compared to aus (1.6 tons ha^{-1}) and *aman* (2.0 tons ha^{-1}), *boro* rice production has expanded in the last two decades (Talukder et al. 2008). During 1991-2013, *boro* rice production increased from 6.8 to 18.8 million tons whereas the production of *aus* and *aman* largely remained constant (Figure 1). *Boro* rice is currently cultivated by 9.8 million households covering an area of 4.8 million ha, contributing about 55% of the overall rice production in Bangladesh (BBS 2013). *Boro* has helped Bangladesh to increase its total rice production from 18.3 million tons in 1991 to 33.8 million tons in 2013.

The dramatic increase in *boro* production was due largely to the extensive exploitation of groundwater. Presently, about 80% of groundwater is used for irrigation, of which 73% is used exclusively by *boro* farmers (Rahman and Ahmed 2008). However, groundwater irrigation also has serious consequences as energy costs are increasing, water levels are declining in the intensive irrigated areas of northern Bangladesh, and groundwater quality is deteriorating. Due to high installation, operational, and management costs, the large-scale development of surface water resources in Bangladesh will remain a challenge in near future. Groundwater irrigation will therefore remain crucial to sustain agrarian growth to meet Bangladesh's future food requirements. Recognizing the important role that groundwater will play in the future to support rural economies within Bangladesh, its availability in terms of quantity and quality must be ensured. Therefore, it is imperative to understand the issues and challenges of groundwater use in Bangladesh and to evaluate options for its sustainable management.

The population of Bangladesh was 145 million in 2008, which is expected to increase to 182 million by 2030 under the median population projection scenario. Accordingly, the total demand for rice to meet the needs of this population will increase to 39 million tons. The food demand for wheat will increase by 0.65 million tons from the 2008 consumption level. On the other hand, the food demand for coarse cereals, mainly maize, will increase 1.46 million tons (or by 124%) from the 2008 level (Amarasinghe et al. 2014). Forecasts of *boro* rice yield, area expansion and production show that the country can meet these targets. However, this will come at a considerable environmental cost because groundwater use for irrigating *boro* will further increase, which will have serious imbalance in groundwater recharge and discharge in many locations. Despite these looming challenges, management of groundwater is still not high on the agenda of farmers or policy makers. The lack of robust information on aquifer reserves, their withdrawal patterns, changes in quality, and consequences of use for irrigation are poorly understood. This paper fills this gap by reviewing patterns of groundwater development, including the benefits it has imparted in terms of increased crop yields and area cultivated, as well as the problems associated with groundwater development and future challenges. We also discuss the prospects of sustainable groundwater management to support irrigated agriculture in Bangladesh, and conclude with policy recommendations for the rational management of groundwater resources.

2. The Physical Context

Bangladesh is located at the lowermost reaches of Ganges–Brahmaputra-Meghna river system which drains 1.72 million km2 of land. Crucially, Bangladesh itself comprises only 8% of the watershed.

Bangladesh is largely covered by the alluvium deposited by the Ganges, Brahmaputra, and Meghna rivers, making it one of the largest deltas in the world (Ahmad et al. 2001). Bangladesh is a riverine country and boasts a network of over 230 tributaries and distributaries. There are 57 cross-boundary rivers, of which 54 are shared with India, with the remaining three entering from Myanmar (Chowdhury 2010). Bangladesh is located at the lowermost reaches of Ganges–Brahmaputra-Meghna river system which drains 1.72 million km^2 of land. Crucially, Bangladesh itself comprises only 8% of the watershed (Ahmad et al. 2001; Chowdhury 2010). These rivers are an essential part of Bangladesh culture. They are the country's lifeline and support a diverse agriculture, provide transportation, support industries, and furnish various types of livelihoods for the inhabitants. Surface water irrigation, however, has not been fully exploited, due to poor maintenance and management, and historical negligence in the development of new surface water infrastructure. Conversely, groundwater irrigation has increased dramatically over the last three decades.

The total length of rivers within Bangladesh is ~22,000 km. The internal renewable water resources are estimated as 105,000 Mm^3 per year. This includes 84,000 Mm^3 of surface water produced internally as stream flows from rainfall, and about 21,000 Mm^3 of groundwater resources (Rajmohan and Prathapar 2013). Part of the groundwater comes from the infiltration of surface water with an external origin. Since annual cross-border river flows and entering groundwater are estimated to be 1,121,600 Mm^3, the total renewable water resources are, therefore, estimated at 1,226,600 Mm^3 $year^{-1}$ (FAO 2011).

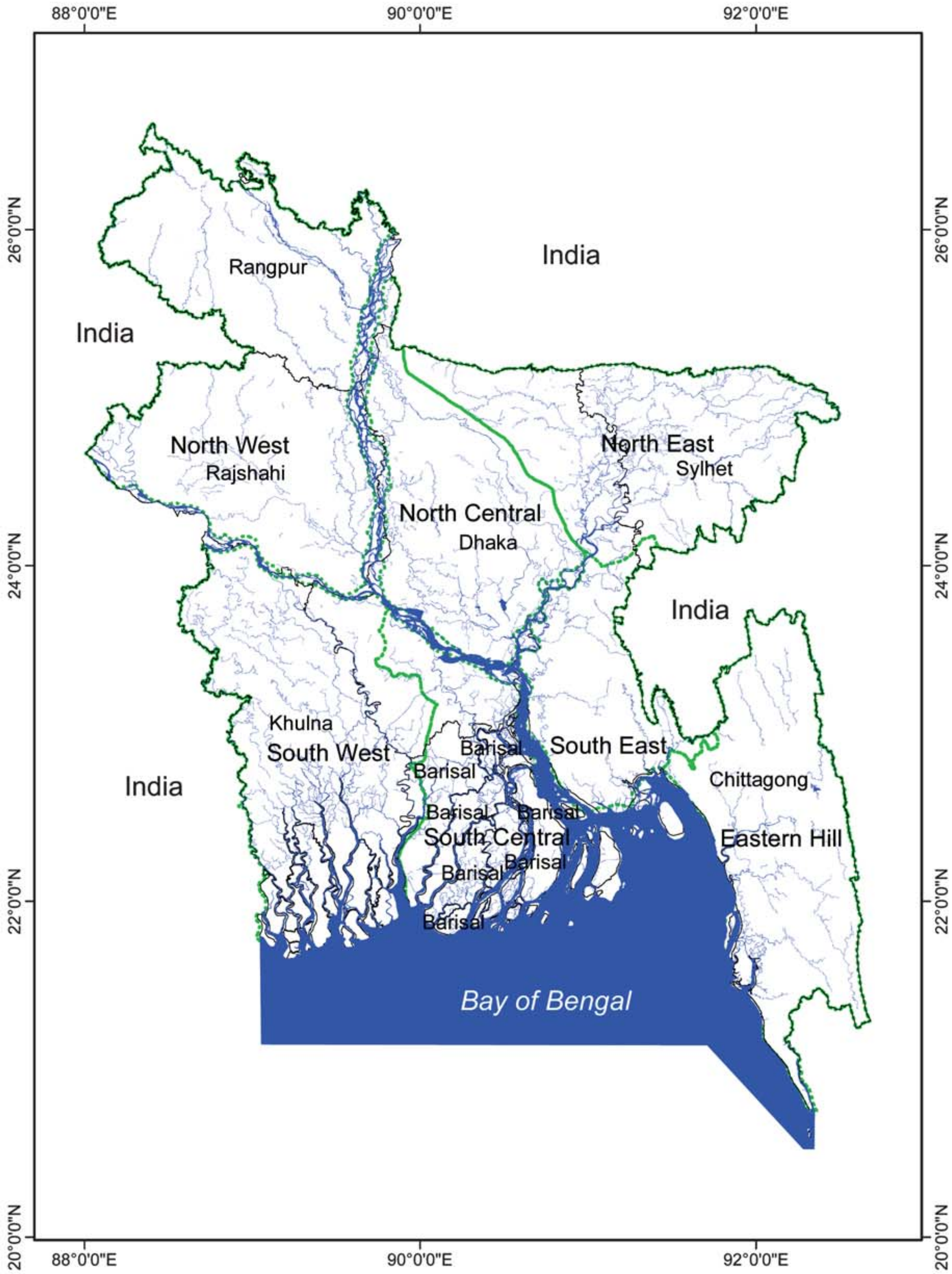


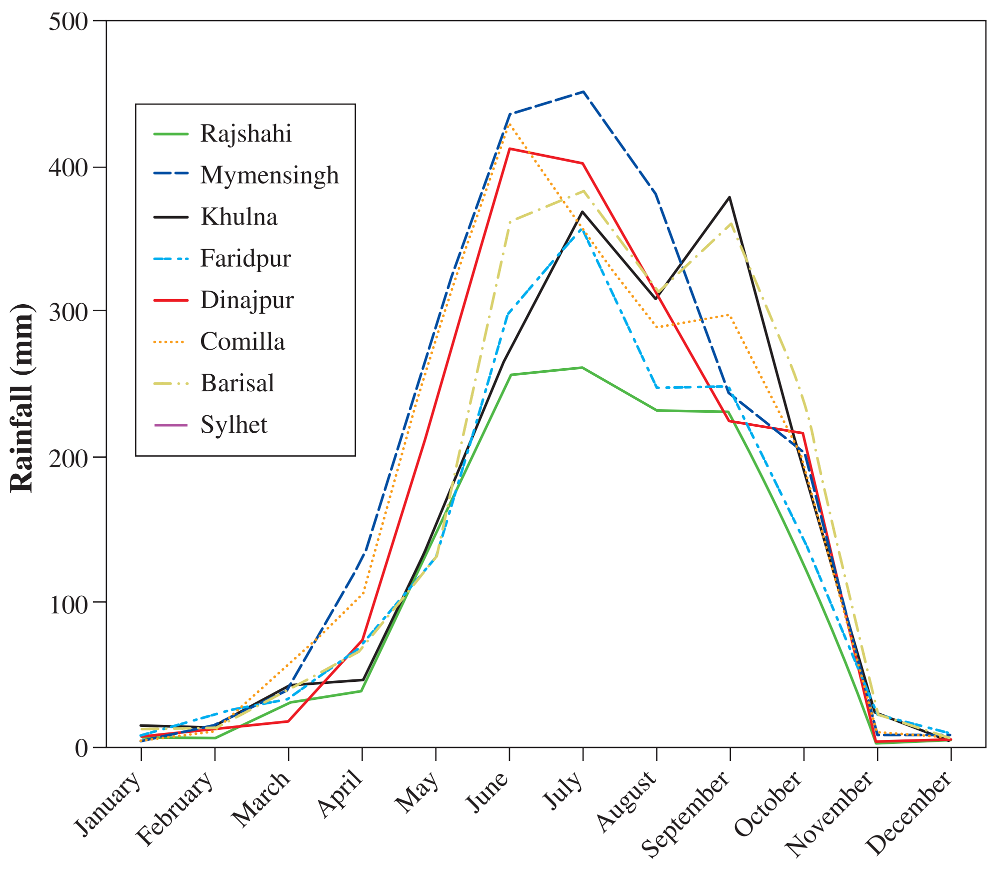
FIGURE 2.

Map of Bangladesh indicating the North West, North East, North Central, South Central, South East, and Eastern Hill hydrological regions.

The availability of surface water is not consistent because of seasonal variation. Ninety-five per cent of the surface water in the river system also originates outside the country (Ahmad et al. 2001). This introduces uncertainty in surface water availability. For example, the availability of surface water in 1990 ranged from 3710 Mm^3 during the dry season to 111,250 Mm^3 during the wet season (Bangladesh Bureau of Statistics 2013). Bangladesh experiences a tropical monsoon climate with significant variations in rainfall and temperature. Average annual rainfall varies from 1,200 mm in the extreme west to over 4,000mm in the northeast (Chowdhury 2010). About 80% of all rainfall occurs during the monsoon from June to September (Figure 3). In the post-monsoon (October–November) and winter period (December–February), only 20% of the annual rainfall is available. Therefore there is a seasonal water shortage depending on the duration of the monsoon.

FIGURE 3.

Average monthly and annual rainfall in selected regions of Bangladesh over 2002-2012 (BMS 2013).



Rice production is the single most important activity in the agricultural economy of Bangladesh. In the dry winter months, more than 70% of crop production is *boro* rice, which can use up to 11,500 m^3 per ha of water in the production process (Biswas and Mandal 1993; Chowdhury 2010). During the dry season, 58% of the Bangladesh's available fresh water is allocated to irrigation, 41% is used for fisheries and navigation, whereas less than 1% is used by domestic and industrial sectors (Chowdhury 2010). In northern Bangladesh, surface water shortages and the easy access to groundwater through STWs has prompted farmers to extract groundwater for irrigation, industrial and domestic purposes. In southern Bangladesh, however, surface water is abundant, though drainage facilities are largely non-existent. Combined with low-lying landscape depressions that can pool water, and tidal water movement in the estuary system, these factors can cause consistent monsoon season flooding.

The food insecurity and poverty nexus is also pervasive in Bangladesh. About 70% of Bangladesh's total population of 152 million is dependent on agriculture (BADC 2013). In the next 25 years, the country's population is expected to increase by 40%, which will increase the rice demand by 29%, unless dietary changes take place. This situation is however complicated because total cultivable land is expected shrink by 4.4% due to increasing urbanization (Hassan et al. 2013), with important ramifications for food security. Despite the increase in aggregate grain production and per capita food availability, Bangladesh is still importing an average of 2.0 million tons of food grain each year to meet domestic demand (Taludker et al. 2008). This imbalance underscores the urgent need to increase land productivity to meet future food security challenges.

3. Patterns of Groundwater Development and use in Bangladesh

3.1. Contours of groundwater development

However, despite large investments, success has been limited and only 7% of the total irrigable area envisioned was covered by these projects.

Until 1970s, the government prioritized the development of surface irrigation schemes such as the Gangees-Kodak Project, Teesta Barrage or Meghna-Dhonagoda Projects. However, despite large investments, success has been limited and only 7% of the total irrigable area envisioned was covered by these projects (Dey et al. 2013). With the introduction of high yielding rice varieties in 1980-90s that responded favorably to irrigation and fertilizer, and which were suitable for *boro* rice, demand for reliable irrigation increased. Since aquifer conditions were favorable in most parts of the Teesta, Brahmaputra-Jamuna and Ganges river floodplain, the attention was diverted to the development of groundwater resources.

The installation of deep tube wells (DTWs)[1] started in the late 1960s, but gained momentum in late 1980s. By the 1992, about 25,500 DTWs were installed throughout the country (BADC 2013). Currently, 35,322 DTWs are working in Bangladesh to provide water for irrigation purposes. The expansion of DTWs was followed by the development of shallow tubewells (STWs)[2] with discharge capacities of 10-12 l sec^{-1}. However, despite visible benefits of groundwater irrigation, STWs were not initially adopted due to restrictions on tubewell spacing and embargo on the import of all types of diesel engines (Dey et al. 2013). Things however changed following the devastating floods of 1988 and subsequent cyclones in the early 1990s. Realizing the need for agricultural machinery to kick-start farming economies back into action, the government lifted all restrictions and embargos on the import of irrigation equipment. Consequently, local markets were flooded with inexpensive and easy to operate irrigation pumps and small (<12 HP) engines, mainly from India and China.

1. *Deep tubewells are defined as the cased wells into which a pump is installed. A diesel or electric motor is mounted above the well and connected to a centrifugal pump by a shaft. Submersible pumps are also used in DTWs for lifting water from deeper depths. These pumps are expensive and require considerable technical skills for installation and operation. There for ehistorically they have usually been owned by government or group of farmers or cooperatives. The average command area irrigated by a DTW in Bangladesh is about 26 ha (BADC 2013).*

2. *Shallow tubewells (STWs) are installed in shallow aquifers and have a discharge capacity of about 12-15 l sec^{-1}. STWs are driven by surface mounted centrifugal pumps and can lift water from a depth of ~50 m. They are relatively inexpensive, easy to install and maintain and are shared by small groups of farmers. The average area irrigated by a STW in Bangladesh is about 2-4 ha (BADC 2013).*

The increased availability of equipment led to the maturation of Bangladesh's mechanized agricultural economy. Today, in addition to 35,322 DTWs, 1,523,609 STWs, there are 170,570 low lift pumps (LLPs)[3] used for surface water that are operating in the country (BADC 2013). The leap in the population of STWs was linked their suitability to the prevailing socio-economic conditions of Bangladesh's burgeoning *boro* farmers (less investment cost, small land holdings, and easy of availability of pumps and spare parts in the local market). The temporal development of DTWs, STWs, and LLPs in Bangladesh is shown in Figure 4. Currently, about 79% of the total cultivated area is irrigated by groundwater, whereas the remaining is irrigated by surface water (BADC 2013).

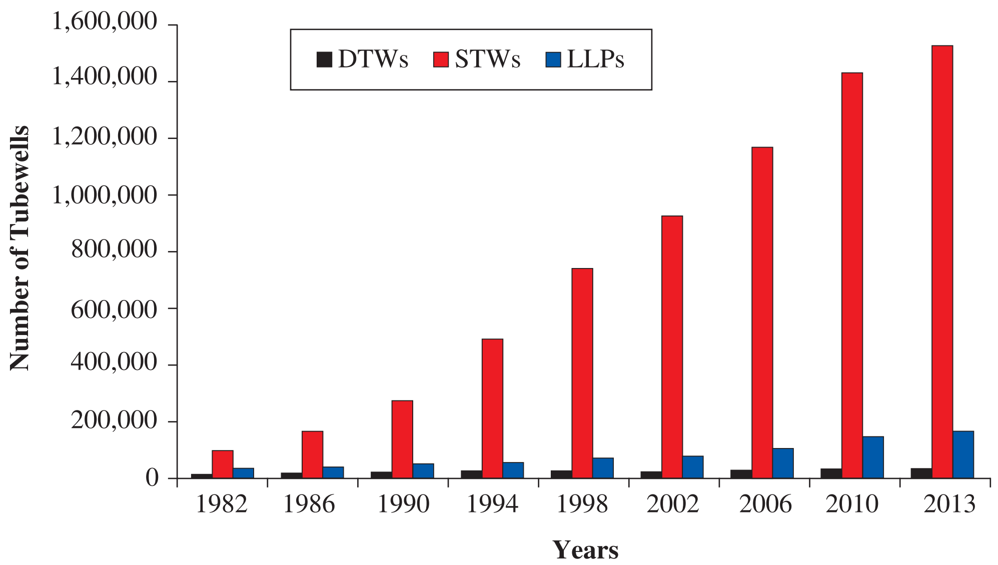


FIGURE 4.

Historical development of different types of pumps in Bangladesh (BADC 2013).

3.2. *Patterns of groundwater use*

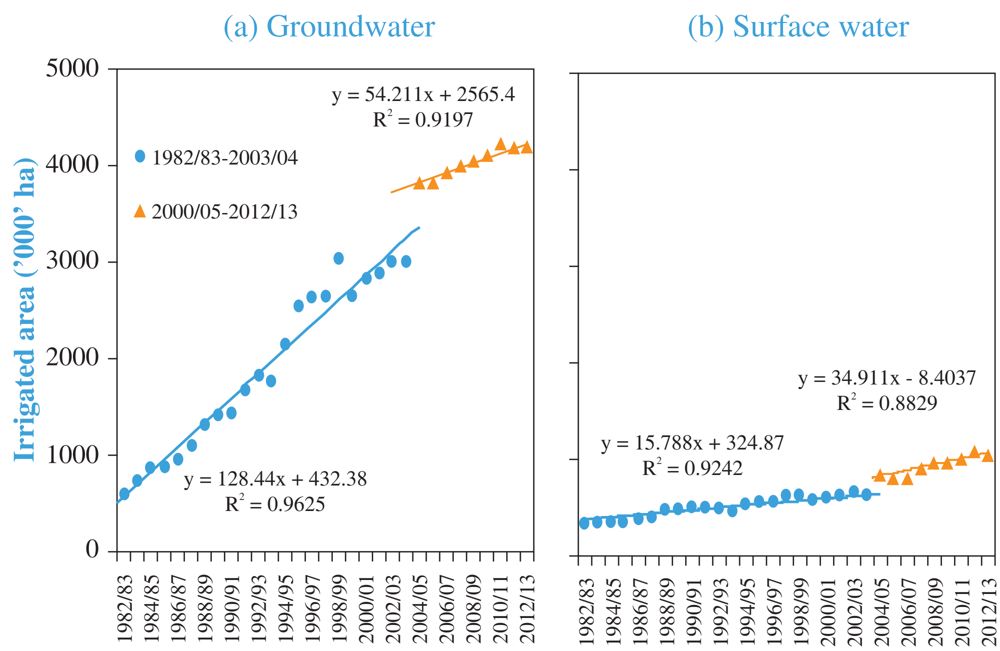
The introduction of high yielding varieties in 1980s revolutionized rice cultivation in Bangladesh. Increased water availability encouraged farmers to grow irrigated *boro* rice during the dry winter season. Currently, about 4.2 million ha of land is irrigated by groundwater (both shallow and deep tubewells) whereas only 1.03 million ha is irrigated by surface water using low lift pumps (BADC 2013).

There was continuous increase in the groundwater irrigated area until 2005, when it slowed. In contrast, area irrigated by surface water expanded more rapidly after 2005. This was probably due to decline in groundwater table depths in most intensified areas which increases costs of groundwater irrigation. The area irrigated by surface water declined from 76% in 1981 to

3. *Low lift pumps (LLPs) are operated by diesel or electric motor for lifting water from different water bodies i.e. rivers, canals or ponds. The discharge of these pumps various from 25 to 100 l sec^{-1} and mainly used for surface water irrigation. The average area irrigated by a LLP in Bangladesh is about 6 ha (BADC 2013).*

FIGURE 5.

Area irrigated with (a) surface water and (b) groundwater in Bangladesh (BADC, 2013).



23% in 2012, whereas for the same period, area irrigated by groundwater has jumped to 80% from 16% (BADC 2013). The expansion in surface irrigated area may be partially attributable to the availability of low lift pumps that increased access to surface water. Compared to other parts of the country, the area under groundwater irrigation is considerably higher in the north-western, mid south-western and north-central regions (Figure 6a). On the other hand, the north-eastern and south-central regions have large areas occupied by surface water irrigation (Figure 6b), though not in the same density as found for groundwater irrigation.

About 80% of the total groundwater is used in three divisions in the north central and western hydrological zones *i.e.* Dhaka, Rajshahi and Rangpur (Table 1). In the north-west, groundwater irrigation is likely to continue until the limits of land or sustainable groundwater withdrawals are reached. Dry season groundwater irrigation over a seven-month period depends on adequate recharge in the five-month monsoon period. If recharge is not more or at least equivalent to discharge, round the year irrigation will accelerate groundwater depletion resulting in an excessive decline in water levels. Shamsudduha et al. (2011) conversely found that groundwater recharge is higher in the north-west than the south and north-east, respectively, a function of increased groundwater extraction in the former zones. Their results are interesting as they demonstrate problems with the concept of safe water yield estimated by hydrologists under non-pumping conditions, a result of the high degree of spatial variability in recharge rates, especially in intensively irrigated areas. They contended that deep groundwater extraction may result in increased shallow aquifer recharge via rainfall and surface irrigation, although the current abstraction rates in irrigated areas were

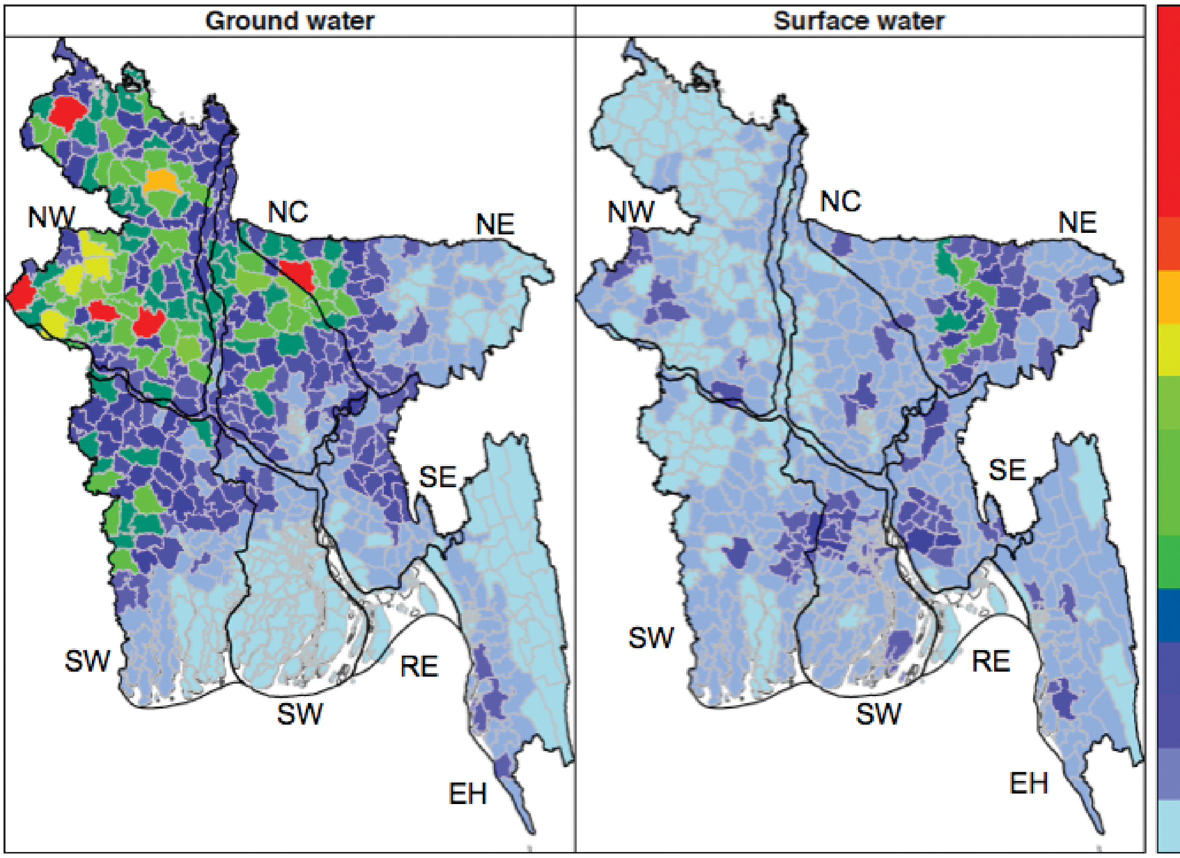


FIGURE 6.

Hectares irrigated by groundwater and surface water by sub-district in the eight hydrological regions of Bangladesh (Data: BADC 2012). NW: Northwest. SW: Southwest. SC: South Central. RE: River and Estuary. EH: Eastern Hills. SE: South East. NE: North East. NC: North Central.

nonetheless deemed to be unsustainable in volume. Farmers of these regions have already started switching to more profitable and less water-intensive crops such as maize. If continued, this trend will slow down the water table drawdown.

About 90% of the pumps within Bangladesh are run by diesel engines. The remaining 10% use electricity (BADC 2013). Diesel pumps usually have higher costs and lower water extraction capacity than electric pumps (Wadud and White 2002). But despite subsidies on electricity, diesel pumps are preferred by farmers due to low capital costs and mobility ease within small and fragmented farm lands. Increasing power cuts and the generally poor electricity network in many rural areas comprise other potential reasons for farmers' diesel pump preferences.

In addition to irrigating their own lands, the owners of STWs also provide irrigation services to their neighbours for a fixed seasonal fee in cash or through payment in produce. These 'informal' water markets are quite

Table 1. Population and area irrigated by DTWs and STWs in seven divisions of Bangladesh in 2013.

Divisions	**Deep Tubewells**		**Shallow Tubewells**	
	Population (No.)	Area Irrigated (ha)	Population (No.)	Area Irrigated (ha)
Dhaka	6918	170,088	408,767	1,054,963
Rajshahi	16352	467,133	348,267	713,389
Rangpur	6515	157,798	414,546	785,944
Chittagong	2329	62,720	63,047	166,268
Khulna	3064	68,895	281,824	484,944
Barishal	1	20	45	240
Sylhet	143	7,688	6,534	36,692
Total	**35322**	**934,352**	**1,523,609**	**3,242,440**

(Source: BADC 2013)

mature, and provide one of the most promising institutional mechanisms for increasing access to irrigation from groundwater, particularly for tenants and small farmers. With the expansion of water markets in the private sector, irrigation sellers have adapted their pricing systems to suit farmers' varying circumstances. Water fees vary from one area to another depending on the type of well and depth of water availability. Initially, the most common practice was sharing one-fourth or one-sixth of the harvest with the owner of the pump in exchange for water, or on a fixed cost-per-season basis (Biswas and Mandal 1993). However, with the increasing diesel prices, the market is slowly moving towards water charges on per hour of tube well operation, which approximates volumetric water pricing, though tail-end farmers often bear the brunt of the costs.

4. Problems of Groundwater Development

4.1. Declining water tables due to groundwater overdraft

The substantial drawdown of aquifers due to over-exploitation of groundwater during the last decade has been widely documented (Jahan et al. 2010; Shahid 2011). Using data from the Bangladesh Water Development Board (BWDB), we have determined that in areas with water tables less than 8 m in depth, decline has increased significantly over time. Between 1998–2002, this area was only ~4% of the country's total, but increased to 11% in 2008 and 14% in 2012 (Figure 7). The most significantly affected areas lie in the north-west (e.g., Braind Tract) and north-central (i.e., Madhupur Tract) regions. These are areas of intensive *boro* cultivation and exhibit declining long-term groundwater trends (Shamsudduha et al. 2009). In the north-western region, water tables are declining steadily but more slowly (0.1- 0.5 m year^{-1}), making the use of STWs tapping shallow aquifers unsustainable for intensive *boro* irrigation (Shamsudduha et al. 2009; Dey et al. 2013).

Using data from the Bangladesh Water Development Board (BWDB), we have determined that in areas with water tables less than 8 m in depth, decline has increased significantly over time.

In contrast, groundwater levels are slowly rising in southern Bangladesh, a consequence of seawater intrusion and tidal movement (1.3–3.0 mm year^{-1}), creating waterlogged conditions (Brammer 2014). In the coastal zone, three groundwater aquifers are recognized: the shallow aquifer, lower shallow aquifer, and deep aquifer, within 20-50 m, 50-100 m, and 300-400 m of the ground surface, respectively. Shallow aquifers may consequently be salinity affected, whereas little concrete information is available for deep aquifers (Mainuddin 2013). Unlike the north-west, water tables are generally shallow and remain consistent for most of the year, except slight increases during the monsoon season. The existing cropping system is therefore dominated by *Aman* rice in the wet season, and *Boro* rice, shrimp or prawn aquaculture (depending on saline and non-saline water availability), and finally leguminous species (lentil (*Lens culinaris*), lathyrus (*Lathyrus sativus*), and mungbean (*Vigna radiate*)) in non-irrigated areas during the dry season. However, the extent of dry season cropping is limited mainly due to lack of irrigation water and soil salinity, meaning that only about 41% of the cultivable area can be irrigated compared to 63% at the country level. There are over 700,000 ha of under-utilized medium highlands that can potentially be brought under intensified cultivation during the dry season by making irrigation available (Chowdhury 2010). Groundwater use in the coastal zone is largely unexploited due to salinity concerns in shallow and lower shallow aquifers, and the prohibitively high cost of DTW installation.

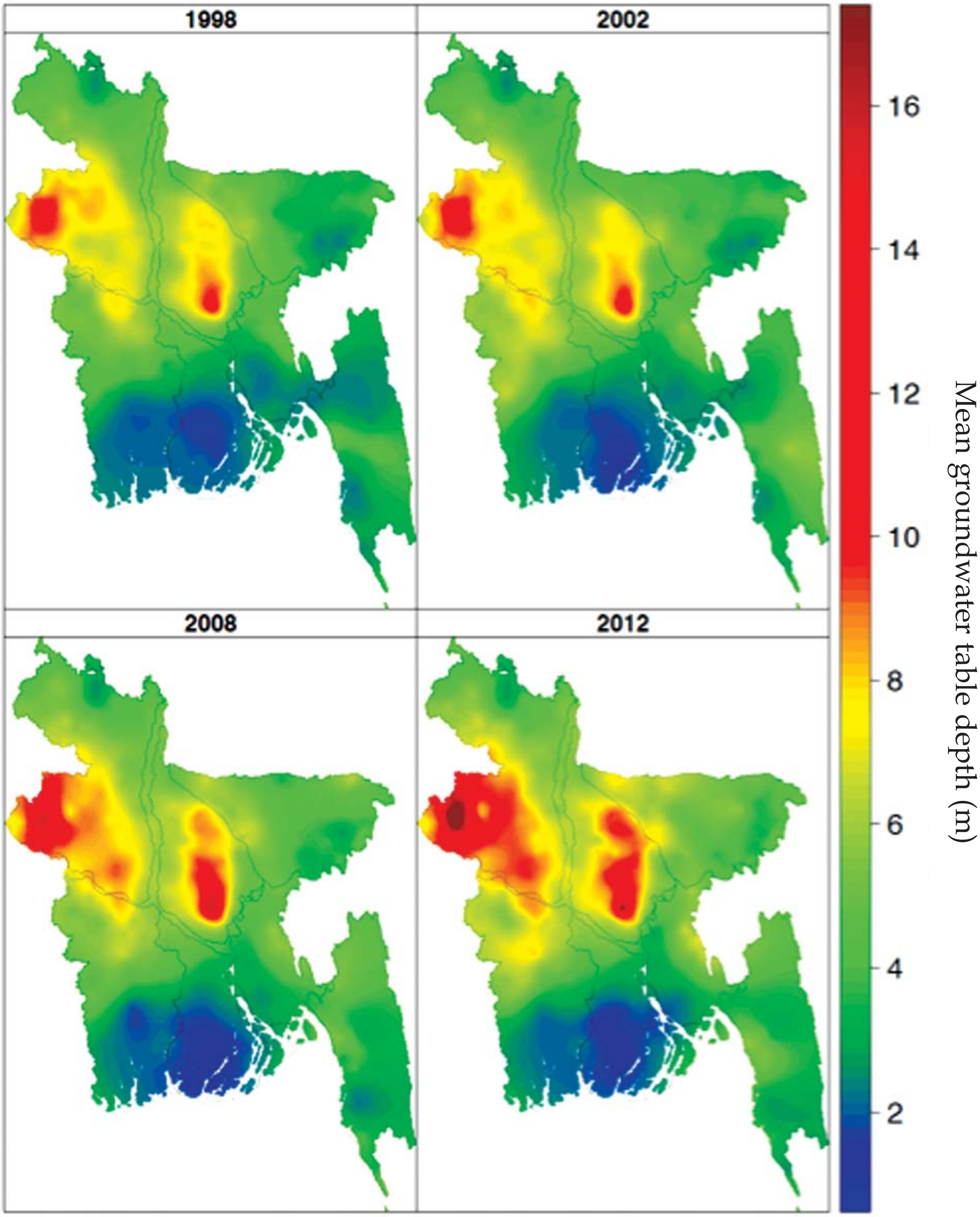


FIGURE 7.

Mean ground water table depth (m) for the height of the dry season (March, April and May). Surface maps were created using multi GussianKriging from the time series data of observed groundwater levels from the Bangladesh Water Development Board (BWDB).

4.2 Groundwater-Energy Nexus for Bangladesh

Groundwater irrigation requires large amounts of energy to lift water from underlying aquifers. Currently, about 32,412 DTWs are electrified; the rest 2910 are diesel operated (BADC 2013). Out of the 1.52 million STWs in Bangladesh, only 0.25 million are electric whereas the remaining 1.27 million are diesel. In 2012, about 49 billion kwh of electricity was generated in Bangladesh, and about 2% of this total generation was used to pump groundwater for irrigation, giving total agricultural consumption of 980 million kwh (BEB 2012). The Government of Bangladesh has consequently introduced a flat tariff system of 0.04 USD kw h^{-1}. The subsidized cost of this electricity is about USD 50 million. Despite subsidies on electricity, diesel pumps are preferred by farmers due to low capital costs and mobility ease within small and fragmented farm lands. Increasing power cuts and the generally poor electricity network in many rural areas comprise other potential reasons for farmers' diesel pump preferences.

In the north-west, diesel operated STWs are used primarily for irrigating *boro* rice, and partially for supplemental irrigation to *aman* and *aus* rice and other crops. During the *boro* season, average operational hours of deep and shallow pumps are about 1,445 (Table 2). For other seasons and crops, operational hours are considerably lower (300-400 hours). Al-Masum (2012) therefore conservatively estimated that each pump used for *boro* is operated for 1,800 hours in a year. Shah (2007) and Mukharje et al. (2009) reported that diesel pumps are operated for 1900 hours per year in Bangladesh.

Table 2. Operational characteristics of deep, shallow and low lift pumps for *Boro* rice season

Pump type	HP	Operation per *Boro* season (days)	Operation per day (hours)	Total operation (hours)	Fuel Consumption (litres/hr)
Deep Pumps	56	85	17	1,445	4.25
Shallow Pumps	10-15	85	17	1,445	1.5 -2.5

(Source: Al-Masum 2012)

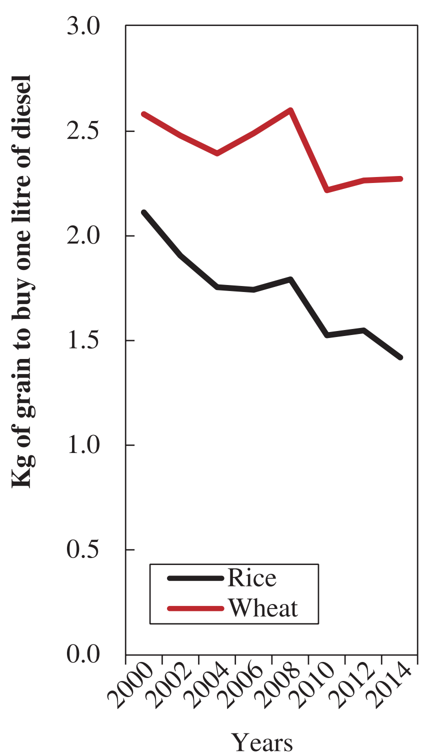
About 95% of shallow tubewells in Bangladesh are run using Chinese diesel engines of 10-15 hp capacity. They consume about 4.6 billion litres of diesel every year to pump groundwater for *boro* and the irrigation of a subsequent crop, costing USD 4.0 billion in aggregate. This cost is in addition to USD 1.4 billion of yearly energy subsidies supplied by the government to sustain groundwater irrigation (BIDS 2012). Such considerable investments have raised serious concerns about the financial sustainability of Bangladesh's groundwater-based agricultural economy. Realizing this situation, the Bangladeshi government recently implemented the "Master Plan for Development in the Southern Region" that requests foreign investments of over $7 billion to increase cropping intensity and to expand the use of surface water irrigation (SWI) in southern Bangladesh (MOA and FAO 2012).

Groundwater irrigation in South Asia generally has begun to contract in response to increasing energy prices (Mukharji et al. 2009). This squeezing is a combined outcome of three factors: (i) progressive reduction in electrical connections on subsidized rates, (ii) growing prices of equipment, and (iii) increasing diesel prices over the last 10 years (Mukharji 2007). A survey of 2,600 tube well owners conducted in India, Pakistan, and Nepal ranked 'energy cost and availability' as the top challenge for groundwater irrigation, in comparison to 'groundwater depletion' and 'rising groundwater salinity levels' (Shah 2007). However, in Bangladesh, groundwater irrigation is still viable, though propped up by considerable government subsidies.

In 2000, the price of one liter of diesel in Bangladesh was equivalent to 2.0 kg of rice, whereas in 2014, the equivalency declined to 1.36 kg (Figure 8). However, due to consistency in the increase of wheat price in relation to diesel prices, the profit margin for wheat remained small (from 2.58–2.27 kg of wheat to buy one liter of fuel). This is perhaps the reason that despite water availability challenges, *boro* is still considered as the most preferred *Rabi* cropping. However, this equation would change with further increases in diesel prices, or if subsidies are even partially withdrawn.

FIGURE 8.

Kilograms of grain to buy one liter of diesel (Data: BBS 2013)



The cost of lifting water with diesel operated STWs in Bangladesh is USD 51 ha^{-1} compared to only USD 20 for electrical pumps of the same capacity (12 l sec^{-1}). Farmers using diesel operated STWs for *boro* spend about 57% of their total production costs on irrigation, compared to 42% for electrically driven pumps (Dey et al. 2013). For diesel operated DTWs, energy costs are about USD 70 ha^{-1} compared to USD 40 ha^{-1} for the electric pumps of the same capacity (50 l sec^{-1}). The energy cost for diesel operated DTWs is consequently 41% of the total production cost of *boro*, whereas for electric DTWs, it is only 34%. In addition to subsidies on electricity, the higher costs for diesel operated pumps are also due to their low efficiency, which rarely exceeds 25%, compared to 35% for electric pumps (Hossain and Deb 2003). This low efficiency is usually attributed to their sub-standard manufacturing and poor maintenance.

The unit price of *boro* rice in Bangladesh is also directly linked to energy markets. The cost of irrigation for *boro* has increased from USD 51 ha^{-1} in 1989 to over USD 141 ha^{-1} in 2011. If the present trends continue, the irrigation cost of *boro* rice is expected to reach to US$ 200 ha^{-1} in 2030 (Dey et al. 2013). As the genetic and agronomic scope for yield increase in rice is limited (Cassman et al. 2003), increasing irrigation costs will reduce farmers' net incomes, further threatening the economic foundations upon which *boro* rice production is based.

4.3 Arsenic contamination of groundwater

Drinking water has been the main focus of attention since the early 1990's when widespread contamination of groundwater by Arsenic (As) was discovered in shallow aquifers of Bangladesh (BGS-DPHE 2001). However, As contamination in groundwater has implications for agricultural as well as potable water supplies. In Bangladesh, nearly 35 million people are at risk from As, as concentrations in drinking water exceeding 50 µg l^{-1}, the current maximum contamination level (MCL) used in Bangladesh, are common (Nordstrom 2002). Considering the World Health Organization (WHO) MCL of 0.01 mg l^{-1} As, some 70 million people, would be considered at risk. According to WHO surveys, an estimated 35–77 million people have been chronically exposed to As via drinking water in what has been described as the "*largest mass poisoning in history*" (Flanagan et al. 2012). A survey of 3,534 tube wells in 61 Districts found that the water in 25% of the wells exceeds the Bangladesh standard. High As concentration was mainly limited to groundwater from shallow aquifers with depths less than 100 m (Figure 9).

The groundwater from shallow aquifer is not used for drinking also widely used for irrigation of crops, especially for irrigation of rice during the *boro* season. Crucially, an estimated 24% of the groundwater irrigated *boro* rice area in the country is using water containing >50 µg As l^{-1} and about 7% of the area is irrigated with water containing >100 µg As l^{-1} (Zev et al. 2006). In a national scale survey of shallow tubewell water quality, similar spatial patterns in arsenic concentration were found (Duxbury et al. 2009). The highest concentrations were also found in the south-east and south-central areas below the union of Ganges and Meghna rivers (Figure 10).

A considerable body of research has focussed on the risk posed by As laden shallow groundwater used for *boro* rice production, which can result in paddy soil As accumulation over time (Ahmed et al. 2011b; Panaullah et al. 2009; Dittmar et al. 2010), because inorganic As species in irrigation water are retained in soils by adsorption of mineral oxide sulphate (Duxbury et al. 2009). For example, application of 1 m depth of water containing 100 µg As l^{-1} would increase soil As in the top 15 cm of soil by about 0.5 mg kg^{-1}, assuming uniform distribution across the command area. But a non-uniform

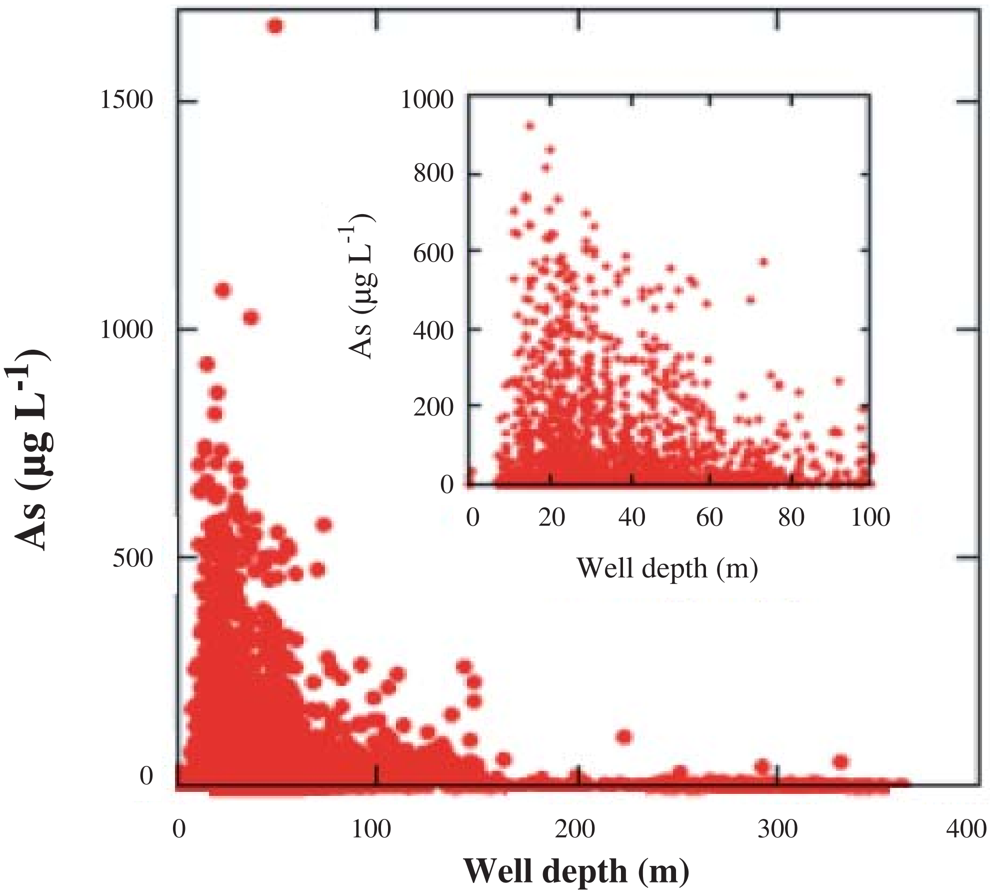


FIGURE 9.

Arsenic concentration in groundwater wells at different depths (Source: BGS/DPHE, 2001).

deposition of arsenic from irrigation water has been found because arsenic is readily absorbed by freshly precipitating iron oxides as reduced irrigation water oxidizes during its flow in irrigation channels and across fields. Heterogeneous As build-up has consequently observed within STW command areas (Ditttmar et al. 2007; Hossain et al. 2008; Panaullah et al. 2009). Moreover, flooding land type is an important factor, (Ahmed et al. 2011a; Roberts et al. 2006), as less As deposition occurs in the highland and medium highland areas, but not in lowland areas typically flooded from 180–360 cm deep during the monsoon (Ahmed et al. 2011a, Roberts et al. 2006). Accumulation of As in rice can also negatively affect rice yield (Panaullah et al. 2009; Duxbury et al. 2009) and elevate arsenic concentration in rice grain (Ahmed et al. 2011b; Williams et al. 2006), posing health risks for consumers. Use of As contaminated irrigation water created a gradient in soil As from 10–60 mg kg^{-1} in a farmers' fields, reducing *boro* rice yield by up to 5 tons ha^{-1} under acute toxicity (Panaullah et al. 2009).

Accumulation of arsenic in rice field soils is a major concern because of its possible impact on yield of rice (Panaullah et al. 2009; Duxbury et al. 2009) and arsenic concentration in rice grain, and then transfer to humans upon consumption (Duxbury at al. 2003; Williams et al. 2006; Ahmed et al. 2011b). It has been shown that use of irrigation water contaminated with naturally occurring As created a gradient in soil As from 10 to 60 mg kg^{-1} in a farmers' field and reduced yield of the *boro* variety BRRI dhan 29 (BR29) from 7-8 to 2-3 tons ha^{-1} (Panaullah et al. 2009).

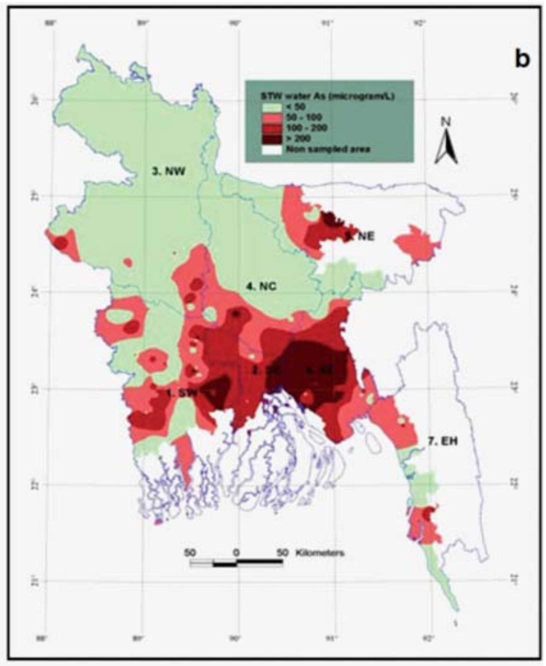


FIGURE 10.

Arsenic concentrations in STWs irrigation water (Duxbury et al. 2009).

High concentrations of arsenic in rice grain have been found in many parts of Bangladesh (Meharg and Rahman 2003; Williams et al. 2006; Zavala and Duxbury 2008) but the geographic variation in grain arsenic is not entirely consistent with arsenic contamination in the environment (Daum et al. 2001; Duxbury at al. 2003). A recent study with a large number high yielding *aman* and *boro* season rice varieties grown at 10 locations in Bangladesh showed that grain As largely control by the growing environment (Ahmed et al. 2011a). This regional variation in poorly crystalline Fe-oxide (AOFe), the ratio of AOFe to associated As, phosphate extractable As (PAs) and soil pH were important environmental variables controlling arsenic concentration in rice grain.

Rice grain with high arsenic could aggravate the health risk of the population of Bangladesh when rice is consumed along with As contaminated drinking water. Daily consumption of 400 g of rice containing 250 µg As kg^{-1} gives an equivalent intake of As to consumption of 2 litres of water at the Bangladesh limit of 50 µg As 1^{-1}. Thus, the risk posed by inorganic As in rice may be considered the same as that from drinking water if bioavailability of inorganic As from rice in the human gut is considered as 100%. Based on groundwater arsenic data from 3,205 locations and rice grain data from 595 locations, Ahmed et al. (2011b) however, showed that geographical variation in arsenicosis incidence was better explained by arsenic intake from drinking water than from rice.

5. Opportunities for Groundwater Management

The consequences of this development have been the expansion of irrigated area, higher yields and cropping intensities, increased access to drinking water, and an ability to hedge against the vagaries associated with surface water supply.

The large-scale development of groundwater in Bangladesh over the last three decades has been driven by increasing population, the pressure to grow more food, risk-aversion, the Government's national policy of making *boro* rice a priority both in terms of food security to assure food supply in the face of potential disasters (e.g., floods, cyclones), the liberalization of agricultural machinery import policies, and the introduction of high yielding rice varieties. The consequences of this development have been the expansion of irrigated area, higher yields and cropping intensities, increased access to drinking water, and an ability to hedge against the vagaries associated with surface water supply. Most importantly, groundwater extraction has helped to lift millions out of poverty. In Bangladesh, the focus unfortunately has however been on the '*resource development*', whereas '*resource management*' has not received much attention. This situation has nonetheless now turned serious because unregulated exploitation of groundwater has brought key aquifers under severe stress, threatening the sustainability of this resource. The fact that eighty-five per cent of Bangladesh's population still lives in rural areas and earn their living through agricultural activities complicates matters (BARI 2013). Unfortunately there is no simple solution to these complex problems, although for long-term sustainability of agriculture sector, the present pace of over-exploitation cannot be continued without increasingly negative consequences. As such, more concerted efforts are needed to bring a balance between aquifer extraction and recharge, and to find alternative ways to reduce the intensity of energy use in irrigation development, requiring work on both supply- and demand-side solutions.

5.1 Improving agricultural water use efficiencies

Despite all scientific progress, farmers' irrigation scheduling practices in much of Bangladesh are based on maximum water holding capacity or, worse, on the maximum amount of water a farmer can capture. Due to lack of sufficient knowledge of irrigation scheduling and the threat of non-availability of irrigation water at the right time, farmers rarely plan their irrigations in advance or attempt to coincide them with critical periods of crop need. Rather, scheduling decisions mainly depend upon visual plant stress (leading to water application at too late a stage), convention (e.g., perceptions that rice requires consistent and deep flooding), and/or in response to availability of water. Application rates are therefore typically higher than crop water requirements and conveyance losses are common. Where hose piping is not used, water is usually delivered through unlined irrigation channels to fields that are poorly levelled. The consequent over application of water and inability to properly manage directional flow has in some areas caused the emergence of serious drainage problems (Chowdhury 2010). Even though much of this lost water may be re-captured by the extensive network of groundwater pumps in some regions, re-capture is not possible in areas with saline shallow aquifers. The additional pumping required as a consequence of inefficient application also involves increased energy and financial costs for pump owners.

Most efforts over the last two decades have been directed towards the expansion of irrigated area using groundwater. Conversely, less attention has been given to the importance of surface water irrigation and improving the performance of existing irrigation systems to increase water use efficiency at the farm and regional scale (Dey et al. 2006). In Bangladesh, *boro* rice cultivation is still largely done in a traditional way, i.e. by applying and maintaining flood irrigation, although studies have shown that keeping *boro* rice fields moist but not flooded 3-4 days after the disappearance standing water did not reduce yields (Kasem 2006).

The practice of continual flooding in rice not only wastes scarce water resource but also increases irrigation costs, as most of the irrigation water for *boro* rice comes from groundwater (Alam et al. 2009). According to BRRI (2000), an average of ~4.0 m^3 of water is typically used for producing one kg of *boro* rice in farmers' fields, compared to 2.0 m^3 from researcher managed trials. Farmers apply more water in excess of crop water requirements because seepage and percolation rates are higher in rice fields, especially when flood irrigation practices are used. In northern Bangladesh, where water tables are relatively deep, seepage and percolation rates in rice fields are high, i.e. from 4 to 8 mm day^{-1}, depending on the soil type (Rashid 2008).

The seasonal crop water requirements of *boro* rice varied from 4,840 to 5,720 m^3 ha^{-1} in Dhaka district and 6,000 to 7,100 m^3 ha^{-1} in the Barind area (Karim et al. 2009; Rashid et al. 2009). In contrast, water application for *boro* rice in Mymensingh was 12,800 m^3 ha^{-1} (Sarkar and Ali 2010), and for the north-western region, it can go up to 13,500 m^3 ha^{-1} depending on the texture of the soil (Dey et al. 2013). Rashid et al. (2009) found that in the highlands of the Barind area, where water tables are generally experiencing rapid decline (Figure 7), the average evapotranspiration rate was 5.1 mm day^{-1}, and the seepage and percolation (S&P) rate was 4.2 mm day^{-1} in *boro* season, showing that out of the total applied irrigation water, only 55% was used for ET and the remaining 45% was lost. Even if water losses such as S&P, and non-productive land preparation is taken into account, only 79% of the applied irrigation is used by the crop, whereas the rest 21% is wasted (Dey et al. 2013). The cost of this excess pumped water is ultimately born by farmers, and ranges from USD 26 ha^{-1} to 65 ha^{-1} for electric DTWs, and up to USD 90 ha^{-1} for diesel operated STWs.

Irrigation deployment to *boro* rice differs distinctly between groundwater sellers (owner of tubewells) and groundwater buyers (farmers). The average amount of water applied to *boro* rice by the former is 15,300 m^3 ha^{-1} compared to 10,500 m^3 ha^{-1} by the latter (Haque et al. 2012). *Boro* rice yields obtained by water buyers were 4.8 tons ha^{-1} compared to 5.2 tons ha^{-1} for water sellers. The yield differences may also be due to higher fertilizer application by groundwater sellers. Due to cost concerns, groundwater buyers apply 42% less water to *boro* rice under the similar conditions. Therefore water productivities for groundwater buyers are higher (0.43 kg m^{-3}) than groundwater sellers (0.38 kg m^{-3}). This advocates a high potential for improving on-farm irrigation efficiency by educating farmers.

Studies in India and Pakistan have shown many advantages of bed planting in rice-wheat systems (Gupta et al. 2000; Hobbs and Gupta 2003a). Studies in Bangladesh also show that more than 40% water saving can be obtained compared to flood irrigation in case of bed planting, in addition to higher gross margins (Mollah et al. 2009). Despite these advantages, bed-planting for rice-wheat systems in Bangladesh is not well adopted, or where it is, bed planting is most commonly used for wheat, with puddling following in rice. Lack of capital and access to the bed making and zero tillage equipment are considered as major constraints to broader uptake (Krupnik et al. 2013), in addition to farmers' cultural preferences for puddling in rice. Studies done in Pakistan have shown that direct seeded rice uses 30% less water whereas conventional transplanted rice on beds uses 15% less water (Qureshi et al. 2006). The above mentioned measures, however, will only be effective if farmers do not at the same time expand their cultivated area, or increase their cropping intensities (Ahmad et al. 2007).

Another potential way to increase water use efficiency in the *boro* is the alternate wetting and drying (AWD) technique. With AWD, farmers allow ponded water to disappear from the field and infiltrate for several days until the perched field water table reaches 15–20 cm depth. Most available evidence indicates that yield increases under AWD are rare, although higher water productivity is commonly obtained (Bouman et al. 2007). In Bangladesh, yield increases between 0.5–1.0 tons ha^{-1} have been reported with AWD (Rahman, 2014), though multi-location studies are still lacking. AWD also help to lower concentrations of As in soils, indicating that the method may be a auditable means to reduce concentrations in rice grain (Roberts et al. 2011). Evidence is also increasing that AWD may boost concentrations of essential nutrients, particularly zinc, in harvested rice (Price et al. 2013).

Despite these benefits, the adoption of AWD in Bangladesh is relatively poor. The reasons for poor adoption appear to be related to the ways in which irrigation is deployed in Bangladesh, rather than due to failure of the technology from an agronomic standpoint. Fixed-irrigation rate arrangements between water sellers and farmers, non-availability of water on needed schedules, and lack of understanding of AWD are considered as the major constraints in the wide scale adoption (Kürschner et al. 2010). Clearly, further work is needed to investigate viable ways to overcome the current mis-match between AWD technology and the broader socio-political setting if further investments are to be made in promoting its use.

5.2 Balancing aquifer recharge and discharge

The emergence of groundwater challenges poses two very major challenges to the State. First, the performance of currently operational surface water supply systems needs to be improved – in particular the Ganges–Kobadak irrigation project in Khulna and the Teesta irrigation project in Rangpur – to ensure greater accountability and effectiveness. Promising movement is being taken in this direction with the advent of the Master Plan for Agricultural development in Southern Bangladesh (MoA and FAO 2012), and the Asian Development Bank's recent investment in a rehabilitation assessment of these schemes. Secondly, groundwater will have to be managed – for related reasons of quantity and quality – much more aggressively than has been the case in the past. In derivative traditional irrigation philosophy, recharge to groundwater is considered as a by-product of irrigation, though, in today's world, groundwater recharge should be considered paramount for making groundwater sustainable (IWMI 2010).

Aquifer management is considered as the most effective away of establishing a balance between discharge and recharge components. This practice is widely used in industrialized countries to recover groundwater reserves. For example, artificial groundwater recharge contributes to total groundwater use at the rate of 30% in Western Germany, 25% in Switzerland, 22% in the USA, 22% in Holland, 15% in Sweden and 12% in England (Li 2001). In recent years, India and Pakistan has also taken serious steps to use harvested rainwater to recharge aquifers. Indian experience of community rainwater harvesting ponds at the village level and introduction of check dams in the Balochistan province of Pakistan are good workable examples (Shah 2007; Qureshi et al. 2008). Rainwater harvesting can also be introduced in public and community wells situated near slums and in villages, draining water from nearby rooftops and seepage infrastructure. Connecting storm water drain lines to tanks and rivers can greatly improve the groundwater position with little effort and maintenance (Qureshi et al. 2008). Similar efforts need to be initiated in Bangladesh, where water availability during the monsoon is much higher than these two countries. Small-scale surface structures (e.g. irrigation tanks - earthen bounded reservoirs constructed across slopes by taking advantage of local depressions and mounds) can be developed to facilitate groundwater recharge and availability. However, the efficacy of investments in rainwater harvesting on a wide scale with regards to the impact on basin availability of water for downstream farmers and costs involved needs to be evaluated (Venot et al. 2007).

Sharma and Smakhtin (2006) have suggested the establishment of groundwater protection zones according to the safe yield of the aquifer, in order to avoid negative consequences of groundwater development such as water level decline, land subsidence, and increased salinity. Groundwater protection zones may be classified according to the level of vulnerability to groundwater extraction. North-western parts of Bangladesh where groundwater tables are continuously declining, and resulting in the development of groundwater depression zones might be a potential case for the establishment of "groundwater protection zone". However, because this has a clear link with the large scale *boro* rice cultivation in this area, implementation of these policies needs caution.

5.3 Diversifying cropping patterns

Although the increase in *boro* area and production has brought the country to near rice self-sufficiency, this has come at the cost of degradation of groundwater quality and quantity, in addition to the costly energy expenditures required to power irrigation pumps. This situation has brought into question the sustainability of *boro* rice as a future strategy for Bangladesh's food security. Since rice is a water-intensive crop, it is essential to review whether Bangladesh should continue to primarily grow rice or instead use this water for other income generating or food security contributing crops in which the country has a comparative advantage. In Bangladesh's main *boro* growing areas, more than 90% of irrigation water is supplied through groundwater. Therefore restricting rice production in groundwater vulnerable areas could therefore reduce the pressure on this resource. The possible reduction in rice production due to area restrictions could be fulfilled through other less water demanding grain crops, for example wheat, maize, legumes, and myriad alternative crops.

Wheat production in Bangladesh gained momentum in 1980s when rapid dietary change also took place. Wheat is currently grown on 0.40 million ha, which is only 3.5% of the total area under cereals (BADC 2012). The total wheat production is 1.38 million tons of grain, whereas another 2.0 million tons is imported annually to meet the national demand of 3.4 million tons (BARI 2014). Despite relatively high nutritional value and industrial and commercial applications, area under wheat cultivation has decreased due to replacement by *boro* rice following increased access to groundwater (Figure 11). Due to reduction in area and less attention on developing high yielding varieties, wheat production has consequently remained low (BADC 2012). In 1999-2000, wheat production reached to its peak (1.83 million tons, however, soon after this it started declining, reaching 0.84 million tons in 2008.

Maize is another potential alternative crop to *boro* rice. Favourable growing conditions result in potential yields in some areas as between 12.0–19.6 tons

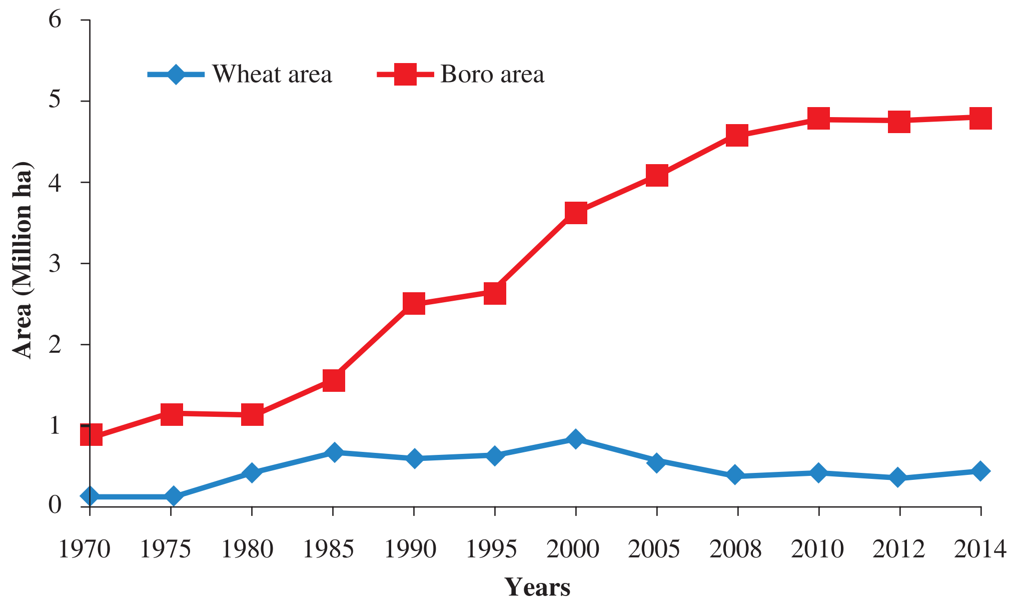


FIGURE 11.
Changes in the cultivated area of wheat and *boro* rice during 1970-2014.

ha^{-1} – the highest encountered in South Asia (Timsina et al. 2010). However, despite a significant increase in the maize cultivated area over the last three decades (170,000 ha in 2013 from 2000 ha in 1981), total production is far less than the annual national demand, resulting in imports of over 1.0 million year^{-1} (BARC 2013). Higher demand for poultry products as a result of changing diet habits are the main reasons for increasing demand for maize. Maize grown area is concentrated in the northwest, and scattered throughout the country in Chauadanga, Kustia, Manikgonj and Comilla districts.

Wheat and maize both need very little water (300 to 500 mm) to meet their evapotranspiration demand, especially when they are grown after the rice crop. A significant water requirement of these crops can be met through the excessive moisture present in the root zone from the previous rice crop especially if the strip or zero tillage method is used. Therefore, adoption of these two crops would not only help in controlling declining groundwater tables but also help the country in meeting its food requirements and saving valuable foreign exchange being spent on the import of these two grain items.

5.4 *Revisiting groundwater governance policies*

Groundwater has acquired a pivotal role in boosting Bangladesh's agricultural economy. Increased ease of access to groundwater fundamentally benefited the livelihoods of millions of rural poor. The major breakthrough came with the large-scale adoption of high yielding irrigated *boro* rice varieties and the expansion of shallow tube wells, which helped to move Bangladesh to near self-sufficiency. Today 80% of all *boro* rice area is groundwater irrigated, with intensive cultivation largely concentrated in the north-west, where groundwater levels are declining much faster than many other areas. Despite clear evidence that groundwater is being over-exploited, a large number of additional wells are being installed every year. Furthermore, there are serious and growing problems with groundwater quality, and increasing energy demand for vertical pumping of water, which may amplify in future.

This suggests that more expensive and poor quality groundwater will be extracted for irrigation in the future. The direct management of groundwater through the introduction of groundwater use rights and limitations on groundwater access by enforcing permit systems will be difficult in Bangladesh due to large number of users, ineffective institutional arrangements, and problems with enforceability and accountability. Such strategies are more feasible where there are few users and the responsible authority has a very clear mandate and capacity. Therefore a well thought-out, pragmatic, patient and persistent strategy is needed to address the issue of groundwater management. Some of the potential drivers of success necessarily include the heavy engagement of users, refinements in water pricing structures, substantial investments in modern water and agricultural technology, provisions to encourage farmers' transition into less water-demanding crops, and the development of enabling policies and decision support systems. Policy research should address which options might be best for future groundwater governance in Bangladesh.

The frontline challenge is not just supply-side innovations, but rather to put into place a range of corrective mechanisms before the problem becomes either insolvable or not worth solving. The emphasis so far has been on the development of groundwater resources but not on the management and conservation of this resource. Increasing uncertainties resulting from the anticipated negative effects of climate change suggest that groundwater use must be supplemented with the development of surface water resources to meet future water needs. Attention should also be given to areas where groundwater resources are relatively less developed, such as southern Bangladesh, though trade-offs with ground water salinity and arsenic contamination require careful consideration. When considered at a national level, the extension of irrigation in this part of the country could help to reduce pressure on areas where the problems of groundwater exploitation are more acute.

Over the last three decades, the Government of Bangladesh (GoB) attempted to introduce policies to monitor and regulate (ground) water resources, though practical and sustainable solutions have proven elusive. In 1985, the GoB introduced an ordinance exclusively for the management of agricultural groundwater resources. In this ordinance, licensing was introduced to restrict installation of private tube wells in critical areas where groundwater was falling at rapid rates and/or where groundwater quality was deteriorating.

Subsequent laws such as the national environmental policy (1992), national policy for safe water and sanitation (1998), and national water policy (1999) stressed the need for the protection of surface water and groundwater resources. The more recently introduced water act of 2013 makes it mandatory for any individual to obtain a license/permit for large-scale withdrawal of groundwater by individuals and organizations beyond domestic use.

However, enforcing laws, installing licensing and permit systems, and the establishment of tradable property rights have so far proven largely ineffective, perhaps due to difficulties in enforcement and accountability, which are characteristic in rural areas. Most policies, including the groundwater management ordinance of 1985, speak of managing groundwater at the *Upazila* (sub-district) level. However, the management of aquifers beyond administrative boundaries has conversely been overlooked. Important lessons on what does not work in improving groundwater governance could be learned from the management experiences of nearby countries such as India, Pakistan, and China, where permit and licensing systems also failed to yield desirable results. In addition to the reduced reach of the State into rural areas and weak accountability and enforcement, the sheer number of tubewell users is also a major reason for the ineffectiveness of licensing policies in these countries (Shah et al. 2003; Shah 2007; Qureshi et al. 2010). The population of shallow groundwater pumps and socio-economic conditions in these countries bear great resemblance with Bangladesh. Conventional groundwater management through the introduction of permit systems and groundwater use rights, direct and indirect pricing, and delivering groundwater on a volumetric basis are therefore not likely to succeed in Bangladesh either.

The success of groundwater management in the Murray-Darling basin in Australia through permit systems lies in the fact that groundwater users' only number in the few thousand. The implementation of regulatory laws is also relatively easy (Shah et al. 2003). In Jordan, permit systems succeeded where efforts targeted DTWs and installation costs were high, while STWs were not considered (Chebaane et al. 2004). Shah (2007) argued that regulating energy prices provided a potent tool kit for the indirect management of groundwater in India. This however was not the case in Pakistan, where increasing electricity prices only forced farmers to shift from electricity to diesel, as has been the case in Bangladesh (Qureshi et al. 2010). As a result, groundwater exploitation continued because it was crucial to meet increasing cereals demands.

Institutional solutions to groundwater management are difficult to implement because policy leaders remain under pressure to assure that adequate food is supplied to feed the population and reduce poverty, especially in rural areas. As major investments in surface water and irrigation systems have declined, governments have few options other than to allow the expansion of irrigated agriculture through groundwater development. Due to this dependence on groundwater for rural livelihoods, national governments are reluctant to implement stringent regulation. In the absence of strong political will for effective management of groundwater in Bangladesh, one potential avenue is the promotion of profitable, but less water demanding crops than *boro* rice, as discussed above. Measures to focus on alternative crops and cropping patterns could be implemented through policy measures to direct international donor investments, as is the case with the Master Plan for the Southern Region (MoA and FAO 2012), though similarly targeted efforts are needed in groundwater using regions.

For all this to happen, institutional capacity needs to be enhanced to undertake systematic development and enforcement of legislation and organizational changes to solve entitlement, pricing, and regulatory issues. Reforms also need to address the management and organizational issues of existing institutions, with increased clarity in their roles and responsibilities. In the absence of proper institutional arrangements, evaluation of strategic options and monitoring the implementation of national policies for the public water sector will remain a challenge. Without a single governing authority responsible for the management of groundwater, it becomes difficult to implement policies that attempt to manage resources in a long-term sustainable way. Therefore, in addition to technical solutions, strong linkages between different organizations involved in the management of groundwater resources, and alignment of objectives, will be required.

In addition to these supply-side solutions, demand for groundwater also requires management. Despite water shortages, irrigation efficiencies are low and the erroneous concept of "more water-more yield" still prevails among farmers. Improving water use efficiencies through the adoption of resource conserving crop management practices such as alternate wetting and drying, direct-seeded rice, and bed planting could help here, though in the case of AWD, effort is required to facilitate water pricing structures that would interest farmers and irrigation service providers alike to reduce irrigation volume in *boro* rice. Work will also be needed to create demand among farmers for alternative land preparation and planting services, and to develop viable markets for the equipment needed to prepare fields and sow crops using these techniques. Cropping patterns also need to be rationalized – starting with the promotion of feasible alternatives to *boro* – considering country needs and the availability and sustainability of aquifers. Decreasing water availability both in terms of quantity and quality suggest that the unchecked expansion of dry season rice cultivation is probably not a long-term option for Bangladesh.

There is also a need to work on awareness raising through educational programs for all stakeholders, heavy promotion of alternative crops, and programs to develop strong output markets for these alternative crops. The central elements will be heavy involvement of users, substantial investments in modern water and agricultural technologies e.g. charging water on a volumetric basis or crop specific pricing, fixing quotas for groundwater extraction for different users, facilitate markets for non-rice crops, promotion of alternative cropping patterns, and extra support for farmers making transition to less water demanding crops.

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References

Ahmad, M.D., Turral, H., Masih, I., Giordano, M., Masood Z., 2007. Water saving technologies: myths and realities revealed in Pakistan's rice-wheat systems. International Water Management Institute, Colombo, Sri Lanka (IWMI Research Report 108): 44 pp.

Ahmad, Q.K., Biswas, A.K., Rangachari, R., Sainju, M.M. (eds.), 2001. Ganges–Brahmaputra–Meghna Region: A Framework for Sustainable Development. The University Press, Dhaka, Bangladesh.

Ahmed, Z.U., Panaullah, GM., Gauch Jr, H., McCouch, MR., Tyagi, W., Kabir, M.S., Duxbury, J.M., 2011a. Genotype and environment effects on rice (*Oryza sativa* L.) grain arsenic concentration in Bangladesh. *Plant Soil*, 338:367–382.

Ahmed, Z.U., Panaullah, G.M., DeGloria, S.D., Duxbury, J.M., 2011b. Factors affecting paddy soil arsenic concentration in Bangladesh: Prediction and uncertainty of geo-statistical risk mapping. *Sci. Total Env.*, 412-413:324-35.

Ahmed, Z.U., Panaullah, G.M., Duxbury, J.M., Lauren, G.J., Meisner, C.A., DeGloria, S.D., Woodbury, P.B., 2013. Arsenic contamination in Bangladesh: Spatial relationship between arsenic exposure from groundwater and rice, and incidence of arsenicosis. *Environmental Health*, March 3-6, Boston, MA.

Alam, M.S., Islam, M.A., Islam, M.A., 2009. Economics of alternate wetting and drying method of irrigation: Evidences from farm level study. *The Agriculturists*, 7(1&2); P: 82-89.

Ali, M.H., Sarkar, A.A., Rahman, M.A., 2012. Analysis on Groundwater-Table Declination and Quest for Sustainable Water Use in the North-Western Region (Barind Area) of Bangladesh. *Journal of Agriculture Science and Applications*, Vol. 1, No. 1: 26-32

Al-Masum, R.F., 2012. Environmental contamination by CO_2 emission through irrigation pumps. MSc. Thesis. Department of Farm Structure and Environmental Engineering. Bangladesh Agricultural University, Mymensingh, Bangladesh.

Amarasinghe, U.A., Sharma, B.R., Muthuwatta, L., Khan, Z.H., 2014. Water for food in Bangladesh: outlook to 2030. Colombo, Sri Lanka: International Water Management Institute (IWMI). 32p. (*IWMI Research Report 158*). doi: 10.5337/2014.213

Asian Development Bank (ADB), 2007a. Recent advances in water resources development and management in developing countries in Asia, Asian Water Development Outlook 2007 Discussion Paper. Manila, Philippines, ADB.

Asian Development Bank (ADB), 2007b. Asian Water Development Outlook 2007 Country Paper Cambodia. Manila, Philippines, ADB.

Asian Development Bank (ADB), 2007c. Asian Water Development Outlook 2007 Country Paper Bangladesh. Manila, Philippines, ADB.

BADC (Bangladesh Agricultural Development Corporation), 2013. *Minor irrigation survey report 2012-2013*. Bangladesh Agricultural Development Corporation, Ministry of Agriculture, Government of Bangladesh.

BARI (Bangladesh Agricultural Research Institute), 2014. ASICT Division, Annual Research Report of 2013-2014. Ministry of Agriculture, Dhaka, Bangladesh.

BBS (Bangladesh Bureau of Statistics), 2013. Agricultural Statistics Yearbook. Dhaka, Bandladesh.

BEB (Bangladesh Energy Board), 2012. Power Sector Data Book, Ministry of Water, Dhaka, Bangladesh.

BIDS (Bangladesh Institute of Develoment Studies), 2012. A citizen's guide to energy subsidies in Bangladesh. Bangladesh Institute for Development Studies (BIDS) and the Institute for Sustainable Development Global Subsidies Initiative. Winnipeg. P. 31.

Biswas, M.R., Mandal, M.A.S., 1993. Irrigation Management for Crop Diversification in Bangladesh, University Press Limited, Dhaka, Bangladesh.

Bouman, B.A.M., Humphreys, E., Tuong, T.P., Barker, R., 2007. Rice and Water. Adv. Agron. 96, 187–237.

Brammer, H., 2014. Bangladesh’s dynamic coastal regions and sea-level rise. *Climate Risk Management*, 1:51-62.

BRRI (Bangladesh Rice Research Institute) 2000. In: BRRI Annual Research Review for 1999. XIX. Rice Farming Systems. October 9-12, 2000. Bangladesh Rice Res. Inst. Gazipur, Bangladesh.

Cassman, K.G., Dobermann, A., Walters, D.T., Yang, H., 2003. Meeting Cereal Demand While Protecting Natural Resources and Improving Environmental Quality. *Ann. Rev. Env.and Res*., 28, 315-358.

Chebaane, M., El-Naser, H., Fitch, J., Hijazi, A., Jabbarin, A., 2004. Participatory groundwater management in Jordan: development and analysis of options. Groundwater: from development to management. *Hydrogeol J.*, 12,14–32.

Chowdhury, NT., 2010. Water management in Bangladesh: an analytical review. *Wat. Policy.*, 12, 32-51.

Dey, N.C., Bala, S.K., Hayakawa, S., 2006. Assessing the economic benefits of improved irrigation management: a case study of Bangladesh. *Water Policy J, International Water Association, UK, 8(6); P:573-84. (www.iwaponline.com/wp/00806).*

Dey, N.C., Bala, S.K., Saiful Islam, A.K.M., Rashid, M.A., 2013. Sustainability of groundwater use for irrigation in northwest Bangladesh. Policy Report prepared under the National Food Policy Capacity Strengthening Programme (NFPCSP). Dhaka, Bangladesh. 89 pp.

Dittmar, J., Voegelin, A., Roberts, L.C., Hug, S.J., Saha, G.C., Ali, M.A., 2007. Spatial distribution and temporal variability of arsenic in irrigated rice fields in Bangladesh. *Paddy Soil. Environ. Sci. Technol.* 41, 5967-72.

Dittmar, J., Voegelin, A., Maurer, F., Roberts, L.C., Hug, S.J., Saha, G.C., 2010. Arsenic accumulation in a paddy field in Bangladesh: seasonal dynamics and trends over a three-year monitoring period. *Environ. Sci. Technol.*, 44, 2925-31.

BGS-DPHE, 2001. Arsenic Contamination of Groundwater in Bangladesh, British Geological Survey (BGS) and Department of Public Health Engineering (DPHE) Govt. of Bangladesh; rapid investigation phase, Final Report.

Daum, D., Bogdan, K., Schenk, M.K., Merkel, D., 2001. Influence of the field water management on accumulation of arsenic and cadmium in paddy rice. Dev. *Plant Soil Sci.*, 92, 290-291.

Duxbury, J.M., Panaullah, G.M., Zavala, Y.J., Loeppert, R.U., Ahmed, Z.U., 2009. Impact of use As-contaminated groundwater on soil As content and paddy rice production in Bangladesh. *Food and Fertilizer Technology Center. Technical Bulletin 180.*

Duxbury, J.M., A.B. Mayer, J.G. Lauren, and N. Hassan. 2003. Food chain aspects of arsenic contamination in Bangladesh: Effects on quality and productivity of rice. *J. Environ. Sci. Health.*, 1, 61-69.

FAO (Food and Agriculture Organization of the United Nations), 2011. AQUASTAT: FAO's information system on water and agriculture. Available at http://www.fao.org/nr/water/aquastat/countries_regions/BGD/index.stm

Flanagan, S.V., Johnstan, R.B., Zheng, Y., 2012. Arsenic in tube well water in Bangladesh: health and economic impacts and implications for arsenic mitigation. Bulletin of the World Health Organization 2012;90:839-846. doi: 10.2471/BLT.11.101253.

Gupta, R.K., Hobbs, P.R., Salim, M., Malik, R.K., Varma, M.R., Pokharel, T.P., Thakur, T.C., Tripathri, J., 2000. Research and extension issues for farm-level impact on the productivity on rice-wheat systems in the Indo-Gangetic Plains of India and Pakistan. Rice-Wheat Consortium Sem. Rep. Ser. 1. Rice-Wheat Consortium for the Indo-Gangetic Plains. New Delhi, India. 26 p.

Haque, M.A., Islam, M.S., Zahid, A., 2012. Groundwater irrigation and crop economy in the lower Gangatic Plain at Madbarer Char, Madripur, South-Central Bangladesh. *J. Asiatic. Soc. Bangladesh Sci.*, 38(1): 29-39.

Hasan, N.M., Hossain, M.S., Islam, M.R., Bari, M.A., Karim, D,, Rahman, M.Z., 2013. Trends in the Availability of Agricultural Land in Bangladesh. Soil Resource Development Institute. Dhaka. 72p.

Hobbs, P.R., Gupta, R.K., 2003a. Resource-conserving technologies for wheat in the rice-wheat system. In: Improving Productivity and Sustainability of Rice-Wheat Systems: Issues and Impact. *American Soc. Agron. Spec. Publ.*, 65: 149-171.

Hossain, M., Deb, U.K., 2003. Trade Liberalization and the Crop Sector in Bangladesh, Paper 23, the Centre for Policy Dialogue, Dhaka, Bangladesh.

Hossain, M.B., Jahiruddin, M., Panaullah, G.M., Loeppert, R.H., Islam, M.R., Duxbury, J.M., 2008. Spatial variability of arsenic concentration in soils and plants, and its relationship with iron, manganese and phosphorus. *Environ. Pollut.*, 156, 739-44.

IWMI (International Water Management Institute), 2010. Water Policy Brief. Banking of groundwater in times of change. Issue 32.

Jahan, C.S., Mazumder, Q.H., Akter, N., Adham, M.I., Zaman, M.A., 2010. Hydrogeological environment and groundwater occurrences in the plio-pleistocene aquifer in barind area, northwest Bangladesh. *Bangladesh GeoSci. J.*, 16,23-37.

Karim, N.N., Talukder, M.S.U, Hassan, A.A., Khair, M.A., 2009. Climate change and its impacts on actual crop evapotransporation of *boro* rice in north central hydrological region of Bangladesh. *J. Ag. Eng. Bangladesh*, 37, 73-82

Kasem, M.A., 2006. Evaluation of water management practices for different methods of rice production. PhD Thesis, Faculty of Agricultural Engineering and Technology, Bangladesh Agricultural University, Mymensingh.

Krupnik, T.J., Santos vale, S., McDonald, A.J., Justice, S., Hossain, I., Gathala, M.K., 2013. Made in Bangladesh: Scale-appropriate machinery for agricultural resource conservation. Mexico, D.F.: CIMMYT.

Kürschner, E., Henschel, C., Hildebrandt, T., Jülich, E., Leineweber, M., Paul, C., 2010. Water Saving in Rice Production– Dissemination, Adoption and Short Term Impacts of Alternate Wetting and Drying (AWD) in Bangladesh.

Li, Y., 2001. Groundwater recharge. Nanjing Institute of Hydrology and Water Resources, China.

Mainuddin, M., 2013. Scoping study to assess constraints and opportunities for future research into intensification of cropping systems in Southern Bangladesh. ACIAR Report. Australia.

Meharg, A.A., Rahman, M., 2003. Arsenic contamination of Bangladesh paddy field soils: Implications for rice contribution to arsenic consumption. *Environ. Sci. Technol*. 37, 229-234.

MOA and FAO, 2012. Master Plan for Agricultural Development in the Southern Region of Bangladesh. Ministry of Agriculture (MoA, Government of Bangladesh) and United Nations Food and Agriculture Organization, Dhaka, Bangladesh, 122 p.

Molden, D.J., 2007. Water for food, water for life: A Comprehensive assessment of water management in agriculture. Earthscan and the International Water Management Institute, London and and Colombo.

Mollah, M.I.U., Bhuyia, M.S.U., Kabir, M.H., 2009. Bed Planting – A New Crop Establishment Method for Wheat in Rice-Wheat Cropping System. *J. Agric. Rural. Dev*. 7, 23-31.

Morris, B.L., Lawrence, A.R.L., Chilton, P.J.C., Adam, B., Calow, R.C., Klinck, B.A., 2003. Groundwater and its susceptibility to degradation: A global assessment of the problem and options for management. Early Warning and Assessment Report Series, RS 03-3. United Nations Environment Programme, Nairobi, Kenya.

Mukherji, A., 2007. The energy-irrigation nexus and its impact on groundwater markets in eastern Indo- Gangetic basin: Evidence from West Bengal, India. *Energy Policy*, 35, 6413-6430.

Mukherji, A., Banerjee, P.S., Daschowdhury, S., 2009. Managing the energy-irrigation nexus in West Bengal, India. In editors A. Mukherji, K.G. Villholth, B.R. Sharma, J. Wang 2009. Groundwater Governance in the Indo-Gangetic and Yellow River Basins: Realities and Challenges. CRC Press/Balkema, The Netherlands.

Nordstrom, D.K., 2002. Worldwide Occurrences of Arsenic in Ground Water. *Science* 296:2143-2145.

Panaullah, G.M., Alam, T., Hossain, M.B., Loeppert, R.H., Lauren, J.G., Meisner, C.A., Ahmed, Z.U., Duxbury, J.M., 2009. Arsenic toxicity to rice (*Oryza sativa L.*) in Bangladesh. *Plant Soil*: 317:31–9

Price, A.H., Norton, G.J., Salt, D.E., Oliver Ebenhoeh, O., Meharg, A.A., Meharg, C., Islam, M.R., Sarma, R.N., Dasgupta, T., Ismail, A.M., McNally, K.L., Zhang, H., Dodd, I.C., Davies, W.J., 2013. Alternate Wetting and Drying Irrigation for Rice in Bangladesh: Is it Sustainable and has Plant Breeding Something to Offer? Food. *Energy Sec*.. 2, 120–129.

Qureshi, A.S., Masih, I., Turral, H., 2006. Comparing water productivities of transplanted and direct seeded rice for Pakistani Punjab. *J. Appl. Irrig. Sci.*, 41,47–60

Qureshi, A.S., McCornick, P.G., Qadir, M., Aslam, Z., 2008. Managing salinity and waterlogging in the Indus Basin of Pakistan. *Agric. Water. Manag.*, 95,1–10. doi:10.1016/j.agwat.2007.09.014

Qureshi, A.S., McCornick, P.G., Sarwar, A., Sharma, B.R., 2010. Challenges and prospects for sustainable groundwater management in the Indus Basin, Pakistan. *Water Resource Management*., 24, 1551-1569.

Rahman, M.W., Ahmed, R., 2008."Shallow tube well irrigation business in Bangladesh," Paper Presented at Summary and Synthesis Workshop at Kathmandu, Nepal, March 20–24, 2008.

Rahman, M.W., Parvin, L., 2009. Impact of Irrigation on Food Security in Bangladesh for the Past Three Decades. *J. Env.Prot.*, 1, 40-49.

Rahman, M.M., Mahbub, A.Q.M., 2012. Groundwater depletion with expansion of irrigation in Barind Tract: a case study of Tanore Upazila. *J. Water Res. Prot.*, 4, 567-575.

Rahman, M.R., Sheikh, H., 2014. Effect of alternate wetting and drying (AWD) irrigation for *Boro* rice cultivation in Bangladesh. *Ag. Forest. Fish.* 3, 86-92.

Rajmohan, N., Prathapar, S.A., 2013. Hydrogeology of the Eastern Ganges Basin: an overview. IWMI Working paper No. 157. International Water Management Institute, Colombo, Sri Lanka. 42 pp. doi: 10.5337/2013.216

Rashid, M.A., 2008. Growth Phase-wise Water Requirements of Rice, Irrigation and Water Management Division, Bangladesh Rice Research Institute (BRRI), Gazipur, Dhaka, Bangladesh.

Rashid, M.A., Kabir, W,, Khan, L.R., Saleh, A.F.M., Khair, M.A., 2009. Estimation of water Loss from irrigated rice fields. *SAARC Agri.*, 7, 29-42.

Roberts, L.C., Hug, S.J., Dittmar, J., Voegelin, A., Kretzschmar, R., Wehrli, B., 2006. Arsenic release from paddy soils during monsoon flooding. *Nature Geoscience*, 2009: 3: 53-9.

Sarkar, A.A., Ali, M.H., 2010. Irrigation Management for Optimizing Rice Yield and Nitrate leaching. Proceedings, paper Meet-2010. Agricultural Engineering Division, Institution of Engineers, Bangladesh. pp:17-28.

Shah, T., Debroy, A., Qureshi, A.S., Wang, J., 2003. Sustaining Asia's groundwater boom: an overview of issues and evidence. *Nat. Res. Forum*, 27,130–140

Shah, T., 2007. The groundwater economy of South-Asia: an assessment of size, significance and socio-ecological impacts. In: Giordano M, Villholth KG (eds) The agricultural groundwater revolution: opportunities and threat to development. CABI, Wallingford, pp 7–36.

Shahid, S., 2011. Impact of climate change on irrigation water demand of dry season *Boro* rice northwest Bangladesh. *Climate Change*, 105, 433-453.

Shamsudduha, M., Chandler, R.E., Taylor, R., Ahmed, K.M., 2009. Recent trends in groundwater levels in a highly seasonal hydrological system: the Ganges-Brahmaputra-Meghna Delta. *Hydrol. Earth Syst*. Sci., 13, 2373–2385.

Sharma, B.R., Smakhtin., V.U., 2006. Potential of water harvesting as a strategic tool for drought mitigation. International Water Management Institute (IWMI).

Talukder, R.K., 2008. "Food security in Bangladesh: National and global perspectives," In Proceedings BKAS 13th National Conference and Seminar on Climate Changes: Food Security in Bangladesh, Vol. 13, Dhaka, Bangladesh.

Timsina, J., Jat, M.L., Majumdar, K., 2010. Rice-maize systems of South Asia: current status, future prospects and research priorities for nutrient management. *Plant Soil*, 335, 65-82.

UNESCO, 2003. The UN World Water Development Report. Retrieved from http://www.unesco.org/

Venot, J.P., Turral, H., Samad, M., Molle, F., 2007. Explaining basin closure through shifting waterscape in the lower Krishna Basin, South India. Research Report, International Water Management Institute, Colombo.

Wadud, M., White, B., 2002. The determinants of technical inefficiency of farms in Bangladesh, *Indian Economic Review*, 37, 183-197. water/wwap/wwdr/wwdr1/pdf/chap4.pdf.

Williams, P.N., Islam, P.N., Adomako, E.E., Raab, A., Hossain, S.A., Zhu, Y.G., Feldmann, J., Meharg, A.A., 2006. Increase in Rice Grain Arsenic for Regions of Bangladesh Irrigating Paddies with Elevated Arsenic in Groundwaters. *Environ. Sci. Technol.*, 40,6.

Zavala, Y.J., Duxbury, J.M., 2008. Arsenic in rice: I. Estimating normal levels of total arsenic in rice grain. *Environ. Sci. Technol.*, 42: 3856-3860.

Zev, R., John, M.D., Stephen, D.D., Debi, N.R.P., 2006. Potential for Arsenic Contamination of Rice in Bangladesh: Spatial Analysis and Mapping of High Risk Areas. *Int. J. Risk Ass. Mgt*. 6, 298-315.

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