Moving from Resource Development *to* Resource Management: *Problems, Prospects and Policy Recommendations for Sustainable Groundwater Management in Bangladesh*

Asad S. Qureshi, Zia Uddin Ahmad & Timothy J. Krupnik

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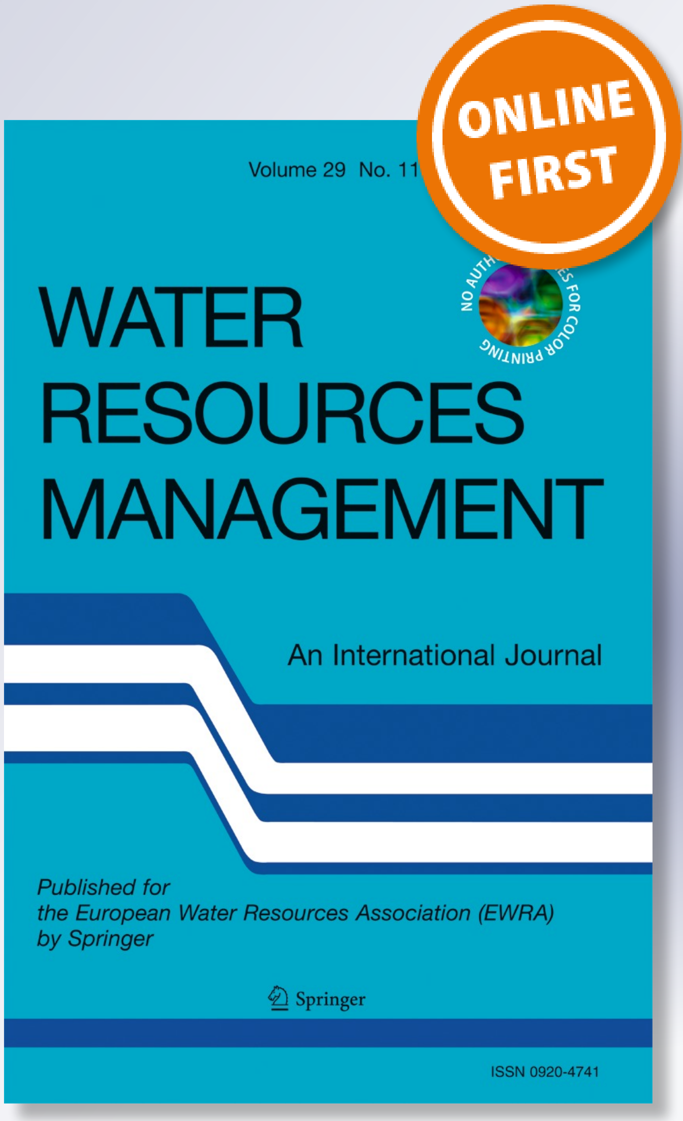

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Moving from *Resource Development* to *Resource Management*: Problems, Prospects and Policy Recommendations for Sustainable Groundwater Management in Bangladesh

Asad S. Qureshi[1] **· Zia Uddin Ahmad**[1] **· Timothy J. Krupnik**[1]

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Abstract 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. However, problems associated with the excessive exploitation of groundwater notably declining water tables, deteriorating water quality, increasing energy costs and carbon emissions are threatening the sustainability of Bangladesh's groundwater irrigated economy. The forefront challenge, therefore, is to shift the focus from development to management of this precious resource. To ease out pressure on groundwater resources, attention must be diverted to further develop surface water resources. In addition to increasing supplies, water demand also need to be curtailed by increasing water use efficiency through the adoption of water conserving practices such as reduced tillage, raised bed planting, and the right choices of crops. Decreasing water availability both in terms of quantity and quality suggest that the unchecked expansion of dry season *boro* rice cultivation may not be a long-term option for Bangladesh. Therefore less thirsty wheat and maize crops may be promoted as feasible alternatives to *boro*. In addition to technical solutions, strong linkage between different institutions will be needed to evaluation strategic options and effective implementation of national policies for the management of groundwater resources.

Keywords Groundwater management · Bangladesh · Water use efficiency · Boro rice · Tubewell · Arsenic contamination

✉ Asad S. Qureshi
busyperson65@gmail.com

[1] International Maize and Wheat Improvement Center (CIMMYT), House 10/B, Road 53, Gulshan-2, Dhaka 1213, Bangladesh

1 Introduction

Over the past three decades, South-Asia has emerged as the largest exploiter of groundwater in the world (Shah 2007). Due to increasing 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 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 (Shah et al. 2003). In Pakistan, groundwater contributes more than 50 % to the total crop water requirements in the Punjab province which produces 90 % of the national grain output (Qureshi et al. 2010). Presently, about 80 % of the cultivated area in Bangladesh is irrigated by groundwater (Rahman and Ahmed 2008). The positive benefit of increasing use of groundwater irrigation is that almost whole region has achieved food self-sufficiency and has contributed significantly to rural wealth creation (Shah 2007).

In Bangladesh, rice is the staple food and is grown on 75 % of 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* a pre-monsoon rainfed crop, *aman* is a rainy season rice crop, whereas *boro* is irrigated 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 2008). *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* production has helped Bangladesh to increase its total rice production from 18.3 million tons in 1991 to 33.8 million tons in 2013. This dramatic increase in rice production was due largely to the extensive exploitation of groundwater.

However, the flip side of this large scale exploitation of groundwater is that the very future of irrigated agriculture, which is increasingly blooming on groundwater, stands threatened due to its unsustainable use and consequent serious environmental outcomes. The population of Bangladesh is expected to reach 182 million by 2030, which will increase the total demand for rice to 39 million tons (Amarasinghe et al. 2014). On the other hand, due to high installation, operational and management costs, the large-scale development of surface water resources will remain a challenge in near future. Groundwater irrigation will therefore remain crucial to sustain agrarian growth to meet Bangladesh's future food requirements. Furthermore, there are much larger implications on the country's economy, notably because of the excessive energy that is being used to lift this resource. Despite these looming challenges, management of groundwater is still not high on the agenda of farmers or policy makers. One of the major bottlenecks in sustainable groundwater management is the lack of robust information on aquifer reserves, their withdrawal patterns, changes in quality, and consequences of use for irrigation. This paper is an attempt to fill this gap by reviewing patterns of groundwater development and use, benefits it has imparted, problems of groundwater development and future challenges. This paper uses the Bangladesh groundwater situation as a study case to suggest water management policies and practices for sustainable groundwater management to support irrigated agriculture. These findings will be valuable for other countries of South-Asia and outside the region where similar groundwater issues are prevalent or expected to develop in future due to increasing use of groundwater for irrigation.

2 Data and Methods

2.1 Study Area

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 with 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). The internal renewable water resources are 105,000 Mm^3 $year^{-1}$. This includes 84,000 Mm^3 of surface water produced internally as stream flows from rainfall, and about 21,000 Mm^3 of groundwater (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). In northern Bangladesh, surface water shortages and the easy access to groundwater through tubewells has prompted farmers to extract groundwater for irrigation, industrial and domestic purposes. In southern Bangladesh, although surface water is abundant, drainage facilities are largely non-existent and accessibility to groundwater is restricted due to quality concerns (Fig. 1).

2.2 Analysis

This paper utilizes a mix of literature review and analysis of primary data. A thorough literature review was conducted considering available peer-previewed literature and reports on groundwater development and management in Bangladesh. In addition, long-term data on groundwater development, water table depth and quality were collected from Bangladesh Agricultural Development Board (BADC) and Bangladesh Energy Board (BEB). Data on tubewell population and their distribution across the country were collected from BADC (BADC 2013) whereas estimates of energy use for agricultural tubewells were obtained from BEB (BEB 2012). Information on total irrigated area for different crops, irrigation patterns, irrigation water use efficiencies and economics of groundwater, were collected from yearbooks of Bangladesh Bureau of Statistics (BBS) and Bangladesh Agricultural Research Institute (BARI) (BARI 2014; BBS 2013). These data were summarized and analyzed to quantify the impact of groundwater development on changes in water table depth and quality of groundwater, in addition to the impact of increasing energy prices on the cost of irrigation.

Despite wide spread Arsenic (As) contamination of groundwater in Bangladesh, no detailed analysis on the extent and severity of this problem is available. In this study, we have used sampling data of 3250 locations collected from shallow (<150 m) aquifers (BGS/DHHE 2001) and analyzed it by developing 100 gridded (1×1 km) equal-probability maps. The probability of exceeding 50,100, 150 and 200 μg As L^{-1} was computed from 100 maps. Using sequential indicator simulation technique, we developed 19 thresholds (5th to 95th percentile, with 5 percentile increments) for As concentration indicator variogram modelling.

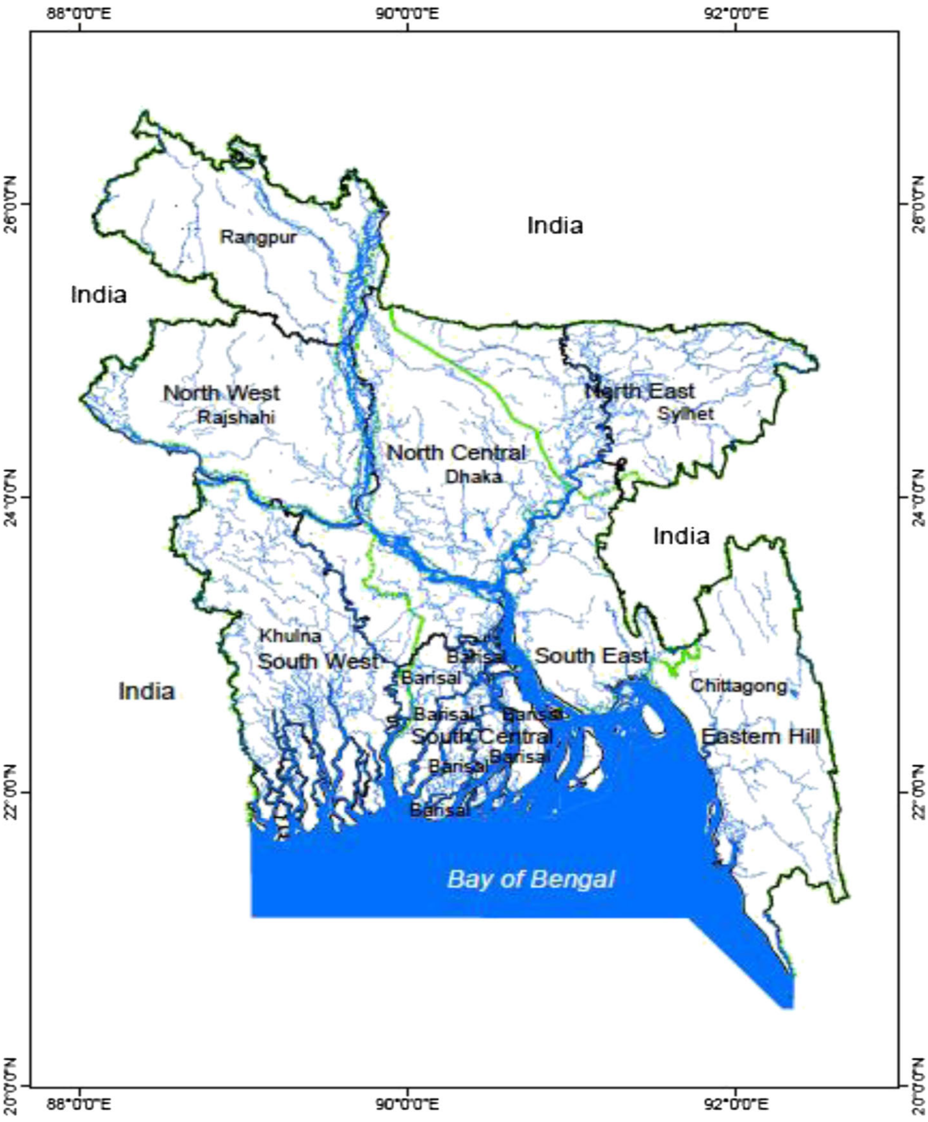

Fig. 1 Map of Bangladesh with different hydrological regions

3 Results and Discussion

3.1 Contours of Groundwater Development and Use in Bangladesh

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 was covered by these projects (Dey et al. 2013). With the introduction of high yielding rice varieties in 1980–90s, 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) started in the late 1960s, but gained momentum in late 1980s. Currently, 35,322 DTWs with a discharge capacity of 50–150 $l\ s^{-1}$ are working in Bangladesh for irrigation purposes. Following the devastating floods of 1988 and subsequent cyclones in the early 1990s, the government lifted all restrictions and embargos on the import of irrigation equipment. Consequently, local markets were flooded with inexpensive small (<12 HP) engines, mainly from India and China. The increased availability of equipment led to the maturation of Bangladesh's mechanized agricultural economy and the expansion of shallow tubewells with discharge capacity of 10–12 $l\ s^{-1}$. Today, 1,523,609 STWs, and 170,570 low lift pumps (LLPs) with a discharge capacity of 25–50 $l\ s^{-1}$ are operating in the country (BADC 2013). STWs became popular due to their suitability to the prevailing socio-economic conditions of Bangladesh's burgeoning *boro* farmers (less investment cost, small land holdings, and easy availability of pumps and spare parts in the local market). The temporal development of DTWs, STWs, and LLPs in Bangladesh is shown in Fig. 2.

Currently about 29.3 billion cubic meters (Bm^3) of groundwater is pumped annually in Bangladesh. Out of this, 25.2 Bm^3 is used for irrigation whereas the rest 4.1 Bm^3 is used for domestic and industrial purposes (Rajmohan and Prathapar 2013). The access to groundwater helped in a continuous increase in the groundwater irrigated area until 2005. After that, surface water irrigated area started increasing mainly due to increasing cost of groundwater irrigation caused by declining water table depths in most intensified areas (Fig. 3). The expansion in surface irrigated area was also partially attributed to the availability of low lift pumps that increased access to surface water. Currently, about 4.2 million ha of land is irrigated by groundwater whereas only 1.03 million ha is irrigated by surface water using low lift pumps (BADC 2013). The area irrigated by surface water has reduced from 76 % in 1981 to 23 % in 2012 whereas for the same period, area irrigated by groundwater has jumped to 80 from 16 % (BADC 2013).

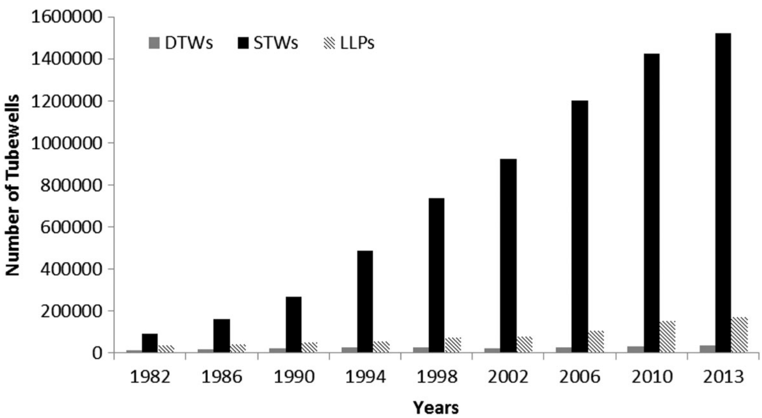

Fig. 2 Temporal development of different types of pumps in Bangladesh (BADC 2013)

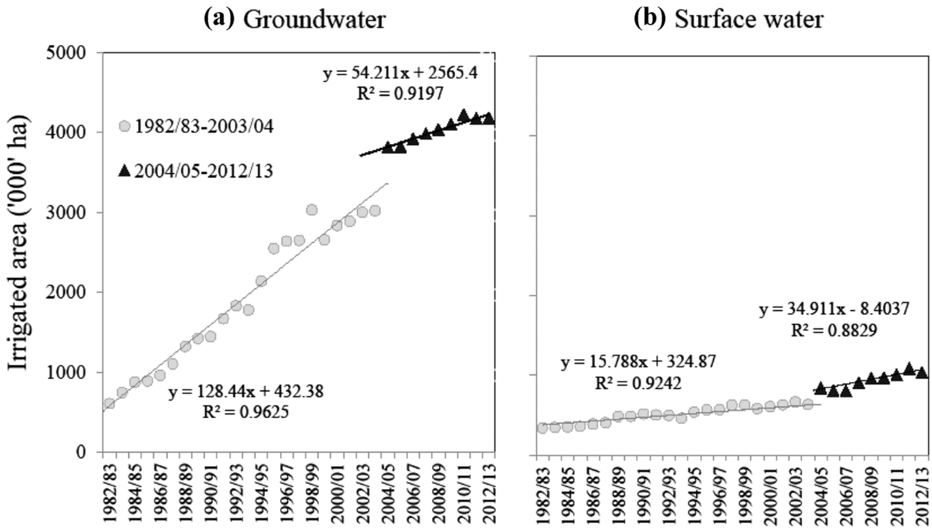

Fig. 3 Area irrigated with (**a**) surface water and (**b**) groundwater in Bangladesh (BADC 2013)

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 (Fig. 4). On the other hand, the north-eastern and south-central regions have large areas occupied by surface water irrigation, though not in the same density as found for groundwater irrigation.

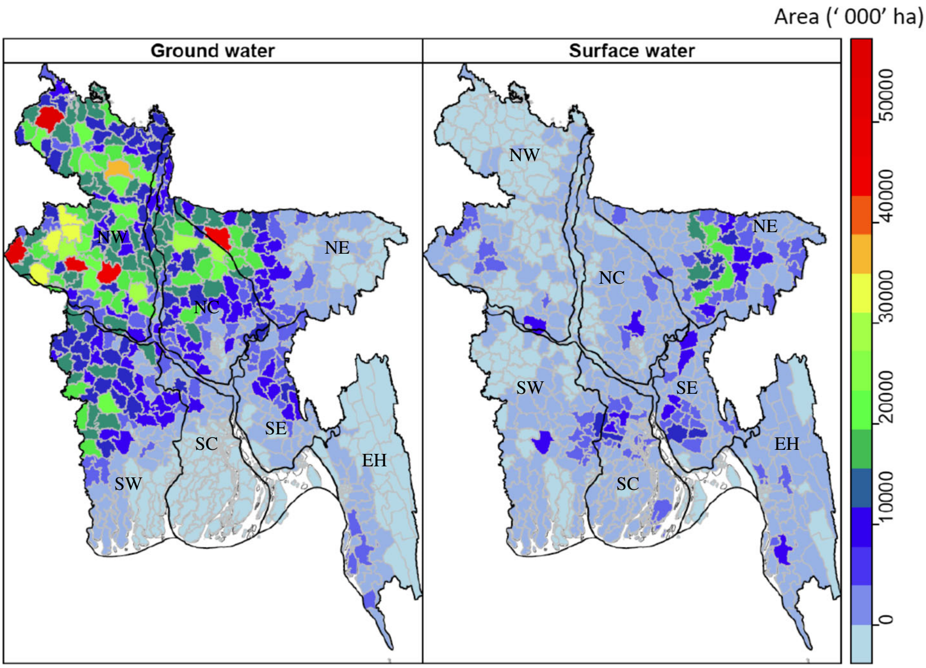

Fig. 4 Hectares irrigated by groundwater and surface water by sub-district in the eight hydrological regions of Bangladesh (Data: BADC, 2013). *NW* Northwest, *SW* Southwest, *SC* South Central, *RE* River and Estuary, *EH* Eastern Hills, *SE* South East, *NE* North East, *NC* North Central

3.2 Problems of Groundwater Development

3.2.1 Declining Water Tables Due to Groundwater Overdraft

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 and 2002, this area was only ~4 % of the country's total, but increased to 11 % in 2008 and 14 % in 2012 (Fig. 5). The most significantly affected areas lie in the north-west (e.g., Barind Tract) and north-central (i.e., Madhupur Tract) regions. These are areas of intensive *boro* cultivation and exhibit declining long-term groundwater trends. In the

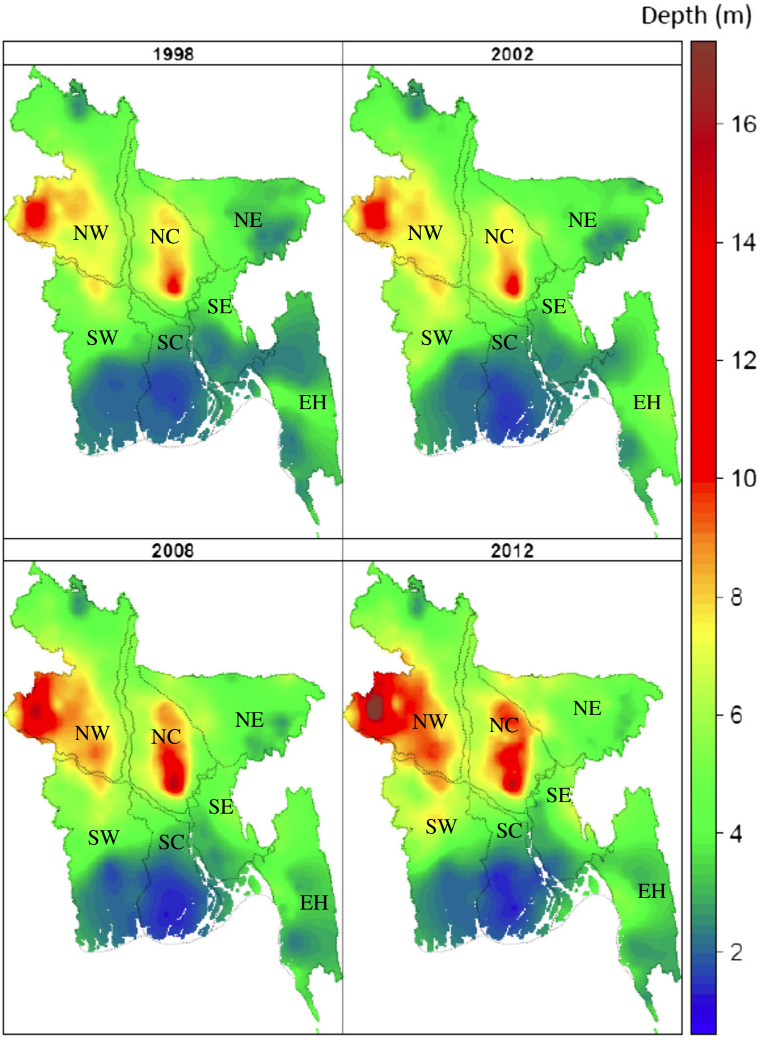

Fig. 5 Mean ground water table depth (m) for the height of the dry season (March, April and May). Surface maps were created using multi Gussian Kriging from the time series data of observed groundwater levels from the Bangladesh Water Development Board (BWDB)

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. The substantial drawdown of aquifers in these regions has also been reported by many other studies done in Bangladesh (Shamsudduha et al. 2009; Jahan et al. 2010; Dey et al. 2013).

Unlike the north-west, water tables in the southern Bangladesh 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. Brammer (2014) argued that rising groundwater levels in southern Bangladesh are a consequence of seawater intrusion and tidal movement (1.3–3.0 mm year^{-1}).

3.2.2 Groundwater-Energy Nexus for Bangladesh

Groundwater pumping and energy are intrinsically linked by the simple fact that energy is required to extract water from the 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 operated. About 95 % of these STWs are run using Chinese diesel engines of 10–15 HP capacity. According to Bangladesh Energy Board (BEB 2012), about one billion kilowatt hours (kwh) of electricity is used to operate electric tubewells each year. 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 1445 (Table 1). For other seasons and crops, operational hours are considerably lower (300–400 h). Al-Masum (2012) conservatively estimated that each pump used for *boro* is operated for 1800 h in a year. Shah (2007) and Mukherji et al. (2009) have also reported that diesel pumps are operated for 1900 h per year in Bangladesh.

Assuming 1800 operating hours and the diesel consumption rates of Table 1, about 4.6 billion litres of diesel is used every year to pump groundwater for irrigation, costing 48 million USD in aggregate. This cost is in addition to USD1.4 billion of yearly subsidies supplied by the government to sustain groundwater irrigation (BIDS 2012). Such considerable investments have raised serious concerns about the sustainability of Bangladesh's groundwater-based agricultural economy.

While groundwater irrigation in South Asia is generally contracting in response to increasing energy prices and progressive reduction in subsidies on energy (Mukherji et al. 2009), it is still largely viable in Bangladesh though propped up by considerable government subsidies. The analysis of economic data reveals that in 2000, the price of one liter of diesel was

Table 1 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)

equivalent to 2.0 kg of rice, whereas this equivalency declined to 1.36 kg in 2014. However, consistency in the wheat prices in relation to diesel prices kept the profit margin for wheat relatively small (from 2.58 to 2.27 kg of wheat to buy one liter of fuel). This explains why *boro* is still considered the most preferred *Rabi* cropping. However, this equation would change if the subsidies are even partially withdrawn.

Due to subsidized electricity in Bangladesh, the energy cost of electric STWs is USD 20 ha^{-1} compared to USD 51 ha^{-1} for diesel pumps of the same capacity. 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. 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 %. The higher costs for diesel operated pumps are also attributed to lower operational pump efficiencies, which rarely exceed 20 %, compared to 35 % for electric pumps (Hossain and Deb 2003). These lower pump efficiencies are generally linked to sub-standard manufacturing and poor farmer maintenance. 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, threatening the economic foundations upon which *boro* production is based.

3.2.3 Arsenic Contamination of Groundwater

In Bangladesh, an estimated 35–77 million people have been chronically exposed to Arsenic (As) via drinking water (Ahmed et al. 2011). High As concentration is mainly found in shallow aquifers with depths <100 m, which poses a serious risk of As accumulation in paddy soils over time because inorganic As species in irrigation water are retained in soils by adsorption on mineral oxide sulphate (Duxbury et al. 2009). Since most of the rice is irrigated with contaminated shallow groundwater, accumulation of As in rice can negatively affect rice yield and elevate As concentration in rice grains (Panaullah et al. 2009) posing health risks for consumers and reducing *boro* yield by up to 5 tons ha^{-1} under acute toxicity (Ahmed et al. 2011).

The analysis of sampling data shows a great variability in As contamination in different regions of Bangladesh with highest values for south-east (SE) and south-central (SC) regions (Fig. 6). All maps show higher probability of exceeding 50, 100, 150 and 200 μg As/L in the south. Because Bangladesh lacks regulatory standards for As in irrigation water, we used two probability thresholds to delineate safe ($P \leq 0.2$), contaminated ($P > 0.8$), and uncertain or unclassified ($0.2 < P \leq 0.8$) areas where further research is needed. In the SE, 47, 32, 20 and 10 % of total land area has As contaminated irrigation water, with respect to the threshold values listed above. Landscape elevation and monsoon flooding class are important factors in the deposition of As from irrigation onto paddy soils, with the highest concentrations found on highland (<90 cm floodwater during the monsoon) and medium-high (up to 90 cm flooding) land, but not in low lying areas that experience seasonal water and soil flushing, and which may require reduced irrigation rates, as observed in the SW (Ahmed et al. 2011). In this area, ~19 % of the land is unlikely to be safe for *boro* cultivation.

Rice grains with higher As concentrations could aggravate the health risk posed by drinking As contaminated water. Daily consumption of 400 g of rice containing 250 μg As kg^{-1} gives an equivalent intake of As to consumption of 2 l of water at the Bangladesh limit of 50 μg As L^{-1}. However, geographical variation in arsenicosis incidences shows that arsenic intake from drinking water is typically more dangerous than from rice (Ahmed et al. 2011).

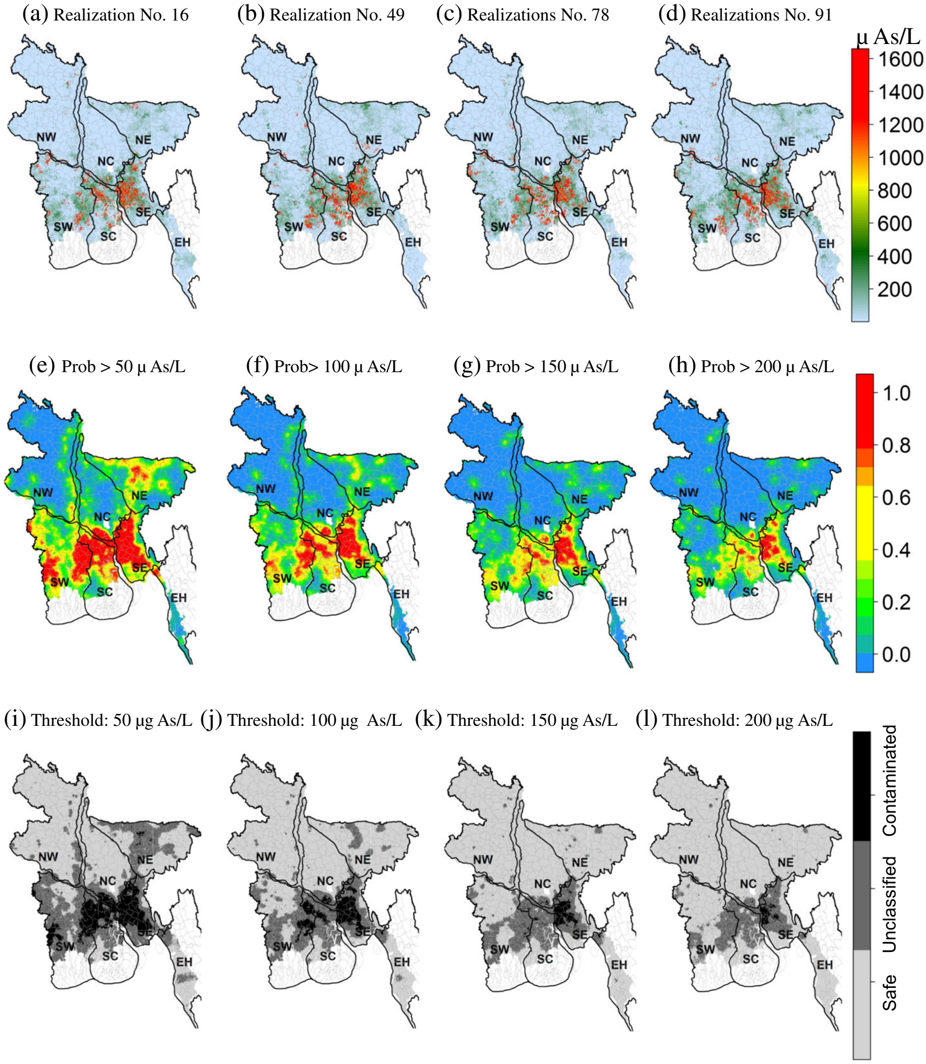

Fig. 6 Top panel (**a-d**): Data realizations (16–91 iterations) utilized to generate the probability of groundwater As contamination. Middle panel (**e-h**): probability of irrigation water As contamination (μ As L-1) at four concentration thresholds. Bottom panel (**i-l**): Safe, uncertain and contaminated irrigation water As (μ As L-1) contaminations at four threshold ranges

3.3 Prospects for Sustainable Groundwater Management

The groundwater extraction in Bangladesh is characterized by millions of scattered pumpers, who typically use small pumps to lift groundwater to irrigate small patches of lands. For example in Iran, less than half a million of tubewells are used to extract 45 cubic kilometers (Km^3) of groundwater whereas, in Bangladesh, over 1.5 million tubewells are used to pump only 28 Km^3 of groundwater. The fact that 85 % of Bangladesh's population lives in rural areas and earn their living through agricultural activities further complicates the issue.

Unfortunately there is no simple solution to these complex problems. Therefore more concerted efforts are needed to bring a balance between aquifer discharge 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. Some potential prospects are discussed below.

3.4 Improving Water Use Efficiencies

Despite all scientific progress, *boro* cultivation in Bangladesh is largely done by applying flood irrigation, although studies have shown that keeping *boro* fields moist 3–4 days after the disappearance of standing water did not reduce yields (Kasem 2006). According to the studies conducted by Bangladesh Rice Research Institute (BRRI 2000), an average of ~4.0 m^3 of water is typically used for producing 1 kg of *boro* in farmers' fields, compared to 2.0 m^3 in researcher managed trials. Farmers apply water in excess of crop requirements to accommodate seepage and percolation rates in rice fields under flood irrigation practices (4–8 mm day^{-1}) (Rashid 2008).

Studies in Bangladesh have shown that bed planting technique can save up to 40 % water compared to flood irrigation, in addition to higher gross margins (Mollah et al. 2009). Despite these advantages, lack of capital and access to equipment are considered as the major bottlenecks in the adoption of bed-planting technique for rice-wheat systems in Bangladesh (Krupnik et al. 2013). Another potential way to increase water use efficiency in rice is the alternate wetting and drying (AWD) technique, which allows ponded water to disappear from the field and infiltrate for several days until the perched field water table reaches 15–20 cm depth. Adoption of AWD in Bangladesh could save 20–30 % of the water used in flooded rice, amounting to US$ 73.5 million worth of irrigation cost on 4.8 million hectares of *boro* land area (Mollah et al. 2009).

3.5 Balancing Aquifer Recharge and Discharge

Aquifer management is an effective away of establishing a balance between discharge and recharge components. For this purpose, regional availability and volumes of groundwater resources that can sustainably be extracted for agriculture need to be evaluated. For basin scale analysis, distributed hydrological budgeting techniques (Chen et al. 2005; Mazza et al. 2014) and quantification methods based on remote sensing and GIS analysis (Casta et al. 2010) have proved successful. For the recovery of groundwater reserves, artificial recharging techniques are widely used in industrialized countries. For example, artificial groundwater recharge contribution varies from 12 % in England to about 30 % in Western Germany (Shah 2007). 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).

Farmers need to be encouraging to harvest rainwater and adopt watershed management strategies to improve the productivity of rain-fed systems and reduce the demands on groundwater. In Bangladesh, rainwater harvesting may also be introduced in public and community wells situated near slums and in villages, draining water from nearby rooftops and streets into them, especially during the monsoon. However, large scale investments on rainwater harvesting needs to be carefully evaluated in view of its impact on the water balance of the basin (Jasrotia et al. 2009) and availability of water for downstream farmers (Venot et al. 2007).

3.6 Rationalizing Cropping Patterns

Declining water availability both in terms of quantity and quality advocates that it is now time to review whether Bangladesh should continue to grow rice to ensure food security 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 and maize are grown on 400,000 and 170,000 ha, respectively (BADC 2013) with their total productions far less than the annual country demand. On an annual basis, Bangladesh import 2.0 million tons of wheat and 1.0 million tons of maize to meet national demand (BARI 2014). Adoption of these two crops would help in stabilizing aquifers and saving valuable foreign exchange being spent on the import of these two grain items.

3.7 Introducing Policy Reforms

Like other South-Asian countries, institutional solutions to groundwater management in Bangladesh have been difficult to implement because political leaders remain under pressure to ensure adequate food supplies for the population and reduce poverty, especially in rural areas. As major investments in surface water and irrigation systems have declined over time, government has few options other than to allow the expansion of irrigated agriculture through groundwater development and is therefore reluctant to implement stringent regulation. Under this complex situation, a multidimensional approach is needed. One potential policy avenue could be the promotion of profitable, but less water demanding crops than *boro* rice. Measures to focus on alternative crops and cropping patterns could be implemented through policy changes.

Government need to adopt policies for promoting water conserving crop practices such as alternate wetting and drying and bed planting techniques. This would require facilitation for water pricing structures that would interest farmers to reduce irrigation volumes for *boro*. Government support is also 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.

Policy reforms are also needed 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. 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. There is also a need to work on creating awareness through educational programs for all stakeholders. The central elements will be heavy involvement of users, substantial investments in modern water and agricultural technology fixing quotas for groundwater extraction, facilitate markets for non-rice crops and promote alternative cropping patterns.

4 Conclusions

In Bangladesh, the emphasis in the past has been on the development of groundwater resources, but *not* on the management and conservation of this resource. This has resulted in numerous problems which are threatening the sustainability of irrigated agriculture and future food security of Bangladesh. The frontline challenge therefore 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 direct management of groundwater through the introduction of groundwater use rights and limitations on groundwater access by enforcing permit systems is probably not a viable solution for Bangladesh due to large number of users, and ineffective institutional arrangements to ensure implementation of laws and regulations. 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 the enabling policies and decision support systems. Policy research should address which options might be best for future groundwater governance in Bangladesh.

Unlike in the past, Government need to revisit the policy of giving priority to *boro* for food security. 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 country needs and the availability and sustainability of aquifers.

The recommendations given in this paper for groundwater management in view of its increasing use for the sustainability of irrigated agriculture are equally applicable to other countries where surface water availability is shrinking and dependence on groundwater is increasing, efficiencies of agricultural water use are low and political and socio-ecological conditions are comparable.

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