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Perspective

Why Technologies Often Fail to Scale: Policy and Market Failures behind Limited Scaling of Alternate Wetting and Drying in Rice in Bangladesh

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Abstract: Rapid expansion of groundwater use for irrigation for dry season rice production in Bangladesh has led to overuse, deterioration of groundwater quality, increased cost of irrigation, and higher greenhouse gas emissions. The divergence between marginal private and social cost of irrigation due to market failures in the presence of these externalities, has resulted in excessive use of groundwater. A combination of policy reforms and improvements in irrigation practices are hence needed to reduce irrigation water use. The paper analyses why an improved irrigation practice, known as "alternate wetting and drying (AWD)" that can potentially reduce irrigation water use substantially, has failed to scale despite widespread testing and promotion in Bangladesh for over a decade. The main reason for this failure to scale is the lack of economic incentives to save water as pricing is based on per unit area irrigated, not on the amount of water used. This paper highlights the dynamics of the water market and pricing in Bangladesh, along with biophysical and social constraints to farmer adoption of AWD. It also proposes changes in policy incentives, new directions for crop and water management research, and institutional reforms for wider adoption of AWD and other water-saving practices.

Keywords: AWD; incentives; social cohesion; technology adoption; water management

1. Introduction

Bangladesh, one of the most densely populated countries in the world, relies heavily on rice to feed its 165 million people. Bangladesh has intensified rice production via the adoption of high-yielding varieties and planting in multiple seasons [1]. A rapid increase in the area of dry season rice (or *boro* rice), which is grown under irrigated conditions, has contributed significantly to increases in rice production and improvements in food security [2–4].

The increase in *boro* rice production during the past three decades was driven mainly by an expansion of irrigation based on the extraction of groundwater. A rapid increase in the number of privately-owned shallow tubewells (STWs) drilled to extract groundwater from a depth of 15–30 m, was the main factor contributing to the expansion of irrigated *boro* rice area [2]. The increase in the number of STWs also led to the emergence of active water markets, with a large proportion of farmers relying on these markets to meet their irrigation needs. While having a substantial positive impact on rice production and food security, the expansion of *boro* rice has also led to increased economic and environmental costs [4–6]. These externalities include excessive use of groundwater, increased cost of irrigation, deterioration of groundwater quality, and increased emission of greenhouse gases due to the use of millions of diesel-powered STWs.

An important challenge is, hence, how to reduce these negative externalities while ensuring that rice productivity growth is not adversely affected. Reducing irrigation water use without sacrificing rice yield is an important strategy [7]. A reduction in groundwater extraction and use can be achieved through improvements in irrigation practices and complementary policy reforms.

Economic efficiency in the use of irrigation requires that the marginal value of irrigation is equated with its marginal cost. A key barrier to achieving this economically optimal outcome is market failures that result in a divergence between marginal private and social costs of irrigation. Aquifers in Bangladesh are a common pool resource with almost open access to irrigators. As a result, irrigators do not factor in the increased future costs resulting from the excessive drawdown of groundwater. Traditionally, farmers have irrigated liberally, wasting irrigation water as the private marginal cost of irrigation is close to zero. In addition, irrigators do not consider environmental externalities such as deterioration of groundwater quality and emission of greenhouse gases. Bangladesh needs effective policy instruments to internalize these externalities resulting from market failures. Water has been largely considered a 'free gift of nature' available without charge and not subject to a pricing policy. Economic instruments such as tax/incentives and regulations are needed to correct for the market and policy failures and encourage more economical use of irrigation water.

There are also irrigation technologies that increase water productivity and, hence, save irrigation water. One example is "alternate wetting and drying" (AWD). AWD is a method of intermittent irrigation that contrasts with the traditional practice of continuous flooding. AWD reduces total irrigation amounts at the field level and saves water [8]. Research in Bangladesh has demonstrated the potential water saving and gain in irrigation water productivity resulting from AWD [9,10]. However, farmer adoption of AWD remains limited despite its promotion since its introduction in 2004 [11,12].

This raises several key questions: what factors determine the economic incentives for the adoption of AWD? How do the nature of the water market and pricing of water shape such economic incentives? How are water markets likely to evolve in the future? What broader policy and institutional reforms are likely to promote the adoption of irrigation saving practices while also ensuring that negative environmental externalities associated with groundwater use for irrigation are reduced? The paper addresses these broader questions one that have not been dealt with adequately in past studies, which have been mainly farm-specific [8,13–15]. The focus of this paper is on the broader biophysical and social constraints, policy incentives, and institutional reforms for a wider diffusion of AWD.

Analysis based on currently available adoption studies, dissemination strategies, and policy discussions, forms the main methodological approach. The specific tools used include desk reviews, field visits to key sites along a transect from Rajshahi to Feni, and key informant interviews of stakeholders, including various agencies involved in irrigation management at the national and local levels, accomplished in October 2018 (Figure 1). Focus group discussions were conducted in Nurpur (Feni district), Joypurhat (Chittagong district), Shivalaya and Dhamri (Dhaka district), and four villages (Shibrampur, Sormongla, Hatpara, and Sultangonj) of Rajshahi district.

The paper is organized as follows. The first section provides a historical account of irrigation development in Bangladesh. The second section discusses some of the salient features of AWD. The features of water markets, water pricing, their likely evolutionary trajectories, and the effects of alternative pricing structure on economic incentives for adoption of water-saving practices are discussed in the third and fourth sections. The fifth section discusses key factors constraining the adoption and diffusion of AWD. The penultimate section elaborates on strategies for promoting the adoption and diffusion of water-saving practices. The final section highlights some key implications for research and policy.

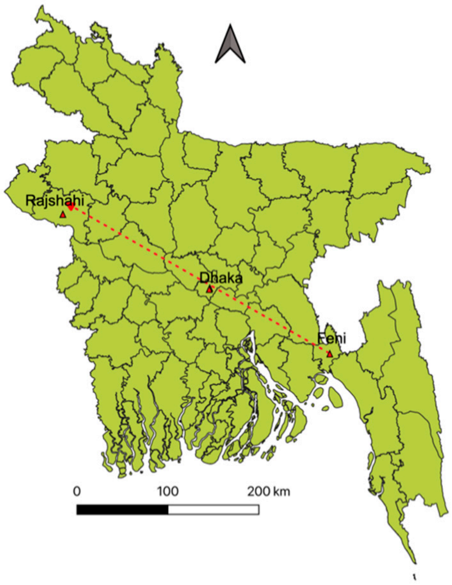

Figure 1. The transact of the field sites surveyed in 2018.

2. Historical Development of Irrigation in Bangladesh

Over the past six decades, the irrigation system in Bangladesh has undergone a transformation in terms of sources of water, technologies, management, and the relative importance of the private versus public sector [2].

Until the 1950s, irrigation mainly involved the use of traditional manual devices for lifting ponded water from natural depressions. This provided supplemental irrigation during the rainy season. Public sector investments in the early 1950s largely focused on large-scale schemes for flood control and drainage as the low-lying southern delta region suffered from frequent flooding and water-logging. Nevertheless, the government also embarked on major surface irrigation projects. These public-funded projects suffered from the usual problems associated with the supply of irrigation over a large command area, namely issues around timely and efficient water delivery and operation/maintenance [16]. As a result, irrigation coverage remained limited.

The next stage of transition involved public investments in diesel-powered low-lift pumps (LLP) to lift water from natural depressions, creeks, and drainage channels for irrigating adjacent fields. This type of irrigation spread quickly during the early 1970s in northeastern and central Bangladesh. Heavily subsidized pumps were initially owned and managed by the public sector but were then rented out to cooperatives (both public and private) and large-scale farmers. Eventually, the pumps were sold to large farmers resulting in a transfer of ownership and management entirely to the private sector.

Simultaneously with LLP, public investments were made in deep tubewells (DTW). These tubewells extract water from deeper aquifers (75–100 m). A parastatal, Bangladesh Agricultural Development Corporation (BADC), initially owned and managed these tubewells, some of which were ultimately transferred to the private sector. A major expansion of DTW took place in the late 1980s after the launch of a special project for the development of the Barind tract, which is the western, high elevation, and low-rainfall region. LLPs and DTW, accounted for most of the irrigated area until the mid-1980s.

These public sector irrigation projects could not provide sufficient irrigation to support the expansion of *boro* rice cultivation during the 1990s. To encourage private sector investments in irrigation (and agriculture generally), the government removed all restrictions on the import of irrigation pumps and abolished duties on such imports in 1988 [2,17]. These reforms, together with the increasing availability of low cost Chinese STWs, led to a rapid expansion of private sector investment in irrigation. The number of STWs increased from around 20,900 in 1980–1981 to more than 1.36 million in 2017–2018 (Figure 2a). STWs have now become the major source of irrigation in Bangladesh, and water markets have developed in response.

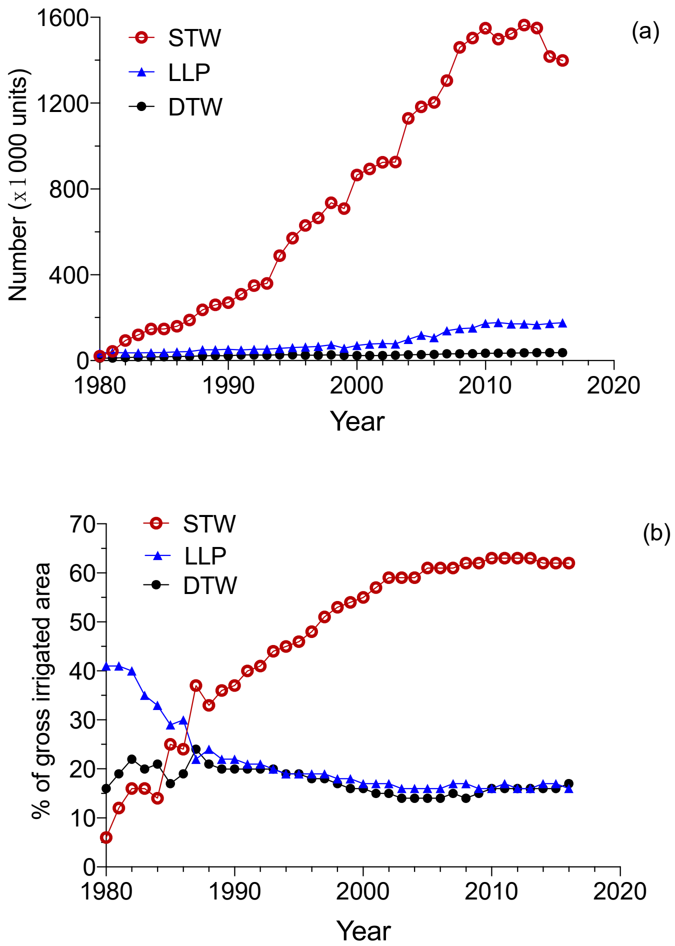

Figure 2. Trends in the number of various types of pumps (**a**) and proportionate irrigation area coverage (**b**) by shallow tubewells (STW), low lift pumps (LLP), and deep tubewells (DTW) overtime. Data source: Bangladesh Bureau of Statistics [18].

In 2016–2017, groundwater uses for irrigation (with DTW and STW combined) accounted for about 79% of the total irrigated area with surface irrigation based on LLP accounting for most of the rest (Figure 2b). The proportion of area irrigated by DTW and LLP decreased over time with the expansion of STW. In 2016–2017, STW accounted for 62% of the total irrigated area. The main reasons for the leveling-off of irrigated areas by STW are the increasing cost of irrigation and low profit in *boro* rice production. Except for DTWs, which continue to be managed by parastatals and some surface irrigation projects still under the public sector, irrigation is now mainly in the private domain.

3. Alternate Wetting and Drying (AWD): Its Features, Adoption, and Effects

Traditionally a rice field is continuously flooded. This practice evolved when water for irrigation was abundant and freely available or heavily subsidized. When water is physically or economically scarce, frequent irrigation becomes less feasible. Farmers are subsequently forced to practice intermittent irrigation. This may result in field-drying between irrigations and minimal to severe yield loss depending on the length of the irrigation interval and the crop growth stages. All such intermittent irrigation practices involve alternate wetting and drying (AWD), but the yield loss associated with “unintended” or “forced” AWD can be substantial.

In contrast, "safe-AWD" is a practice that maintains the yield level. It involves practicing intermittent irrigation guided by the observed soil moisture status. For example, a form of safe-AWD involves monitoring the depth of the perched water table, as indicated in perforated plastic tubes embedded in the soil, and irrigating when the perched water table falls below 15 cm from the soil surface [19]. These guidelines were outputs from the Irrigated Rice Research Consortium (IRRC) under which many field experiments were conducted across Asia. The research showed a 15-cm fall in the water table is a safe threshold value to avoid any yield decline due to water stress while simultaneously significantly increasing the water productivity [20,21]. Safe-AWD also includes ponded water at panicle initiation to flowering to avoid any stress at these critical growth stages. Different variants of safe-AWD allow for suitable adjustments in the timing and frequency of irrigation depending on the crop growth stage and farmers' ability to control irrigation flow [8].

3.1. Adoption of Safe Alternate Wetting and Drying (AWD) in Bangladesh

Safe-AWD was introduced to Bangladesh in 2004 and targeted at northwest Bangladesh—a major *boro* rice-growing area that suffers from water scarcity due to the rapid expansion of groundwater use for irrigation. Various agencies, including the Bangladesh Rice Research Institute (BRRI), Department of Agricultural Extension (DAE), and BADC, carried out farmer field evaluations and demonstrations trials together with farmer training from 2005 to 2009 [8,9,13,15]. Studies highlighted the potential irrigation water saving and economic benefits that could be realized with AWD [10,22,23].

Despite these findings, there are limited data on AWD adoption and diffusion. Adoption is when a farmer voluntarily uses new technology in its original form or with some adaptation in a substantial portion of the farm [24,25]. This goes beyond the initial testing and experimentation phase. Initial adopters may discontinue the use if their expectations are not met. A technology is considered to be in the process of 'diffusion' if additional farmers decide to adopt over time and expand the area under the technology [25].

There are no known studies that confirm a continued use (or expansion of coverage area) by those farmers who participated in the original piloting and field testing of AWD or by other non-participating farmers. It is also unclear how many farmers who participated in validation trials decided to continue with the practice as no follow-up surveys were carried out. Activities to promote safe-AWD seem not to have expanded beyond the initial field testing and validation despite several national level deliberations on the need to address water scarcity. A recent survey conducted in the northwest region of Bangladesh did not find any farmer who practiced AWD [11]. This suggests constraints within and outside the irrigation sub-sector, stymying the diffusion of safe-AWD.

3.2. Effects of Safe Alternate Wetting and Drying Discerned from Field Testing and Validation Trials

Indications of the effects of safe-AWD in Bangladesh can be discerned from field testing and validation trials. Most of these trials were conducted on farmers' fields and involved comparing results from the safe-AWD treatments and farmers' irrigation practices (see Table 1).

Most of the studies indicate that the number of irrigations applied to *boro* rice under safe-AWD treatment is lower than farmers' normal practices. Farmers used 14–21 irrigations under conventional practices compared to 10–16 irrigations under safe-AWD, a reduction of 27–35%. The reduction in the volume of water is likely to be less than the proportionate reduction in the number of irrigations as the amount of water applied to safe-AWD plots at each irrigation is generally more than water added to already-saturated or flooded plots. The observed savings in irrigation at the field level do not translate directly into savings at the system level due to return flows and recycling of drainage water [26]. The drainage, runoff, and seepage losses from an individual field are often not losses at higher spatial scales. Runoff makes its way to other farmers' fields or surface water bodies from where it may be reused in various ways, and drainage flows to the groundwater, from where it can be recycled by groundwater pumping (unless the groundwater quality is poor). Seepage flows to adjacent fields, surface drains, or the groundwater. Thus, any irrigation water savings estimated through such field trials overestimate the actual water savings at a larger scale.

The average reduction in the cost of irrigation was found to be in the range 27–35%, depending on the trial location and sources of water (Table 1). This matches well with the reduction in the frequency of irrigation. The cost-reduction estimates obtained in these trials, however, represent only a potential cost reduction. Such reductions typically are not realized by farmers as the dominant practice is to pay for irrigation on per unit area basis irrespective of the number of irrigations or the volume of water applied. This is a major disincentive to the adoption of safe-AWD.

One of the disadvantages of safe-AWD is the increased cost of weed control relative to conventional practice. Increased costs range from 11–85% and include labor costs and herbicide (when applied). In safe-AWD, the dry periods favor weed growth relative to the conventional method. Increased weed infestation and higher cost of weed control may be an important consideration in farmers' adoption decisions.

In contrast, the yield of *boro* rice with safe-AWD is reported, in some of these trials, to be higher than under conventional practices. The yield advantage of safe-AWD ranges from 0–12%. This yield advantage is attributed to lower incidences of diseases and insect infestation [22], better root growth [23], higher panicle density [9], and a higher proportion of productive tillers and higher harvest index [27]. However, a meta-analysis of data from research trials covering 56 separate studies conducted in 18 countries does not show significant yield increases from safe-AWD [28]. The positive yield effects reported in Bangladesh, hence, appear to be outliers.

4. Water Markets and Pricing

Water markets influence water pricing and economic incentives to adopt water-saving practices. We focus on water markets based on STWs as they account for a major share of the irrigated area. The price of water varies according to the nature of contracts between water buyers and sellers. Three major types of water contracts exist in Bangladesh [14]. The first stipulates payment for water in the form of a share of the harvested crop. A water buyer agrees to pay a share, usually 25%, of the harvested crop as payment for water for the whole season. The seller is expected to provide full irrigation for the duration of the crop. The buyer is assured of irrigation without incurring any cost for water prior to harvest. The seller has an incentive to ensure that the crop will not suffer from water shortage because payment is linked to crop yield. The first type is being replaced by a second type of contract, which consists of a fixed pre-negotiated cash payment for irrigation based on per unit area for the whole season. The actual payment may be staggered as agreed between the two parties.

The third type of contract, which is new and less common, involves buyers paying a fixed amount per unit area for the right to use the sellers' pumps for the whole season. In addition, the buyer needs to provide fuel, operate the pumps, and carry out supervision at their own cost to ensure that irrigation is applied properly. Often referred to as the "two-part tariff," this contract unbundles the right to use STW from the actual operation of STW and unpacks the payment into two components that are paid for separately. The two-part tariff evolved in response to the conflict between sellers and buyers inherent in the second type of contract in which the former benefit by pumping less water than agreed and the latter benefit from increased yield from irrigating more.

Table 1. Reported effect of alternate wetting and drying (AWD) estimated from farm trials.

Source	Year	Location	Sample Size	Number of Irrigations			Yield (t/ha)			Cost of Irrigation (×1000 Tk/ha)			Labor Cost of Weed Control (×1000 Tk/ha)			Gross Returns (×1000 Tk/ha)		
				Conv	AWD	% diff	Conv	AWD	% diff	Conv	AWD	% diff	Conv	AWD	% diff	Conv	AWD	% diff
Neogi et al. [23]	2013–2014	Rangpur	109	17	11	−35	4.0	3.9	−3	nr	nr	−35	7.4	11.1	50	88	85	−3
Neogi et al. [23]	2014–2015	Rangpur	324	11	8	−32	4.1	4.1	0	nr	nr	−32	10.1	12.7	26	101	101	0
Hasan et al. [22]	2012–2013	Rajshahi/Rangpur	54	20	16	−20	5.1	5.4	6	13.7	8.9	−35	10.6	9.4	−11	91	96	5
Kurschner et al. [13]	2009–2010	Rajshahi	272	21	15	−29	4.2	4.6	10	6.7	5.5	−18						
Kurschner et al. [13]	2009–2010	Rangpur	272	16	11	−31	4.3	4.8	12	5.0	4.0	−20						
Sattar et al. [9]	2008–2009	Various districts	Variable	14	10	−29	5.0	5.4	8									
Kabir [29]	2008–2009	Various districts	460	14	10	−30	5.3	6.0	13	13.0	9.3	−28				76	86	13
Husain and Kabir [30]	2007–2008	Gazipur	6	nr	nr	29												
Husain and Kabir [30]	2008–2009	Gazipur	6	nr	nr	27												
Hossain [2]	2008–2009	Rajshahi	100				6.4	6.7	5	5.1	3.7	−27	4.8	5.1	−5			

nr: the data is not reported in the research paper.

Survey data indicate that the fixed pre-negotiated payment system is the most popular accounting for about 50% of the total number of contracts, although considerable spatial variability exists (Table 2) [14]. The second most popular is the two-part tariff accounting for 32% of the total number of contracts. Crop share contracts account for only 18% of the contracts. Between 2003 and 2013, the proportion of the two-part tariff contracts did not change, but that of fixed charge contracts expanded by substituting for crop-share contracts. These results are similar to those reported in a recent study [11].

Both the crop-share and fixed charge contracts provide little incentives to buyers for saving water as the total cost of irrigation, which is fixed on per unit area basis, does not vary with the volume of water applied. The third type of contract provides some incentive as farmers control the volume of water pumped. This is further elaborated below.

Table 2. Types and frequencies of water market contracts.

Types of Contracts	Number of Contracts (%)	
	2003	2013
Crop share	27	18
Fixed charge	40	50
Two-part tariff	33	32

Source: Rahman [14]

5. Transaction Costs, Economic Efficiency, and Likely Evolutionary Pathways for Water Markets

We propose a hypothetical but likely evolutionary pathway shaped by historic and economic factors as a framework for assessing the impact of alternate market structures on incentives for the adoption of water-saving practices. Based on institutional economics, we hypothesize that the nature of the water market contract results from an interplay between the scarcity value of water and the transaction costs associated with various forms of contracts. Many economic and social factors (such as rural agrarian relationships and social stratification) also influence the dominant mode of payment for water and its evolution over time [31]. We focus here on economic factors.

Transaction costs involved in implementing a water contract include the costs of negotiation, monitoring, and enforcement. When the opportunity cost of water is low (or when water is plentiful), water contracts tend to be simple and easy to implement. Such contracts seldom result in economically efficient use of water; irrigators often tolerate efficiency losses due to the low opportunity cost of water. Complex contracts involving higher transaction costs emerge when the opportunity cost of water increases. The trade-off is between the low transaction cost of simpler contracts and the efficiency gains of improved control of irrigation resulting from more complex contracts with higher transaction costs.

The evolution of water market contracts could be hypothesized to follow the stages of transition illustrated in Figure 3. The increasing opportunity cost of water is the main driver from the initial stages to Stage 5. This leads to the increased economic efficiency of irrigation. The transition is not always linear, some stages may be bypassed, and a mix of contracts may exist concurrently.

The contracts involved in the first two stages are simple to negotiate, and their compliance easy to monitor. The water seller guarantees the supply of full irrigation throughout the growing season, and the water buyer agrees to pay the stipulated payment per unit area. The volume of irrigation applied is not actively manipulated. As the charge remains the same regardless of the volume of irrigation, the water buyer has no incentive to adopt water-saving technologies.

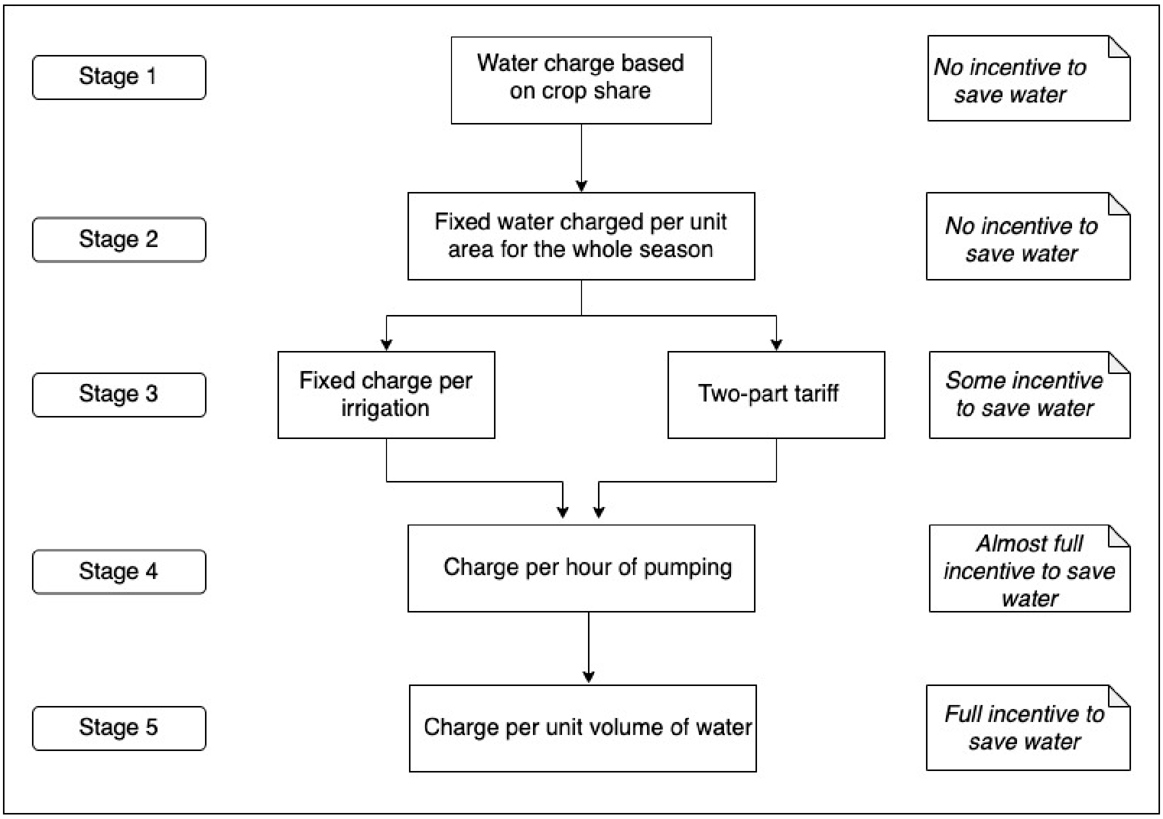

Figure 3. Likely evolutionary pathways for water markets.

The next stage (Stage 3) involves a contractual system that facilitates some degree of control of the volume of irrigation (the product of the frequency of irrigation and the volume of water applied per irrigation). A contractual stipulation that leaves at least one of these variables at the discretion of the buyer provides flexibility on how much irrigation to apply while assuring some level of income to the water seller. In the 'flat charge per irrigation' contract, the buyer pays a pre-agreed amount per irrigation but is free to choose the number of irrigations. The depth per irrigation is customary and implicit. The adjustments in water volume in this system occur in discrete steps by varying the number of irrigations. In the 'two-part tariff' system, the cost consists of a fixed component (payment for the right to use the pump) and a variable component (cost of fuel and labor). Once agreed, the total variable cost is under the control of water buyers and depends on the duration of pump operation.

Both these types of contractual arrangements provide incentives to adopt water-saving practices as one of the variables is under the buyer's control. However, non-adoption of 'flat charge' contracts and limited adoption of 'two-part' tariff contracts in Bangladesh suggest that farmers perceive the opportunity cost of water to be low enough not to switch to contracts with higher transaction costs.

Stages 4 and 5 are very similar. In Stage 4, the duration of pump operation varies as a proxy for volume. For a given pump capacity, the volume of water pumped is directly proportional to the duration of pump operation and depth of pumping. This is a good proxy for economically efficient volumetric charging, provided the conveyance losses in the turn-out catchment are minimal. In Stage 5, the actual volume of water applied is metered at the field turn-out. This enables farmers to adjust the volume of water applied and to achieve greater economic efficiency. Stage 5 systems are rare in Asia because of the high cost of infrastructure (e.g., control structures, pipes, and meters) needed for volumetric pricing.

6. Key Factors Constraining the Adoption/Diffusion of Alternate Wetting and Drying (AWD)

6.1. Lack of Economic Incentives to Save Water

The most common method of pricing water in both public and private irrigation schemes in Bangladesh is a fixed charge per unit area. There are variations in the timing of payment, proportions of cash/kind in total payment, and sharing arrangements for the cost of fuel and pump between water sellers and buyers [11,14]. The price of irrigation may also vary according to the season, local field conditions such as soil (e.g., sandy, clayey, etc.) and land types (e.g. location in the toposequence), and the social relationships between water buyers and sellers (e.g. kinship, neighbor, etc.). However, the price of irrigation is pre-negotiated largely on a per unit area basis rather than the volume of water applied. Water buyers have little incentive to save water as the marginal cost of water is effectively zero when the irrigation fee is fixed per unit area. Any benefit of reduced water use would accrue to the water seller only. Furthermore, a buyer may also irrigate profligately to control weeds and reduce risk if, for example, subsequent irrigations are delayed due to pump breakdown and/or unavailability of diesel, etc.

Pump owners/managers who irrigate their own farms do have an incentive to reduce water use as the benefit of water-saving accrues to them directly. In response to increased pumping costs, they may reduce irrigation water use through intermittent irrigation (rather than continuous flooding) and/or lengthening the irrigation interval. Whether they further shift to safe-AWD depends on further cost reductions that may result from such a switchover relative to negative consequences such as potential increases in weed control costs. Currently, there are no detailed studies to assess these incremental benefits and costs under farmers' field conditions across locations and over time. Limited adoption of safe-AWD among pump owners/managers suggests low returns.

In public irrigation schemes such as DTW and LLP, the irrigation fee is largely based on a pre-negotiated fixed rate per unit area. The rates may vary across schemes and locations. An innovative method of time-based charging, which approximates volumetric pricing, has been practiced in the DTW area managed by the Barind Multipurpose Development Authority (BMDA). This charging system uses pre-paid cards (PPCs) for regulating the duration of pumping. A farmer who wishes to obtain water for a given duration simply has to pre-load the required fee in PPC to run the motor for a certain duration [32]. This system represents a form of volumetric pricing; pumping duration has a fixed proportional relationship for a given pumping capacity.

There are no data to suggest that water pricing in the PPC system reflects water scarcity. Interviews with BMDA authorities and farmers indicate that the water price is derived from consultation with farmers by including the average cost of pumping, some proportion of repair/maintenance costs, and management cost. Such an administered price, designed to partially recover the operational cost of the system, is unlikely to reflect the true marginal cost of water. In addition, the current administered price seems too low to incentivize farmers to reduce the volume of water applied, given other benefits of irrigation, such as reductions in yield risk and better weed control.

6.2. Heterogeneity within Command Area and Limited Control Structures for Flexible Delivery of Irrigation

Most smallholder farmers in Bangladesh have fragmented and scattered land holdings. The plots located within the command area of a tubewell generally belong to a number of farmers. The average command area varies from 2–4 ha for STWs and 26 ha for DTWs [33]. The soil-drying pattern varies significantly based on the position of the tubewell, land gradient, soil physical properties, crop management practices (tillage, varieties, time of planting, etc.). It is not feasible for a tubewell owner to apply irrigation based on the drying pattern of each parcel; the water could deplete to 15 cm from the surface in one plot while it could remain flooded in other plots.

A pre-requisite for incentives to adopt water-saving practices is control structures to deliver the right volume of water at the right time for the farmers. In the absence of such control structures, water supply to farmers may be too much or too little and/or mistimed. The potential economic benefit from the adoption of water-saving practices will not be realized under such conditions.

In Bangladesh, the current surface schemes are based mainly on LLP. They lack adequate control structures beyond the secondary canal, making it almost impossible for individual farmers to regulate the irrigation volume. In the case of DTW, the control of water flow is most effective in cases where pipes are buried as pressurized water can be delivered close to farmers' fields. In addition, pressurized delivery overcomes the constraint of water flow across an undulating topography. However, the coverage of DTWs is small (less than 15% of the total area irrigated). The absence of control structures is not a significant issue for STWs due to a small command area (normally 2–4 ha). However, the current practice of conveyance based on open channels is less water-efficient than the use of flexible pipes that reduce water losses and enable spot irrigation according to need.

6.3. Uncertain Electricity Supply

Frequent disruptions in electricity supply that are common in rural Bangladesh translate into uncertainty in irrigation availability when water extraction is powered by electricity. Although only about 21% of STWs are powered by electricity [34], a rational response of a risk-averse farmer is to over-irrigate when electricity is available. Farmers indicated their preference to keep the electric pump switched on during power interruptions so that water is pumped automatically as soon as the electricity supply is restored.

6.4. Risk of Increased Weed Infestation and Rice Yield Losses

Another factor that reduces the incentive to adopt water-saving practices is the risk of weed infestation. Flooding helps reduce weed growth, and farmers have traditionally used this method for weed control. Weed control costs increase with AWD. The net gain to adopters of safe-AWD depends mainly on the balance of savings in the cost of irrigation versus the increased cost of weed control. A low cost of weed control, together with the high cost of irrigation, makes AWD attractive and vice-versa. When the costs of irrigation and weed control are high, the net effect cannot be predicted a priori and will depend on the specific cost and price parameters (Table 3).

Table 3. Effects of costs of irrigation and weed control for adopting water saving practices.

		Cost of Chemical/Manual Weed Control	
		Low	**High**
Cost of irrigation	**Low**	No incentive to save water	No incentive to save water
	High	High incentive to save water	Effect on incentives to save water uncertain

7. Strategies for Promoting the Adoption and Diffusion of Water-Saving Practices

The water market based on private STWs in Bangladesh is largely informal. Millions of primary agents draw groundwater to sell directly to buyers without any intermediation. The water economy is essentially dominated by a self-provisioning of water services. This informal water economy is mostly outside the legal, regulatory, and administrative control of the government. Some of the established pricing tools and regulations that work well with formal water economies of developed countries are simply not effective, due to high transaction costs when the water economy is informal. With around 10 million farmers buying water from 1.5 million privately-owned STWs over a vast agricultural area, the transaction costs of direct instruments to regulate the water market in Bangladesh are bound to be prohibitively high.

A feasible way to influence the behavior of water users in such situations is through indirect approaches. These include influencing the "environment of conduct," rather than the individual conduct [35]. Such approaches often work through a long impact pathway, and simple cause-effect relationships are not quickly discernible. Identification of policy interventions that influence the environment of conduct in the informal water markets of Bangladesh is critical for improving water productivity.

7.1. Shift Away from a Rice-Centric Policy of the Past

Bangladesh has prioritized self-sufficiency in rice. Policy support has included substantial investment in research and development (R&D) for rice, seed and fertilizer subsidies, and power subsidies for irrigation. With Bangladesh at the cusp of achieving self-sufficiency in rice, the government can shift from the rice-centric policy of the past. This would not only encourage crop diversification but also reduce the pressure on groundwater extraction. Bangladesh has a comparative advantage in producing several crops either for import substitution or for export. These include maize, pulse, and potato [36]. The irrigation needs of these crops are less than that for rice. Successful production and marketing of these crops will require public- and private-sector investments in market development, including roads, cold storage chains, distribution networks, and financial and business development services (credit, product standardization, food safety, and marketing information, etc.).

A complementary policy option would be to encourage seasonal and spatial relocation of rice production away from northwestern Bangladesh—a major *boro* rice area with increasing water scarcity. Seasonal relocation may involve the expansion of rice production in *aus* season in areas where rainfall is adequate for rice, perhaps with some supplemental irrigation during dry spells. Similarly, *boro* rice production could be promoted in south-western areas where low-cost, small-scale surface irrigation schemes are viable [37].

7.2. Rationalization of Energy Subsidy for Irrigation

The annual energy subsidy for irrigation in Bangladesh is estimated at USD450 million: USD400 million for diesel and USD50 million for electricity [5,38,39]. The cost of diesel subsidy for irrigation in 2012 accounted for almost 2% of the public expenditure in agriculture. The cost of the subsidy in terms of forgone opportunity to invest in other more productive avenues in agriculture is substantial.

In addition, considerable efficiency costs are associated with such subsidies. First, by making irrigation cheaper than it would have been otherwise, it reduces incentives for farmers to save water. Irrigation charges as a proportion of the gross value of rice production have remained in the range of 13–17% over the past ten years. Second, the institutional evolution of water pricing from the traditionally fixed charge per unit area towards other contracts (such as charging on an hourly rate for STW operation), that incentivize water saving, has been slow. Some increases in water price resulting from a rationalization of the diesel subsidy may catalyze the institutional evolution of water markets towards more efficient pricing. Marginal cost pricing is not being advocated here as there are strong reasons why it is not practical in Asian irrigation systems [40] but an institutional evolution in that direction could improve the overall efficiency.

7.3. Shift Away from Diesel to Electricity as a Power Source for Irrigation

A shift away from diesel-powered pumps to electric pumps is desirable for several reasons. Despite subsidies, the farmer cost of irrigating *boro* rice with diesel-powered pumps is 25–30% higher relative to electric pumps [5,14,41]. Subsidies have helped reduce the impact of diesel price increases. Still, farmers are likely to face increasing cost pressures if the government reduces subsidies. In eastern India, the cost increases have curtailed the expansion of irrigation-based on diesel-powered STWs [42]. In Bangladesh, cost increases could make diesel-powered pumps economically unviable. The environmental footprint of diesel-powered STWs is higher than electric ones. Thus, there may be a rationale for switching to electric pumps on environmental grounds, even when the cost of water extraction from such pumps may be higher than from diesel-powered ones.

In this context, public investments are needed to develop the required power station, electricity grid, and segregation of agricultural and domestic feeders. Some of the current expenditures on diesel subsidy may be utilized to subsidize electric STWs, to set-up the initial electricity connection for STWs, and installment of meters in STWs. Metered STWs will also incentivize irrigators to adopt practices that save water as their irrigation cost will depend on electricity consumption. Experience from India indicates that sustainable utilization of groundwater can be achieved through intelligent management of electricity that assures stable supply combined with some rationing [35].

7.4. Agricultural Research

A long-term approach to overcoming water scarcity in agriculture is to develop varieties, cropping patterns, and crop management practices that increase water productivity, hence, reducing irrigation per unit of crop production.

In the context of *boro* rice production in Bangladesh, this would involve developing shorter duration varieties and/or varieties that can be grown with less irrigation water. The evapotranspiration of a shorter duration variety is less than a longer duration one because of the crop's time on the ground. For example, the percentage increase in grain yield of suitable genotypes under AWD over the locally adapted long-duration variety BRRI dhan28 in Bangladesh ranged from 2.0 to 32.7% [43]. Even in cases where there is a trade-off between higher yield and shorter duration, the balance may be in favor of a shorter duration variety as it will facilitate early planting and higher yields of the next crop. Developing rice varieties with root structures more suited to AWD conditions would not only stabilize rice yield under safe-AWD but also provide yield gains over the currently-grown rice varieties. Research shows that increased numbers of nodal roots and root dry weight at 10–20 cm soil depth at 22–30 days after transplanting provided yield stability and no yield reduction under AWD compared to continuous flooded conditions [43]. Genotypes possessing an increased number of nodal roots provided a higher yield under AWD as well as no yield reduction compared to flooded irrigation.

Tuong et al. [26] discuss various strategies to reduce water inputs and increase water productivity at the field level. These include strategies to reduce (i) evaporation from fields during land preparation, (ii) unproductive transpiration losses such as from weeds, (iii) bypass flows during land preparation, and (iv) seepage/percolation. Option includes soil and water management practices such as laser leveling, puddling, additional shallow tillage to close soil cracks before land soaking, applying shallow irrigation to reduce seepage/percolation losses, and AWD.

Improved weed control technology will reduce the need to use water to smother weeds as practiced currently. Better land preparation, use of rice varieties with early seedling vigor, and a combination of mechanical and chemical weed control technologies are some of the promising areas of research. As a broad strategy, the use of substitute technologies to perform the functions of irrigation other than to support crop transpiration will reduce the overall field water demand. Research investments are also needed to promote agricultural diversification. Varieties of suitable crops such as maize, wheat, pulses, potato, and vegetables need to be developed and made available to farmers. Suitable crop agronomic practices for these crops also need to be developed, validated, and disseminated.

In addition to biophysical research, socioeconomic research includes monitoring of changes in irrigation practices over time and the impact of such changes on rice production and farmers' incomes. This is needed not just for better technology targeting but also for establishing a benchmark for future impact assessment. When water is scarce, one of the farmers' first responses is to reduce the number of irrigations. Understanding the process by which farmers make such adjustments can provide new insights into improving the acceptability of safe-AWD.

7.5. Irrigation Development and Management

7.5.1. Improvements in Irrigation Scheduling

The rotational irrigation scheduling currently practiced in Bangladesh in LLP/DTW area is based on a time interval (e.g., weekly, every 10-days). Its virtue lies in its simplicity and low monitoring cost. Schedules that are not conditional on soil moisture content are unlikely to achieve the most efficient allocation of water under water scarcity. However, monitoring soil moisture content can be costly and time-consuming using conventional procedures.

Scientific advancements allow for continuous real-time monitoring of soil moisture status of the entire command area using low-cost automated monitoring devices. These transmit data to a central monitoring system and facilitate efficient water management by sharing information with different stakeholders engaged in water governance and allowing for effective coordination, transparency, and improved overall management of irrigation systems. Considerable progress has been made in testing such systems [44]. Although some initial investment is needed to obtain the required hardware/software, and build capacity, Bangladesh could initiate work in this area to address increasing water scarcity and environmental footprints caused by current irrigation practices.

7.5.2. Extending the Field-Level Results to Command Area Scale

The effects of safe-AWD assessed at the field scale do not lend themselves to simple extrapolation at the command area level in DTW/LLP systems. In most systems, the responsibility of the irrigation manager ends with water delivery at the command area level. Implementation of safe-AWD at the field level with water delivery at the turn-out level requires collective action among farmers in the command area. The relationship among stakeholders using a fixed amount of exclusive resource (water in this case, when used by one is not available to another) is likely to be competitive, not cooperative unless the stakeholders are homogeneous in economic/social status, and their numbers are small [45]. Social regulations involving local community leaders and village elders may be needed to engender collective action. The structure and suitable mode of operation of such social regulations are, however, context-specific and depend on local conditions making any generalization difficult [46].

7.5.3. Reducing Conveyance Losses by Promoting the Use of Flexible Pipes

The use of flexible pipes for water distribution can reduce conveyance losses. In DTW/LLP systems, these can be used for water distribution in the turn-out catchment area. In STWs, such pipes can be similarly used to transport water from STW to the field. The use of flexible pipes in the eastern part of India is common where buyers pay for groundwater by the hour of pump operation [47]. The use of flexible pipes has also promoted crop diversification as water can be delivered to specific fields without irrigating the neighboring fields. In Bangladesh, the use of flexible pipes for irrigation is not common. There is, however, a clear rationale for STW owners to use flexible pipes for irrigation. Demonstration of flexible pipes and subsidies may be needed to encourage initially the use of such pipes.

7.6. Dissemination Strategies

Following the introduction of safe-AWD in Bangladesh, the strategy has been to promote the practice through initial testing, validation trials, farmer field trials, demonstration trials, farmer training, information dissemination, farm field days, and technical support to farmers, including free provision of mini-kits consisting of promising new varieties and fertilizers and training on the use of safe-AWD. Several organizations are involved, but without much coordination, dissemination continues to be based on piecemeal activities. This fragmented piecemeal approach has stymied the scaling of AWD [13].

The dissemination strategy has been missing a clearly delineated suitability domain for technology targeting. As a result, technology promotion activities have been broad and generic, covering heterogeneous locations and diverse farmers, resulting in high costs and inefficiencies.

Hence, there is a need for targeted dissemination based on a characterization of suitability domains at the plot level. The incentive structures are right for STW owners who irrigate their own land as cost reductions from irrigation water savings accrue to them directly. Almost 20% of rice farmers belong to this category [2]. Yet, dissemination programs have not explicitly targeted such farmers. Even if only 20% of such farmers adopt safe-AWD at least in parts of their fields in the next five years, the coverage of safe-AWD would increase to 4% of farmers—a substantial achievement compared to past dissemination efforts.

7.7. Groundwater Governance and Regulation

Bangladesh has introduced several policies for governance and sustainable use of groundwater. These include the Groundwater Management Ordinance in 1985, National Water Policy in 1999, and Bangladesh Water Act in 2013. These policies have often failed to provide detailed guidelines and specific steps for implementation, monitoring, and compliance. As a result, they have had little impact on groundwater use and management [48]. In addition, any direct approach that involves legal and administrative means is unlikely to be successful due to the high administrative cost of covering millions of smallholders who use groundwater but also to the resulting negative impact on their livelihoods.

Institutional reforms are needed to identify organizations responsible for groundwater governance and develop an effective coordination mechanism. Effective governance requires monitoring, planning, coordination, implementation, and regulation. A system for regularly monitoring the quantity and quality of groundwater is needed to provide a scientific basis for groundwater planning and use. Land-use zoning, enhancement of groundwater recharge in depleted areas, and regulation of groundwater extraction are some of the key steps that are needed. Groundwater governance involves many trade-offs. Shah [49] has suggested a three-step approach that includes getting incentives right, building the capacity of government agencies and local communities, and institutionalizing governance.

8. Concluding Remarks

The limited scaling of technologies/practices tested and evaluated mainly at farm-level practices such as AWD illustrates that policy and market failures have reduced the economic incentives to adoption. Overexploitation of groundwater and the associated negative externalities are the result of market failures that have driven the marginal cost of water to almost zero under the dominant water market contracts in Bangladesh. It is also illustrative of conflicting policy signals that promote water saving practices while simultaneously subsidizing irrigation for achieving self-sufficiency in rice production. Clearly, a technology "push" to scale AWD will not be successful without overcoming these market and policy failures.

A largely informal self-provisioning water economy based on millions of buyers and sellers of irrigation services without any intermediation severely constrains the effectiveness of administrative and regulatory policies alone to influence Bangladeshi farmers' irrigation practices. Hence, the challenge is to design a mix of improved farm-level technologies that increase water productivity, improve water management practices at the irrigation systems-level, and introduce policies that provide economic incentives for the adoption of sustainable irrigation practices. An interdisciplinary approach is needed because any improvement in irrigation practices needs to be in the context of underlying socio-political systems and the economic opportunities for millions of farmers.

The theory of induced institutional innovation [50] dictates that institutional arrangements tend to evolve towards saving resources that are increasing in scarcity unless such an evolution is constrained by policies or some other external factors. Government policy has supported farmers by keeping the price of water lower relative to rice price through the provision of power subsidies. This policy, while successful in achieving the objective of ensuring self-sufficiency in rice, may have also slowed down the evolution of water markets towards more efficient pricing systems that reflect the true scarcity value of water. A gradual and rationalized reduction of power subsidy may be warranted as the resulting increase in water price may catalyze the institutional evolution of the water market towards more efficient pricing.

A strategic approach to overcoming water scarcity in rice production in Bangladesh requires effective demand management as opportunities for supply augmentations are limited. The choice of cropping patterns, crops, suitable varieties, agronomic practices, and production locations should be guided by the objective of increasing the overall economic efficiency of irrigation. Increased investments in agricultural R&D, technology dissemination, and capacity building are needed so that farmers can have a larger set of productive and water-efficient production options to choose from. Working on field-level technologies of water management may be important, but care must be taken not to lose sight of other broader opportunities that can generate a much bigger impact at the irrigation system-level. There may be more effective opportunities for saving large volumes of irrigation water at the system level with the existing technologies than extrapolating the gain at the field-level.

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