Geotechnical Engineering Journal of the SEAGS & AGSSEA Vol. 54 No. 2 June 2023 ISSN 0046-5828

Performance of Cost-Effective Deep Tube Wells for Groundwater Development in Bangladesh

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ABSTRACT: Different water-lifting devices have ensured irrigation and public water supplies for urban and rural areas of Bangladesh. A cost-effective deep tube well (DTW) model was developed by the Rural Development Academy (RDA), Bogura when the government subsidized groundwater withdrawal in Bangladesh. The aim of this study was to analyse the performance of borehole technology in terms of cost, design, effectiveness, and adoption in rural Bangladesh. The cost of the RDA-developed DTW was lower (0.06–0.5 million BDT) than that of the traditional DTW, and the discharge capacity varied from 20 to 200 m^3/hr. The modified borehole by the RDA used its developed design, locally available materials, local human resources, and manual drilling to construct a DTW that exhibited excellent performance with minimal cost. The output of the DTW is demand-based technology, in which the discharge capacity depends on the farm size and the number of beneficiaries. Therefore, RDA-developed DTW technology is highly appreciated by non-governmental organizations and local-level entrepreneurs in Bangladesh to improve groundwater development.

KEYWORDS: Irrigation, Groundwater utilization, Rural development, and Water resources.

1. INTRODUCTION

World food security is significantly controlled by the sustainability of irrigated agriculture (Shamsudduha et al., 2022), and groundwater plays a principal role in water supply in Bangladesh (Mridha and Rahman, 2021). However, with increasing river water pollution and growing water demand for irrigation in recent years, an adverse threat to groundwater and agricultural productivity has been created in Bangladesh (Bhattacharjee et al., 2019). The rural economy of Bangladesh significantly depends on agriculture, which accounts for 90% of poverty reduction in Bangladesh (World Bank, 2016). More than 70% of the population and 77% of the workforce of Bangladesh live in rural areas, where the agricultural sector contributes approximately 20.5% of the national economy (Hossain, 1988). Therefore, groundwater irrigation in agriculture significantly contributes to poverty alleviation and increased food production in Bangladesh (Zahid and Ahmed, 2006). Access to drinking water via tap connection contributes 12%, hand tube well (HTW) and deep tube well (DTW) contribute 84.7%, surface sources (lake/pond/canal) contribute 3.0%, whereas others (dug well and waterfalls) contribute 0.3% (BBS, 2006).

Groundwater is a renewable and significant water resource, serving many developing countries such as Bangladesh as a dependable source of water supply for agricultural, industrial, and domestic purposes. The rapid increase in population and food demand in Bangladesh requires an enormous amount of groundwater (Shamsudduha et al., 2022). In addition, the rainfall pattern is non-uniform and fluctuates over the years. Consequently, the groundwater table has diminished, which affects sustainable water use for irrigation and drinking supplies in this area. Groundwater withdrawal during the dry-season irrigation in Bangladesh augments seasonal freshwater capture by increasing pressure on water resources (Shamsudduha et al., 2022). The total production land in Bangladesh is watered by 75% of groundwater and 25% of surface water, whereas 90% of drinking water demand is satisfied by groundwater (BADC, 2008). The Development and utilization of groundwater for irrigation and public supplies in urban and rural areas have been actualized by installing several types of water-lifting devices. The most widely used devices are the DTW, which functions in a force mode for drawing underground water from a borehole, and the shallow tube well (STW), which operates as a suction mode via connection to a centrifugal pump. These devices have been widely used nationwide for groundwater withdrawal, with possible economic and environmental impacts. For example, groundwater is used for cultivating the high-yielding boro rice variety in dry winter (January–June) and ensuring arsenic-free drinking water supply to households. Recent studies have shown that groundwater development in irrigation systems increases the suitability and productivity of the alluvial aquifers, particularly in Bangladesh, compared to other countries (Qureshi et al., 2014; Khan, 1988). Therefore, groundwater is a major contributor to irrigation expansion and can play a significant role in the future water resource development of Bangladesh.

Sources of surface water are limited during the dry season, whereas the water demand is satisfied by groundwater lifting through STWs and DTWs using centrifugal and turbine pumps, respectively (Mridha and Rahman, 2021). Recently, groundwater lifted through STWs, and low lift pumps (LLPs) has been contaminated with heavy metals and arsenic in mostly shallow aquifers of 50 m depth at many locations in Bangladesh (Rahman et al., 2009). Consequently, DTW is becoming more crucial for water withdrawal from deeper aquifers (60–250 m), which is safe and clean. DTWs are drilled wells of large-diameter boreholes (approximately 55 cm) with gravel packs around the screen and upper well casing of sufficient diameter (35 cm) and length (approximately 25 m) to enable turbine pump installation. The depth of a DTW in Bangladesh typically varies from 60 to 200 m, depending on the aquifers. The good design and management of DTWs may contribute to an increased discharge with decreased power consumption, which requires detailed studies. The prime mover (pumps) connected by a shaft of a DTW is a diesel engine or an electric motor mounted above the borehole. In addition, force–mode-type pumps are always submerged below the average operating water level in the wells, and discharge is no longer limited by the severe restrictions on drawdown. Typically, the discharge capacity of DTWs is 20–200 m^3/h, which can irrigate 10–80 ha of cultivable land. Therefore, the accurate design of boreholes is crucial to determine the maximum discharge and increase the irrigation command area for the productive utilization of water resources.

DTW expansion is a vital agenda of the government strategy for enhancing agricultural production through safe water irrigation to achieve food security in Bangladesh (Qureshi et al., 2014). The role of DTWs in groundwater management has been a significant concern of the national policy owing to increasing fuel costs. Moreover, small-scale irrigation projects in Bangladesh have attracted minimal interest, although they may equally be important as large irrigation schemes in enhancing productivity in Bangladesh

(Mottaleb et al., 2019). Several DTW projects failed because of inaccurate design, indiscriminate installation, and farmers' inadequate water use without considering the sustainability of groundwater resources. The total cost of a 200 m^3/h DTW is approximately 1.0–1.5 million BDT, depending on aquifer conditions, which is expensive for an average farmer (Matin et al., 2000). Most farmers in Bangladesh are poor, and their socio-economic conditions do not permit them to introduce imported capital-intensive machines. Small-scale agricultural machinery can play a critical role in increasing food production in Bangladesh. In this situation, installations of STWs are increasing yearly to satisfy irrigation requirements during the dry season (December–April). Consequently, groundwater levels drop during the dry season, increasing the total water lift from upper aquifers. Thus, the suction head of suction-mode pumps, such as STWs, becomes useless. Under such conditions, DTWs remain the only viable technology for lifting groundwater. However, the initial and installation costs of DTWs are high, which is unaffordable for poor farmers. The installation of demand based DTWs with low capital investment and year-round water utilization for multi-purpose use should be encouraged to overcome these difficulties and help farmers.

A safe and reliable borehole design significantly depends on the construction materials, well development, appropriate water supply system management, water quality and contaminations, and aquifer yields. Hence, considering locally available resources, a cost-effective DTW with optimal design parameters is required. For improved installation and operation of demand based DTWs with low capital investment, an appropriate DTW design and an adequate investigation of the aquifer are essential. An adequate well design and Development of the DTW system may increase the discharge yield, decrease pumping costs, increase irrigation efficiency, and increase the pump service life, significantly impacting the national economy. Based on this perspective, the Rural Development Academy (RDA), Bogura, has developed cost-effective DTW technology for the effective use of water resources, improving agricultural productivity in Bangladesh. The aim of this study is to analyze the performance of a cost-effective DTW and compare it with the traditional DTW in terms of cost, effectiveness, design parameters, operation, and water quality and to investigate its acceptability in rural Bangladesh. The specific objectives of this study are as follows:

1. To assess the performance of demand-based RDA-DTWs for multi-purpose use compared with the traditional DTW.
2. To determine the popularity and acceptability of RDA-DTW in rural Bangladesh.

2. METHODOLOGY

Diesel-powered DTWs were first introduced by the Bangladesh Water Development Board in 1963–1966 (Banerjee and De Silva, 2020). By around 1990, the energy source powering DTWs changed to electricity because of the unreliability of diesel DTWs and the resulting crop losses. Thus far, the RDA has installed more than 500 low-price DTWs at various locations in the country under the Government of Bangladesh-funded projects. In this study, we investigated 40 selected DTWs located in the Khulna division of Southern Bangladesh (22.8° N and 89.3° E, 9 m above sea level) (Appendix Table S1). Figure 1 shows the location map of each DTW alone with the RDA. The parameters are collected in relation to the performance and workability of RDA-developed DTW technology at each of the selected sites to assess these systems (Appendix Tables S1 and S2). Vital information on aquifer lithology, tube well design, installation fixtures, and cost estimates were collected from the reports file of the RDA (RDA, 2010). Technical and socio-economic information, operation, and maintenance costs and utilization of DTWs were obtained by interviewing DTW owners and beneficiaries through a Focus Group Discussion (FGD) survey for three years. Field visits were made to interview the owners of the DTWs. The owner's perception of the socio-economic utilization of DTWs, operation and maintenance, tube-well use advantages, and water quality were obtained through a pre-structured questionnaire survey. All the data obtained through the questionnaire survey were stored and analyzed to determine the relationship patterns, specifications of DTW fixtures, pump, and prime movers, and information regarding the O&M water utilization quality aspects. The details of the RDA DTW design compared with those of the traditional DTW are depicted in Figure 2. A simple cost analysis was conducted to determine the effectiveness of low-price DTWs compared with traditional DTWs. First, the installation procedures of the RDA-developed DTW are explained. Finally, the findings of the survey and analysis are presented and discussed.

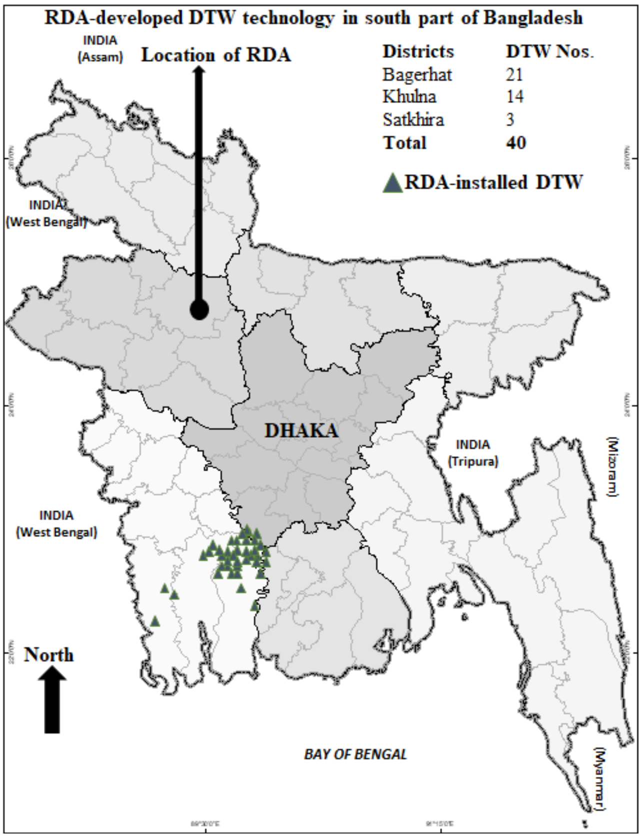

Figure 1 Location map of RDA-developed DTW technology installed in southern Bangladesh

2.1 Detailed Procedure of Borehole Positioning

2.1.1 Test Tube Well and Confirmation of Borehole

Before installing the production DTW, test boring was performed to determine the actual lithology of the aquifers at all the study sites. It is necessary to obtain appropriate lithological information and aquifer quality of the selected sites. A 100-mm-diameter pipe was installed as test boring to verify whether it could release the desired quantity of discharge for testing. During the test boring, soil samples were collected from each 3 m depth until a suitable groundwater formation was obtained. The production well was designed based on the lithological information and sieve analysis results of the collected soil samples. Finally, the depth, diameter, and slot opening of the strainer were confirmed. It should be noted that the test boring and sieve analysis costs were included in the total cost of the developed RDA-DTW.

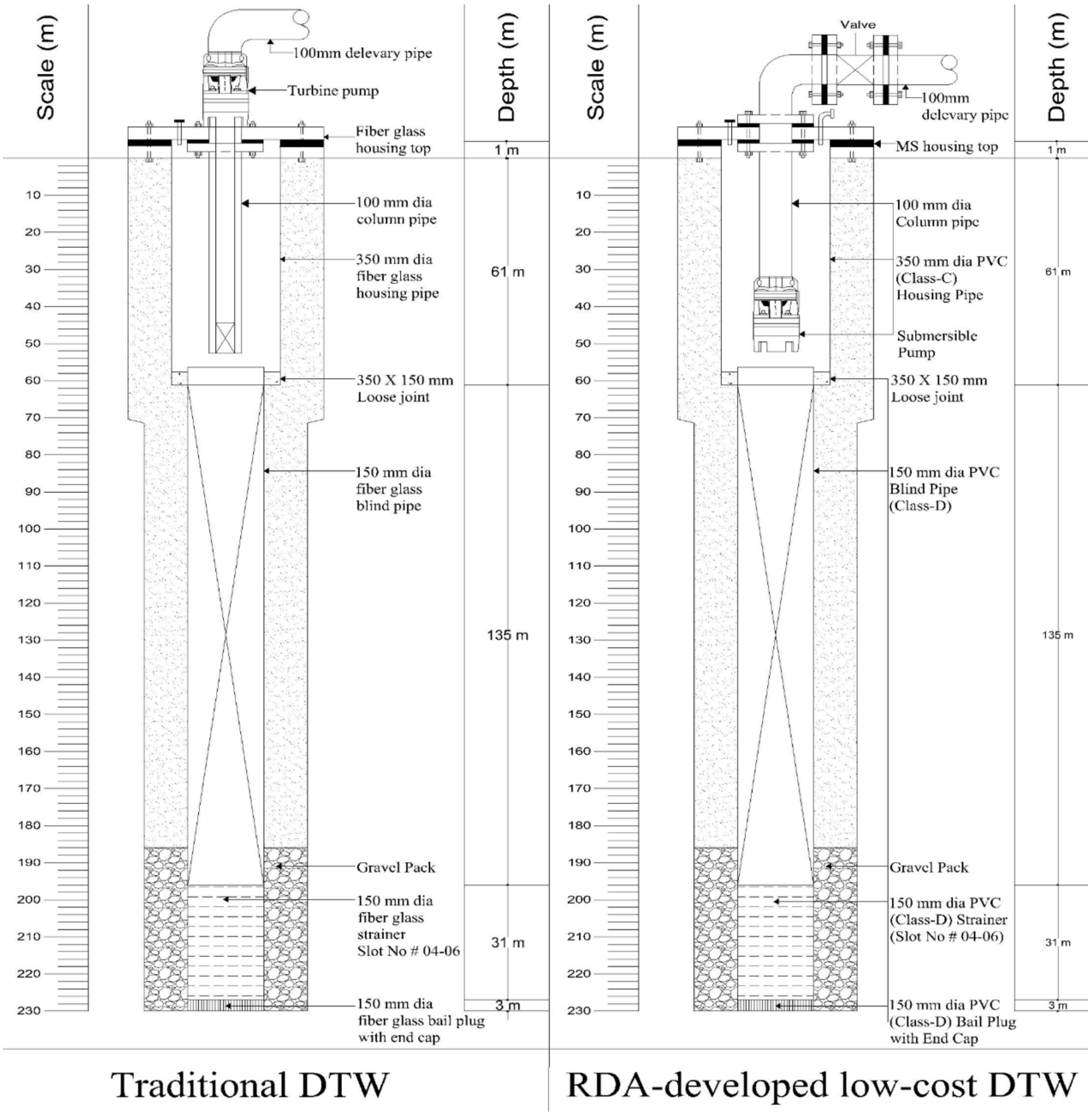

Figure 2 Well design features of traditional DTW and RDA-developed DTW in Bangladesh

2.1.2 Drilling of Production Borehole

The hydraulic–rotary system was adopted to drill the DTWs using manual reverse circulation methods, which drills rapidly and economically. This technique was applied for test boring and drilling of the main production well. The high-cost drilling rig is not used in this installation procedure, whereas it is frequently used to install the traditional DTW. A 650-mm-diameter borehole was excavated up to a desired depth to install the housing pipe, and approximately 450/500-mm-diameter drilling was performed to install the blind pipe, strainer, and sand trap. Soil samples were collected during the main boring period from the specified depths to confirm the lithology of the production well. Moreover, the materials used for the RDA-DTWs, such as sand and appropriate-sized gravel, are locally available. These materials were obtained from the study area to save labour and transportation costs.

2.1.3 Well Design

The screen design and well size selection were entirely based on test drilling data. The well-screen design parameters included the length and diameter of the screen, its location, entrance velocity, and percentage of opening area, that is, the slot size. The optimal length of the well was determined based on the maximum aquifer depths estimated from the lithological data. The opening area and slot size of the screen were adopted based on the gradation curve and material size obtained from the sieve analysis in the laboratory.

2.1.4 Sieve Analysis

Sieve analysis and grain-size distribution curves of the formation material samples collected during test-hole construction are essential to identifying aquifer materials and designing the intake section of a well. Based on the grain size distribution curve, the slot size can be selected by considering the maximum percentages of the opening area.

2.1.5 Screen Selection

The screen length and the diameter and slot size of the strainer were selected based on the aquifer thickness and aquifer material gradation, respectively. The diameter of the screen was set to 20 cm based on the water demand of the concerned authority such that the entrance velocities near the well screen did not exceed 3–6 cm/s to prevent clogging and corrosion and to minimize frictional losses. The well screen of the RDA-DTW technology was packed with sand and gravel to become active and increase the service life of the well. However, the developers of the traditional DTW often failed to set appropriate screen lengths and slot sizes owing to insufficient scientific knowledge.

2.1.6 Well Development

Well Development is the process by which flow reversal is generated through screen opening to wash out the fineness and rearrange the natural formation particles and graded filter.

Table 1 Comparison between RDA-developed low-cost DTW system and traditional DTW

Components/ Materials	RDA-DTW	Traditional DTW
i. Drilling method	Manual water jetting and reverse circulation, which is simple and cost-effective	Traditional rig methods (Hydraulic rotary and reverse rotary)
ii. Housing pipe	PVC, RCC, or 4 mm MS sheet	MS sheet, fiberglass
iii. Strainer	PVC, bamboo net	Stainless steel, fiberglass
iv. Prime mover size	Demand-based (0.75–30 hp)	Not demand based (20–30 hp)
v. Pumping plant	Submersible/mono-sub-pump	Deep well turbine pump
vi. Pump house/ shed	Not required	Required
vii. Pump efficiency	Higher	Lower
viii. Power transmission loss	Lower	Higher
ix. Prime mover breakdown and repair	Rewinding and repair are easy to perform	Repair is complicated
x. Damage caused by natural hazards and floods	No damage and can be operated during floods	Possibility of damage and cannot be operated during floods
xi. Threat of stealing	Impossible	Possible
xii. Construction cost	Cheap (Tk. 0.06–0.8 million)	Expensive (approximately Tk. 1.00–1.50 million)

Well Development is essential for maximising the well yield and optimising the filter capacity of the gravel. In addition, it increases the porosity and permeability of aquifer materials near the well. Several methods are used for well Development, such as over-pumping, surging, using compressed air, high-velocity hydraulic jetting, hydraulic fracturing, and using explosives. Generally, over-pumping and air compression methods are adopted for well Development. In RDA-developed DTW technology, we applied the over-pumping method because of its lower cost than the other methods.

2.1.7 Water Test Results

After the well Development, pump water samples were subjected to water quality tests in an RDA laboratory. In some cases, the samples were tested at the Bangladesh University of Engineering and Technology (BUET) for further analysis. The samples were collected and tested according to RDA water testing standards.

2.1.8 Pump Selection

Proper pump selection is vital to minimize electricity bills. Depending on the results of the well performance tests, the RDA authority selects the submersible pump set based on the expected DTW yield and the required head that matches the specified pump characteristic curve supplied by the pump manufacturing company. The pump is immersed at a specified depth for continuous water flow. After lowering the pump, the well is covered with appropriate sealing materials. Finally, it is ensured that the production tube well is ready by confirming the parameters and processes, for example, the yield, diameter, depth, casing and screen, gravel formation, appropriate well development, water quality analysis, and pumping test.

3. RESULTS AND DISCUSSIONS

3.1 Performance of Low-Cost Borehole

A low-cost DTW model developed by the RDA, Bogura, Bangladesh, performed better than the traditional DTWs in terms of well design and construction, water quality, water system management, and total cost. The total cost of abstracting water using traditional DTWs was high because of the selection of oversized pumps and prime movers (engines/motors) without considering the actual water demand, which increased the power consumption and total cost (Figure 2 and Table 1). A traditional DTW connected to 22 kW turbines requires increased annual power consumption, increasing the electric bill for the owners. Typically, DTWs remain useless during the irrigation off-season. If the power line is not disconnected, the rural electrical supply company provides a minimum bill cost for line renting. The operational cost of such a traditional DTW is burdensome to users unless the command area is large. Because of the high capital investment in well construction and operation and the high maintenance costs, using DTWs only for seasonal irrigation is not economically viable for rural farmers (Chowdhury, 2012). In contrast, RDA has developed the user water-demand-based economic DTW technology with a 20–200 m^3/hr capacity. A few design parameters for the production well, pump specifications, and water quality of the RDA-DTW are listed in Tables 1 and 2. For the RDA-designed DTW, the borehole size varies from 82.3–275 m, depending on the available aquifer at the study site, and the housing pipe diameter is fixed at 0.20–0.25 m (Table 2). The blind piper diameter depends on the aquifer thickness: a larger aquifer is followed by a smaller blind pipe, which may also vary with the piper diameter. The length and diameter of the blind piper in the selected six study areas were 98–214 m and 0.07–0.15 m, respectively, and the strainer length was 6–25 (Table 2). RDA-DTW ensures water supply from the main aquifer by a lower-price DTW, which can play an influential role in sustainable groundwater utilization in Bangladesh.

3.2 Comparative Analysis of RDA-Developed and Traditional DTWs

Comparisons between the RDA-developed and traditional DTW technologies for groundwater drilling are listed in Table 1. RDA-DTW technologies based on manual water jetting and reverse circulation drilling techniques decrease the boring cost and make the drilling process more accessible and reliable than the traditional method (Table 1). From inception, the RDA adopted reinforced cement concrete and polyvinyl chloride (PVC), whereas the traditional DTW uses MS sheets made of stainless steel/fibre glass. The RDA method has successfully decreased the costs (Figure 2). RDA-DTWs use PVC pipes and bamboo-made strainers/filters, which are locally available and significantly decrease borehole installation costs. The variability of the prime mover size based on the farm holdings reduces the power load, whereas it is fixed to 30 hp in the traditional type. Approximately 95% of STWs in Bangladesh are operated by diesel engines with 8–20 hp capacity, which increases the power consumption, whereas RDA-DTWs use submergible motors with relatively lower electrical power. The submersible option is the major inspiration for farmers to adopt the technology, as it is inexpensive for pump house construction and ensures protection against theft of the pump and motor. In addition to this overload protection, dry protection ensures the safeguarding of the motor. The RDA-developed borehole decreases the installation cost by Tk. 0.06–0.8 million compared to conventional technology (Tk. 1.0–1.5 million). In contrast, Matin et al. (2000) reported that the lower cost of the RDA - developed technology is owning to its low cost, local materials, and simple drilling technique used. They also reported that 64% of owners/users advocated for this technology for its fully automatic system, low power consumption, and overall benefits.

Table 2 Design parameters of RDA-developed production wells (boreholes) in southern regions of Bangladesh.

DTWs	Well	Aquifer	Housing		Blind area		Strainer	
	Depth	Thickness	Length	Diameter	Length	Diameter	Length	Diameter
				Units in metres (m)				
1	170.7	24.4	64.02	0.25	109.8	0.10	24.4	0.10
2	146.3	6.1	45.7	0.20	98.8	0.07	6.1	0.07
3	82.3	18.3	24.4	0.20	35.7	0.10	18.3	0.10
4	82.3	12.2	45.7	0.25	22.0	0.15	12.2	0.01
5	268.3	24.4	45.8	0.20	192.1	0.07	24.4	0.07
6	274.4	18.3	45.8	0.20	213.4	0.07	18.3	0.07

Grade C polyvinyl chloride (*PVC*) was used as the pipe material for DWT construction.

Table 3 Specification of pump and water quality of RDA-developed DTW used in the Southern regions of Bangladesh.

DTWs	Year	Discharge	Head	Power	Operating	Water quality		
		(m^3/h)	(m)	(kW)	Hours	EC (μs/cm)	Iron (mg/l)	As (mg/l)
1	2011	28	45	3.2	4.5	899	1.00	0
2	2011	20	40	3.0	4.5	654	0.60	0
3	2011	22	35	2.5	4.5	1233	4.00	0.03
4	2011	25	40	3.0	4.5	1542	5.00	0.01
5	2011	20	40	3.0	4.5	1498	1.00	0
6	2011	35	38	3.5	4.5	1407	0.20	0

A submersible pump was used as prime mover in all the locations. EC: Electrical conductivity.

The cost of an RDA-DTW is 30%–40% lower than that of the traditional DTW with a capacity of 16–56 l/s, and the total cost reduction ranges from Tk. 0.06 to 0.5 million. It should be emphasized that the quality of socio-economic life in the project locations have improved through the multi-purpose use of low-cost DTWs with safe-drinking water supply facilities in rural Bangladesh. The irrigation coverage under the investigated DTW schemes is satisfactory. In addition to irrigation, multiple uses of these water resources are ensured. The DTW water supplied to households for drinking and domestic uses has superior quality (Table 3). The chemical concentrations of the DTW water are within the permissible limits prescribed by WHO and Bangladesh standards. The iron concentration was 0.3–1.00 mg/litre, and the arsenic concentration was below 50 ppb. The survey of the farmers in the study area reveals that 80% of DTW owners and 94% of beneficiaries are highly satisfied and express positive responses regarding the utilities (water quality, electricity bill, and water supply system) of the RDA-DTW technology. Consequently, RDA-DTWs have become widely used in the study site and all over Bangladesh.

3.3 Discharge and Pumping Performance of Borehole

Figure 3A shows the average design capacity of a DTW (146.31 m^3/h) and pumping capacity (103.81 m^3/h). All the pumps are 80% efficient, and the actual discharge of the DTW is 82.38 m^3/hr. This shows that the design capacity of the DTW is higher than the actual discharge of the DTW. Therefore, there is no chance of drying the DTW during the boro-season when the groundwater table is significantly low. The aquifers in the selected locations were observed to be unconfined and semi-confined. The drilling depths of the selected RDA-DTWs range from 30 to 230 m. The borehole can discharge sufficient quantities of water throughout the year for different purposes. The irrigation water quality was good, except in a few cases (Khan and Hori, 2014).

The average static water level (6.56 m) indicates that the water lies within the suction lift range of the force-mode tube well. However, the groundwater table drops below the suction lift limit of the production well in a specific DTW in the later part of the dry season (March–April), particularly in locations where unconfined aquifers exist (Figure 3B).

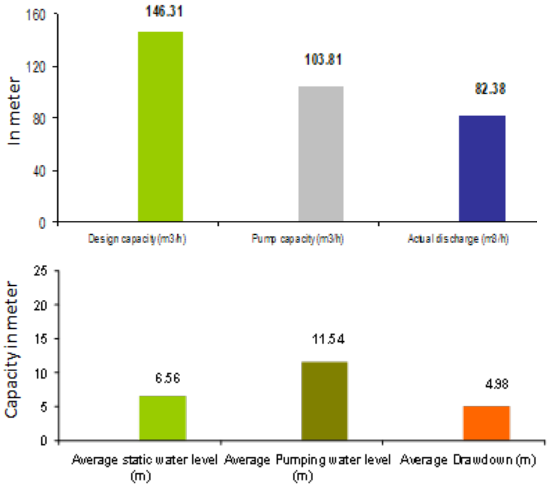

Figure 3 Average discharge, pump capacity, and drawdown of RDA-developed boreholes installed in selected areas in Bangladesh.

The time recovery test results indicate that groundwater depletion during the dry season can be wholly replenished in the monsoon season. In the study area, the DTWs had different water discharging capacities (32–118 m^3/hr). The average pumping level of the DTW is 11.54 m, and the drawdown is 4.98 m, indicating that the well has an efficient (well-constructed and developed) yield. Therefore, the high discharge and pumping capacity of the RDA-DTW resulted in its higher performance than the existing traditional DTW.

Table 4 Community opinions and performance survey analysis based on social survey of RDA-developed cost-effective borehole in selected study area.

Question	Technical, operational, and management issues	Comments	Opinions (%)
a	DTW can be run throughout the year, and multi-purpose use is possible (irrigation, drinking, gardening, aquaculture, and dairy rearing)	Yes	70
		No	30
b	Borehole and overhead tank pipeline technically sound	Yes	83
		No	17
c	Length of the water supply pipeline given by the project fund sufficient	Yes	48
		No	52
d	Tap pressure and required water supply	Satisfied	71
		Not satisfied	29
e	Taste and physical quality of water	Excellent	29
		Good	71
f	Easily repairable after the breakdown of the system	Easy	79
		Not easy	21
g	The happiness of the community about the managed supply of water	Good	85
		Not good	15
h	Community/owner capable of operation and maintenance of the project	Yes	86
		No	14
i	Attitude for changing HTW water to tap water	Fast	24
		Medium	48
		Slow	28
j	Tariff for water consumption	Affordable	82
k	Repayment of the full cost of the project by the owner/community	Not affordable	18
		Possible	36
		Not possible	64
l	Subsidy required for pipeline connection to the house and capital investment of the project	Required	100
		Not required	0
m	Opinions regarding the sustainability of the system	Possible in a long run	85
		Not possible in a long run	15

3.4 Community Opinions of RDA-Developed Deep Tube Wells

Questions were asked during the field survey to know the owners' perceptions regarding the operation and maintenance of DTWs. The findings of the community survey on using the rural pipe water supply in the study area are listed in Table 4. There were 30 respondents from each sub-project in the study area, and the total number of respondents was 840. The degree of satisfaction related to the system sustainability was higher for the RDA-developed DTW than the traditional DTW. The water users were asked about the performance of the RDA-developed low-cost DTW in terms of its multi-dimensional uses, and 70% of the respondents stated that they are now positively using RDA-DTW technology (Question a, Table 4). For Question (f), 79% of the respondents affirmed that the components of the RDA-DTW system could be easily repaired when they break down (Table 4). However, 86% of the community stakeholders can operate and maintain the project systems in terms of cost and durability (Question h, Table 4). This is because the installed water supply system comprises simple components: DTW with a submerged pump, an overhead storage tank, and a buried pipeline. The purification component is installed only when the raw water quality is below the acceptable limit. Therefore, it is vital that the owners can maintain the water supply system by themselves to ensure an extended system operation. The effectiveness of the RDA technology for multi-purpose functions of the DTW was measured by sampling the users' opinions regarding the operation and maintenance, advantages of different aspects, and water quality. The high-cost involvement is the main constraint in sinking a DTW by an owner/farmer instead of using RDA-developed technology. Although farmers' communities served by DTWs have benefited, communities without access to DTWs have reported an increase in challenging conditions. This has significant developmental implications in Bangladesh (Banerjee and de Silva, 2020).

Self-maintenance and easy reparability of water supply systems, particularly in rural areas, are critical issues, leading to high marks in the question on system sustainability (Questions m and j, Table 4). The technical and socio-economic aspects are essential for making water supply systems sustainable. The water supply model proposed in this study has two economic aspects: the repayment of construction costs by the community/owners and the water use charges. The owners receive financial payments from the users based on the water use and make payments to repay the initial costs. Regarding the water charge, more than 80% of the users believe that the water tariff is affordable, suggesting that the system is well designed regarding consumer price (Question j, Table 4). In contrast, only 35% of the owners think they can repay the total project costs (Question k, Table 4). The aim of introducing the RDA-DTW model is to economically pump water and utilize the water for multi-purpose uses so that the owners and users benefit. It is necessary to utilize the water for productive uses such as livestock, fishery, and poultry, which will increase the income of the communities.

4. CONCLUSIONS AND RECOMMENDATIONS

A modified borehole technology by RDA is a complete package of deep tube well designs using local resources for a group of beneficiaries, appropriate water distribution, and year-round operation for irrigation and domestic purposes. This system minimizes the cost of RDA-DTWs over the traditional DTW. As the technology is demand-based, that is, the system capacity depends on the farm holdings, the technology is highly adopted by local entrepreneurs. RDA-developed DTW technology is a flexible design, and demand-based water can be abstracted from deep aquifers using this DTW at low energy (hp) and financial costs. Hence, the RDA-DTW model can be used as an efficient groundwater abstraction technology in the rural areas of Bangladesh. However, the following recommendations are made for the optimal use of groundwater resources in Bangladesh.

1) Regular monitoring of the groundwater level and detailed design of the hydrological and water quality parameters should be

ensured to achieve detailed design and construction of RDA-DTWs under different aquifer conditions for improved groundwater utilization in the future.

2) The combined approach of the RDA-DTW model may attract NGOs/entrepreneurs to provide credits and financial support to water users to apply this technology throughout the country.

5. ACKNOWLEDGEMENTS

The authors are grateful to the Rural Development Academy (RDA), Bogura, Bangladesh, for providing relevant DTW data and interviewing rural dwellers in Bangladesh.

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Appendix Table S1 Specification of RDA DTW Model in different pump and Water Treatment plants used in the SW Region

DTW No.	Location	District	Year of installation	Pump type	Discharge (m^3/h)	Head (m)	Power requirement (kW)	Operating hrs/day	Water quantity			Type of treatment plant	Owner comments
									Conductivity (µs/cm)	Iron (mg/l)	As (mg/l)		
1	Nalta, Kaligonj	Satkhira	2011	Submerssible	20	40	3	4.5	899	1.00	Nill		Good
2	Compaful,Kaligonj	Satkhira	2011	Submerssible	20	40	3	4.5	654	0.60	Nill		Good
3	Ratanpur, Kaligoni	Satkhira	2011	Submerssible	20	40	3	4.5	1492	0.20	Nill		Good
4	Horinagar, Shamnagar	Satkhira	2011	Submerssible	20	40	3	4.5	3.02	1.00	Nill		Good
5	Nawbeki, Shamnagar	Satkhira	2011	Submerssible	20	40	3	4.5	2.7	1.00	Nill		Good
6	Shodkona, AShashuni	Satkhira	2011	Submerssible	20	40	3	4.5	699	3.00	Nill		Good
7	Raghunathpur, Domuria	Khulna	2011	Submerssible	20	40	3	4.5	699	0.04	Nill		Good
8	Paikgacha, Pourshova	Khulna	2011	Submerssible	20	40	3	4.5	520	6.00	Nill		Good
9	TS Bahirdia, Rupsa	Khulna	2011	Submerssible	20	40	3	4.5	1233	4.00	0.025		Good
10	Sreefoltola, Rupsa	Khulna	2011	Submerssible	20	40	3	4.5	1230	0.20	Nill		Good
11	Shovna, Domuria	Khulna	2011	Submerssible	20	40	3	4.5	1230	0.4	Nill		Good
12	Saciadah, Terakhada	Khulna	2011	Submerssible	20	40	3	4.5	899	0.20	Nill		Good
13	Rudaghara, Domuria	Khulna	2011	Submerssible	20	40	3	4.5	534	0.04	Nill		Good
14	Madhupur, Terakhada	Khulna	2011	Submerssible	20	40	3	4.5	1542	5.00	0.01		Good
15	Gongarampur, Batiaghata	Khulna	2011	Submerssible	20	40	3	4.5	899	0.20	Nill		Good
16	Baliadanga, Batiaghata	Khulna	2011	Submerssible	20	40	3	4.5	1534	0.40	Nill		Good
17	Naihati, Rupsa	Khulna	2011	Submerssible	20	40	3	4.5	899	1.00	Nill		Good
18	Jaima, Batiaghata	Khulna	2011	Submerssible	20	40	3	4.5	899	0.20	Nill		Good
19	Chagladah, Terakhada	Khulna	2011	Submerssible	20	40	3	4.5	699	0.20	Nill		Good
20	Icegati, Rupsa	Khulna	2011	Submerssible	20	40	3	4.5	899	0.20	Nill		Good
21	Ghatvog, Rupsa	Khulna	2011	Submerssible	20	40	3	4.5	1700	0.20	Nill		Good
22	Naldha Mouvag, Fakirhat	Bagerhat	2011	Submerssible	20	40	3	4.5	1700	0.20	Nill		Good
23	Lokhpur, Fakirhat	Bagerhat	2011	Submerssible	20	40	3	4.5	1265	0.20	Nill		Good
24	Bisnopur, Bagerhat Sadar	Bagerhat	2011	Submerssible	20	40	3	4.5	1498	0.40	Nill		Good
25	Chitalmari	Bagerhat	2011	Submerssible	20	40	3	4.5	654	8.00	0.01		Good
26	Gangni, Mollahat	Bagerhat	2011	Submerssible	20	40	3	4.5	899	6.00	0.01		Good
27	Gotapara, Bagerhat Sadar	Bagerhat	2011	Submerssible	20	40	3	4.5	1498	0.40	Nill		Good
28	Sreefoltola, Rampal	Bagerhat	2011	Submerssible	20	40	3	4.5	1700	0.20	Nill		Good
29	Kodalia, Mollahat	Bagerhat	2011	Submerssible	20	40	3	4.5	723	2.00	0.01		Good
30	Shuvodia, Fakirhat	Bagerhat	2011	Submerssible	20	40	3	4.5	1498	1.00	Nill		Good
31	Mulghar, Mollahat	Bagerhat	2011	Submerssible	20	40	3	4.5	1700	6.00	0.025		Good
32	Kulia, Mollahat	Bagerhat	2011	Submerssible	20	40	3	4.5	1700	6.00	0.05		Good

33	Bahirdia Mansha, Fakirhat	Bagerhat	2011	Submerssible	20	40	3	4.5	699	0.20	Nill		Good
34	Girishnagar, Udai, Mollahat	Bagerhat	2011	Submerssible	20	40	3	4.5	699	5.00	0.01		Good
35	Surigati, Gaula, Mollahat	Bagerhat	2011	Submerssible	20	40	3	4.5	1700	5.00	0.075		Good
36	Fakirhat Sadar, Fakirhat	Bagerhat	2011	Submerssible	20	40	3	4.5	1407	0.20	Nill		Good
37	Chunkhola, Mollahat	Bagerhat	2011	Submerssible	20	40	3	4.5	1265	0.20	Nill		Good
38	Betaga, Fakirhat	Bagerhat	2011	Submerssible	20	40	3	4.5	899	0.02	Nill		Good
39	Pilgang, Fakirhat	Bagerhat	2011	Submerssible	20	40	3	4.5	1223	0.20	Nill		Good
40	Chagladah, Terakhada	Bagerhat	2011	Submerssible	20	40	3	4.5	699	0.20	Nill		Good

Appendix Table S2 Information about Fixture of Production Wells in the SW Region

DTW No.	Location	District	Depth of well (m)	Depth of aquifer thickness(m)	Housing Pipe			Blind Pipe			Strainer		
					Length(m)	Dia (mm)	Material	Length(m)	Dia (mm)	Material	Length(m)	Dia (mm)	Material
1	Nalta, Kaligonj	Satkhira	170.73	24.39	64.02	250	PVC	109.76	100	PVC	24.4	100	PVC
2	Compaful, Kaligonj	Satkhira	146.34	6.10	45.73	200	PVC	98.78	75	PVC	6.1	75	PVC
3	Ratanpur, Kaligoni	Satkhira	28.96	9.15	16.16	150	PVC				9.1	250	PVC
4	Horinagar, Shamnagar	Satkhira	73.17	21.34	49.70	250	PVC				21.3	250	PVC
5	Nawbeki, Shamnagar	Satkhira	207.32	21.34	42.68	250	PVC	140.24	100	PVC	21.3	100	PVC
6	Shodkona, AShashuni	Satkhira	24.39	6.10	16.16	350	PVC				6.1	350	PVC
7	Raghunathpur, Domuria	Khulna	201.22	24.39	64.02	200	PVC	109.76	75	PVC	24.4	75	PVC
8	Paikgacha, Pourshova	Khulna	30.49	6.10	21.34	350	PVC				6.1	350	PVC
9	TS Bahirdia, Rupsa	Khulna	82.32	18.29	24.39	200	PVC	35.67	100	PVC	18.3	100	PVC
10	Sreefoltola, Rupsa	Khulna	70.12	12.20	36.59	250	PVC	21.34	150	PVC	12.2	150	PVC
11	Shovna, Rupsa	Khulna	274.39	12.20	45.73	200	PVC	211.89	75	PVC	12.2	75	PVC
12	Saciadah,Terakhada	Khulna	243.90	24.39	47.26	200	PVC	172.26	75	PVC	24.4	75	PVC

13	Rudaghara, Domuria	Khulna	201.22	18.29	45.73	200	PVC	140.24	75	PVC	18.3	75	PVC
14	Madhupur,Terakhada	Khulna	82.32	12.20	45.73	250	PVC	21.95	150	PVC	12.2	150	PVC
15	Gongarampur, Batiaghata	Khulna	201.22	15.24	45.73	200	PVC	140.24	75	PVC	15.2	75	PVC
16	Baliadanga, Batiaghata	Khulna	280.49	24.39	46.65	200	PVC	209.45	75	PVC	24.4	75	PVC
17	Naihati, Rupsa	Khulna	268.29	18.29	46.65	200	PVC	206.71	75	PVC	18.3	75	PVC
18	Jaima, Batiaghata	Khulna	286.59	18.29	48.78	200	PVC	222.56	75	PVC	18.3	75	PVC
19	Chagladah,Terakhada	Khulna	268.29	21.34	44.51	200	PVC	202.44	75	PVC	21.3	75	PVC
20	Icegati, Rupsa	Khulna	256.10	24.39	45.73	200	PVC	198.17	75	PVC	24.4	75	PVC
21	Ghatvog, Rupsa	Khulna	82.32	12.20	30.49	250	PVC	36.59	150	PVC	12.2	150	PVC
22	Naldha Mouvag, Fakirhat	Bagerhat	42.68	9.15	30.49	150	PVC				9.1	250	PVC
23	Lokhpur, Fakirhat	Bagerhat	33.54	12.20	18.29	150	PVC	3.05	250	PVC	12.2	250	PVC
24	Bisnopur, Bagerhat Sadar	Bagerhat	268.29	18.29	44.51	200	PVC	199.39	75	PVC	18.3	75	PVC
25	Chitalmari	Bagerhat	27.44	9.15	15.24	150	PVC	0.00			9.1	250	PVC
26	Gangni, Mollahat	Bagerhat	28.96	9.15	15.24	150	PVC	0.00			9.1	250	PVC
27	Gotapara, Bagerhat Sadar	Bagerhat	243.90	15.24	45.73	200	PVC	201.22	75	PVC	15.2	75	PVC
28	Sreefoltola, Rampal	Bagerhat	286.59	18.29	45.73	200	PVC	213.41	75	PVC	18.3	75	PVC
29	Kodalia, Mollahat	Bagerhat	30.49	9.15	17.38	150	PVC	0.00			9.1	250	PVC
30	Shuvodia, Fakirhat	Bagerhat	268.29	24.39	45.73	200	PVC	192.07	75	PVC	24.4	75	PVC
31	Mulghar, Mollahat	Bagerhat	21.34	9.15	8.23	150	PVC				9.1	250	PVC
32	Kulia, Mollahat	Bagerhat	36.59	9.15	23.48	150	PVC				9.1	250	PVC

33	Bahirdia Mansha, Fakirhat	Bagerhat	28.96	9.15	15.24	150	PVC				9.1	250	PVC
34	Girishnagar, Udaipur, Mollahat	Bagerhat	27.44	9.15	14.33	150	PVC				9.1	250	PVC
35	Surigati, Gaula, Mollahat	Bagerhat	33.54	9.15	21.34	150	PVC				9.1	250	PVC
36	Fakirhat Sadar, Fakirhat	Bagerhat	274.39	18.29	45.73	200	PVC	213.41	75	PVC	18.3	75	PVC
37	Chunkhola, Mollahat	Bagerhat	195.12	24.39	46.95	200	PVC	128.05	75	PVC	24.4	75	PVC
38	Betaga, Fakirhat	Bagerhat	262.20	15.24	45.73	200	PVC	201.22	75	PVC	15.2	75	PVC
39	Pilgang, Fakirhat	Bagerhat	268.29	18.29	45.73	200	PVC	204.27	75	PVC	18.3	75	PVC
40	Chagladah,Terakhada	Bagerhat	28.96	9.15	15.24	150	PVC				9.1	250	PVC