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Headquartered in Mexico, the International Maize and Wheat Improvement Center (known by its Spanish acronym, CIMMYT) is a not-for-profit agriculture research and training organization. The center works to reduce poverty and hunger by sustainably increasing the productivity of maize and wheat in the developing world. CIMMYT maintains the world's largest maize and wheat seed bank and is best known for initiating the Green Revolution, which saved millions of lives across Asia and for which CIMMYT's Dr. Norman Borlaug was awarded the Nobel Peace Prize. CIMMYT is a member of the CGIAR Consortium and receives support from national governments, foundations, development banks, and other public and private agencies.

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Executive Summary

With conventional centrifugal pumps (CEN), less than 50% of southern Bangladesh's farmers invest in dry season irrigation, partly due to high and continually increasing diesel energy costs. Diesel pump efficiencies in Bangladesh are only 25% (compared to 35% for electric pumps) mainly due to techno-mechanical problems. New policies championed by the Government of Bangladesh prioritize sustainable crop intensification in Bangladesh's delta. A key example is the Master Plan for Agricultural Development in the Southern Region of Bangladesh, which focuses strongly on the development of surface water irrigation to spur increased crop output within this impoverished region. However, this objective is unlikely to be achieved without fundamental changes in the energetics and cost of irrigation. Where surface water is available in the complex deltaic environment of Southern Bangladesh, axial flow pumps (AFPs) may comprise part of the solution to this problem. Through a partnership between the Bangladesh Agricultural Research Institute (BARI) and the International Maize and Wheat Improvement Center (CIMMYT) in the Cereal Systems Initiative for South Asia (CSISA) project, we conducted two experiments to help test this hypothesis. In our first experiment, we assessed pulley arrangements to arrive at optimal configurations for water discharge at 1-, 2- and 3-m heads for prototype AFPs manufactured in Bangladesh. The second experiment compared the hydraulic, energetic, and economic performance of AFPs and CENs. CENs produced less discharge than AFPs at all heads. Both CENs and AFPs showed an inverse relationship between discharge and increasing head, although AFPs showed considerably less flow as head increased. Importantly, as a measure of energy efficiency, discharge per unit of fuel was highest for AFPs (+51% and +21% at 1- and 2-m lifts), though this declined with rising head until convergence with CEN at 2.8-m. High AFP discharge reduced irrigation time requirements when simulated for Boro rice, wheat, and maize. Compared to CEN, AFPs can save between 5,444–2,955 BDT (70–38 USD) ha^{-1} $season^{-1}$ for Boro rice at 1- and 3-m heads, respectively, and 1,167–622 BDT (15–8 USD), and 2,022–1,089 BDT(26–14 USD) ha^{-1} $season^{-1}$ for wheat and maize. Fuel efficiency reductions above 2.8-m highlighted the importance of technology targeting to ensure AFP deployment in environments where the greatest efficiency gains are achievable.

Key Messages

1. Prototype axial flow pumps made in Bangladesh save fuel and deliver more water than centrifugal pumps for low-lift irrigation up to 2.8 m in height.

2. Water discharge with prototype axial flow pumps is higher than centrifugal pumps at 1-, 2- and 3-m head levels.

3. Higher discharge of water with the prototype axial flow pumps reduces irrigation time requirements for wheat, maize, and Boro rice.

4. Considerable fuel savings can be obtained where prototype axial flow pumps are used in place of centrifugal pumps. These savings can help to offset the higher current capital costs necessary to purchase an axial flow pump.

5. Axial flow pumps offer significant opportunities to improve the efficiency of low-lift surface water irrigation in Bangladesh. Further research is needed to optimize technical efficiency and consumer appeal for these pumps, but for the moment our results clearly demonstrate improved water discharge and energy efficiencies for low-lifts up to 2.8 m, which makes the pump an appealing technology for use in southern Bangladesh where Government initiatives are placing emphasis on the expansion of surface water irrigation.

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1. Introduction

Beginning in the late 1990s, the expansion of deep and shallow tube wells across northern Bangladesh enabled farmers to widely adopt dry season *Boro* rice production, bringing the country to near riceself-sufficiency (Rahman and Parvin, 2009). However, this 'irrigation boom' (*sensu* Shah et al., 2003) was and continues to be dependent on large energy reserves – namely diesel and electricity – which are used to fuel vertical water extraction from groundwater to the surface for crop use. Use of fuel and electricity for ground as opposed to surface water pumping contributes proportionally more to greenhouse gas emissions and thus climate change (*e.g.* Shah, 2009), and has resulted in gradual yet consistent decline in groundwater levels. Though dominated by considerable change from season to season, Shamsudduha et al. (2009) showed that the groundwater is declining by between 0.1-0.5 m year^{-1} in areas of intensive *Boro* cultivation in northern Bangladesh, mainly near Rajshahi and to a lesser extent near Jessore and Chauadanga Districts. When combined the 5-fold growth in diesel costs since the late 1990s (Figure 1), this has increased the price farmers must pay to lift water to their fields (Chowdhury, 2010; Ministry of Power, 2013). These issues have resulted in concern regarding the physical and financial sustainability of Bangladesh's groundwater irrigation economy, thereby focusing attention on the need for more resource use efficient production strategies. In response, the Government of Bangladesh (GoB) recently implemented the "Master Plan for Development in the Southern Region", which encourages foreign donor investments of over $7 billion to increase cropping intensity on currently poorly productive land, and to expand the use of surface water irrigation (SWI) in southern Bangladesh (see MOA and FAO, 2012).

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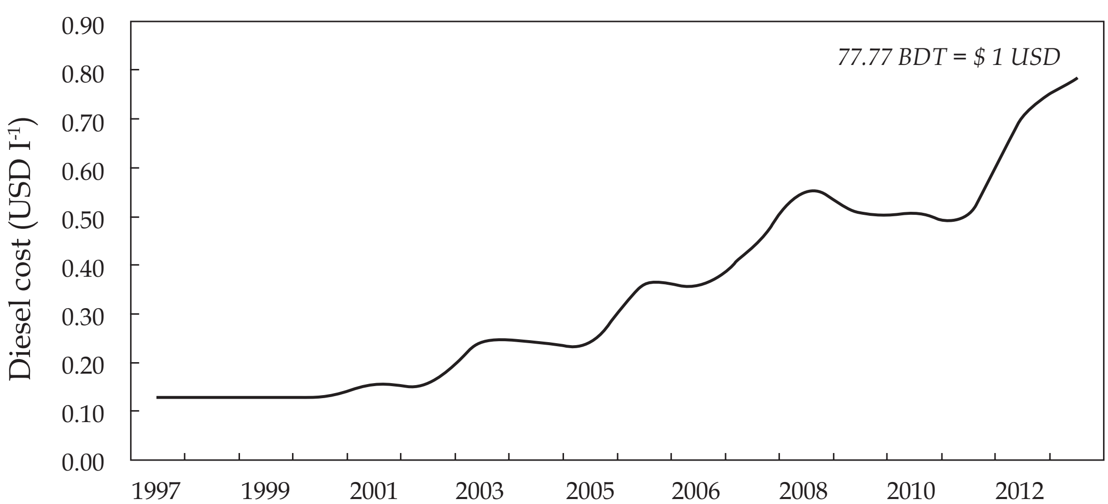

FIGURE 1.

Evolution of diesel costs in USD per liter of fuel from 1993-2013 (Ministry of Power, 2013).

The logic for the Master Plan is clear. Surface water is perceived as being abundant in parts of the south where river and canal networks have perennial flow, and where salinity levels do not cross crop-damaging thresholds. Conversely, saline shallow aquifers are common and prohibit the easy installation of shallow tube wells. Compared to the investment required to sink deep tube wells and vertically pump water, low-lift surface water pumps are typically less energy intensive (Shah, 2009). SWI therefore offers a means by which double cropping could be encouraged on currently fallow or poorly productive dry season land, which ranges in size from between 136,000–800,000 ha in southern Bangladesh, depending on the year studied and different estimation methods (*cf.* MoA and FAO, 2012; Rawson, 2011). An estimated 50% of southern Bangladesh's farmers currently grow only one rain fed rice crop per year; GoB policy therefore focuses on increasing the cropping intensity of these marginal farmers to contribute more strongly to National grain stocks (MoA and FAO, 2012).

SWI initiatives, however, are not new in Bangladesh. The GoB has previously invested in SWI infrastructure, including the 72,000 ha Gangees–Kabadak irrigation scheme and the Barisal Irrigation project, planned for 42,000 ha but which achieved only 10,000 ha (Brammer, 2002). In many SWI schemes, farmers were initially asked to rent low-lift water pumps (BADC, 2012). Farmers, however, tended to be unwilling to invest in irrigation under these conditions. Lack of pump ownership, management difficulties, and lack of autonomy in irrigation supervision caused coordination problems (Brammer, 2004). As a result, while surface water irrigation pumps are available, the measures to encourage their use were not efficient enough to ensure a wide spread uptake of SWI practices.

Where SWI or low-lift pumps are available, the centrifugal pump is the most common technology. Introduced in the 1970s, centrifugal pumps (CEN) rely on the action of an internal spinning impeller located above the surface water, immediately below or horizontal with the point of discharge. CEN pumps are driven by an external engine to lift water through a flexible or rigid tube. Water is lifted due to the negative pressure created by the centrifugal force made by the impeller. Before centrifugal pumps are used, it is necessary to 'prime' them by manually adding water through the outlet until the entire tube and interior pump system is completely filled to avoid efficiency losses resulting from air pockets in the suction system. Despite the availability of centrifugal pumps, their wide scale adoption by farmers remains limited for dry season irrigation in southern Bangladesh.

To address these issues, in this paper we examine the potential impact of an alternative low-lift SWI pump. We focus on the axial flow pump (AFP) which is widely used in the Thailand and Vietnam where irrigation head requirements are low, and where large volumes of water need to be lifted at low pressure (Biggs, 2011; Kay and Hatcho, 1992). This situation is similar to that found in the southern delta of Bangladesh. A typical AFP consists of an impeller encased in and located at the base of a sealed and inflexible pipe (Figure 2). The impeller is driven by an internal or external shaft, which is in turn driven by pulley mechanisms or direct coupling to an engine. Unlike centrifugal pumps, AFPs do not need to be primed (with pumps that requiring priming, the user must manually fill the shaft and/or hose full of water before use, thereby enabling suction force to be applied). At times, the term 'mixed-flow' pump is used to describe the AFP, though in actuality the two differ slightly due to their impeller size and shape, and capacity to lift water to high head levels, and because mixed flow pumps use both the force of the impeller and suction force to move water. In the case of mixed flow pumps, water can be discharged at rates from 200–12,00 m^3 $hour^{-1}$, and at lifts up to 40 meters in height. Mixed flow pumps are a compromise between centrifugal and AFPs in that they allow water lift to high head levels with increased efficiency over centrifugal pumps, although they are not self-priming as are AFPs, and are less widely used for decentralized agriculture as opposed to drainage and industrial purposes (Fraenkel, 1986).

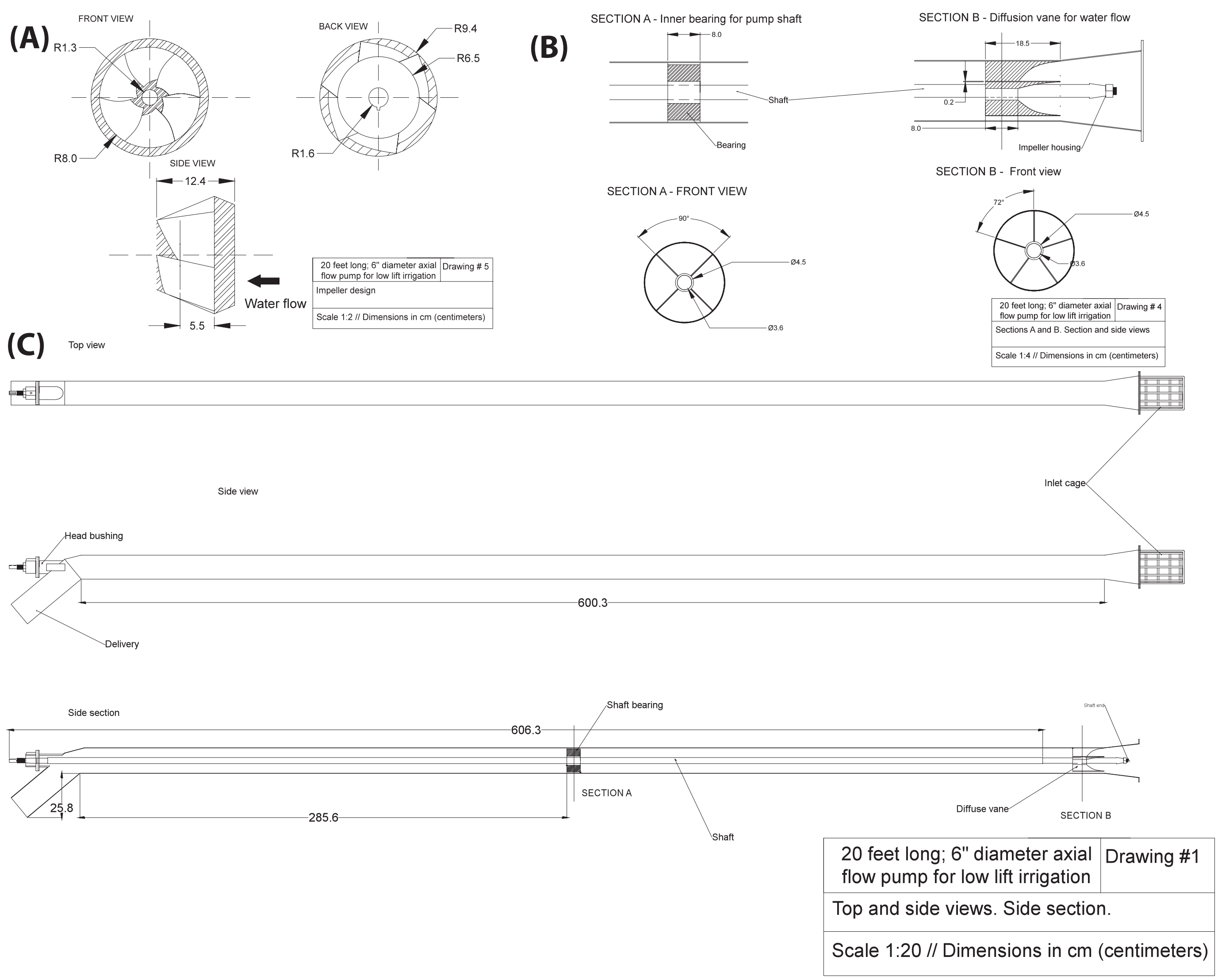

FIGURE 2.

Computer aided drafting (CAD) scaled technical designs of one of the tested axial flow pumps showing (a) detail of the pump impeller, (b) detail of the pumps' diffuser vane structure and (c) detail of the pump body. Adapted from Krupnik *et al.* (2014).

In Asia, use of AFPs for SWI can be traced back to the 1970s in the Mekong Delta, where farmers innovated and modified boat impellers to lift irrigation water from rivers for rice cultivation (Biggs, 2011). Use of the AFP in nearby Thailand enabled many farmers to move from single to double rice cropping (Chinsuwan and Cochran, 1986). Today, there exists a relatively mature AFP manufacturing industry in Thailand and Vietnam (Figure 3), although in Bangladesh, AFPs remain relatively unknown despite the country's similar deltaic geomorphology and potential for SWI.

FIGURE 3.

Large diameter axial flow pumps on sale outside a factory near Bangkok, Thailand.

Photo: Badrul Alam

In some locations of southern Bangladesh, farmers have already begun irrigating crops grown with water supplied by AFPs (Figure 4). Here, we report on technical and economic assessments of the potential for AFPs to provide surface water irrigation in Bangladesh, by comparing different prototype AFPs to CEN pumps as a control. All pumps were assessed at the Bangladesh Agricultural Research Institute's (BARI's) Farm Machinery and Post Harvest Engineering Division for their hydraulic and energetic performance. The first step was to determine the optimal pulley arrangements for use with the locally manufactured AFP prototypes for the best discharge rate. After this, we fully compared CEN and AFPs. The second experiment compared centrifugal with axial flow pumps, and assessed them for water discharge, energy requirements and efficiency, and specific speed at different head levels. We implemented additional *ex-ante* economic comparisons to assess the potential economic performance of AFPs with respect to capital investment and variable costs, field irrigation time requirements, and fuel-use break-even scenarios. The latter analysis was important to assess the feasibility of investing in an AFP to irrigate dry season '*Boro*' rice *(Oryza sativa)*, wheat *(Triticum aestivum)*, or maize *(Zea mays)*, the three primary cereals grown in Bangladesh that make substantial contributions to food security.

FIGURE 4.

A local service provider in Barisal Sadar, southern Bangladesh, using an axial flow pump (in blue). Note the disconnected centrifugal pump (brown color) that this service provider has stopped using in preference of the axial flow pump.

Photo Timothy J Krupnik

2. Materials and methods

Two experiments were conducted from April through May of 2013 at the Bangladesh Agricultural Research Institute (BARI), located in Gazipur, Bangladesh (23º 59′ 13; 90º 24′ 51). In the first experiment, four prototype axial flow pumps (AFP1, AFP2, AFP3 and AFP4) built by two Bangladeshi manufacturers were compared to determine optimal horsepower and coupling arrangements for maximal water discharge (Table 1). The second experiment included the same axial flow pumps and two additional centrifugal pumps as controls to assess hydraulic and energy performance of each pump and pump type. The economic performance of the pumps used to irrigate *Boro* rice, wheat, and maize was subsequently compared through *ex-ante* analyses.

Table 1. List and characteristics of the tested Axial Flow (AFP) and Centrifugal (CEN) pumps in Experiments 1 and 2.

Pump	Manufacturer	Type	Length (m)	Diameter (mm)	Power requirement (HP)	Number of impeller blades	Weight (kg)	Pulley diameter (mm)
AFP1	Rahman Eng.	AFP	3.70	150	10	5	52.0	150
AFP2	Rahman Eng.	AFP	4.45	150	12.5	5	60.0	130
AFP3	Rahman Eng.	AFP	5.46	150	12.5	5	68.0	132
AFP4	Hira Eng.	AFP	3.80	146	12.5	2	39.0	75
CEN1	Milners Pump Ltd.	LLP	N/A	102	10	7	62.5	N/A
CEN2	Milners Pump Ltd.	LLP	N/A	127	12.5	7	64.6	N/A

Abbreviations: N/A indicates not applicable.

2.1. Experimental Test Facilities

The experimental test facilities consisted of a hand-dug pond with a 620 m^2 surface area and 2.6 m depth that provided water for the tests. After pumping, water was deposited in a gauged concrete-lined test bed (6.1 m long, 0.72 m deep and 1.25 m wide) located parallel to, and 2 m from the edge of the pond. The water level in the pond was controlled through daily replacement of any water losses through pumping, seepage, or evaporation. The pumps and engines were placed perpendicular to the bank of the pond and outer wall of the test bed, 1.5 m from the pond bank (Figure 5). A bamboo structure was utilized to manipulate the height of the pumps at different head levels.

2.2. Power transmission

Power was transmitted to the pumps with ‘V-shape’ rubber belts connecting the engine and pump pulleys. The cross sections of the belts were the same for all pumps (1.6 cm wide the external face, 1 cm wide the internal and 1.1 cm thickness), though we varied the diameters and belt models depending on the pump types. The belts utilized included B49 and B60 of 102 and 152.4 cm diameter, respectively, manufactured by Dongil Runner Belt (Busan, Korea). B50 belts (Hanoning Company, China) with a diameter of 127 were also used, as were 130 cm diameter B51 belts (Mitsubishi Belting, Kobe, Japan), and 188 cm diameter B74 belts (Roulunds Rubber, Odense, Denmark). The engines used to power the pumps included a 12.5 HP model S195N (Changchai Co. Ltd., Changzou, Jiangsu. China) and 10 HP model EM190 (Sifeng Group, Shandong, China).

FIGURE 5.

The test bed at the Bangladesh Agricultural Research Institute being used to measure the delivery of water from one of the tested AFPs.The inset photo shows BARI staff measuring pulley speed.

Photo: Santiago Santos Valle

2.3. Experiment 1

Experiment 1 was conducted to determine the optimal V-belt pulley configuration to deliver the maximum water volume for each AFP tested at each head lift level (1, 2, and 3 m head). Each pump was tested with 3 pulleys of different diameters, replicated thrice. The pulleys used in these tests included 75, 89, 102, 114, 130, 132 and 140 mm diameters, respectively, at both the engine and pump shaft. As such, each diameter tested was the same in that there were no alterations in the transmission ratio for each of the configurations tested. After the pumps had been turned on and the engine had stabilized, discharge was measured by directing water from the pump into the test bed, stopping water input when 4.5 m^3 of water had accumulated.

The time to fill the bed was also recorded, and discharge ($m^3\ h^{-1}$) was determined by dividing water volume by time requirement. All measurements were conducted 3 times for each repetition and averaged. Hydraulic performance was assessed using the standard head versus discharge ($H\ Q^{-1}$) relationship for each pump.

2.4. Experiment 2

In Experiment 2, all AFPs (AFP1, AFP2, AFP3 and AFP4) and two additional centrifugal pumps (CEN1 and CEN2), were compared. Pump specific speed was also analyzed to assess cavitation potential. Equation 1 was used to calculate specific speed:

$$N_s = \frac{n \times Q^{\frac{1}{2}}}{h^{\frac{3}{4}}} \tag{1}$$

where N_s is specific speed (a non-dimensional parameter), n is the speed of the AFP impeller (rpm), Q is pump discharge ($m^3\ s^{-1}$) and h head (m). As a measure of energy efficiency, the consumption of fuel compared to water discharge by all pumps was calculated using Equation 2:

$$F = \frac{Q(H)}{f\ (H)} \tag{2}$$

where F is fuel use (m^3 water discharged per L fuel used), $Q(H)$ is discharge ($m^3\ h^{-1}$) at the lift height 'H' (m), and $f(H)$ is fuel consumption ($I\ h^{-1}$) at a given lift 'H'. Water horsepower (WHP) is a measure of the power transferred to water by an irrigation pump. It was calculated according to Equation 3:

$$WHP = \frac{w \times Q \times h}{75} \tag{3}$$

where WHP is water horse power (HP), w is the unit weight of water, $\left(\frac{1000\ \mathrm{L}}{\mathrm{m}^3}\right)$, Q is pump discharge ($m^3\ s^{-1}$) and h is head (m).

The experiment was considered as a randomized complete block design. Data for water discharge, fuel consumption, and fuel use were analyzed using JMP 8.0.2 (SAS Institute Inc., San Francisco). After assessing normality, data were subjected to analysis of variance (ANOVA) between groups of pumps at each head level, and within pumps at each head level. Where significant effects were found, means were separated using Tukey's Honestly Significant Different test at α=0.05. Least square means contrast statements employed to separate the treatment means of each pump type. Where significant differences were detected, means were separated using the Student's T-Test (α=0.05).

2.4.1. Economic analysis

Ex-ante economic analysis included both fixed and variable costs. The former encompassed primarily the capital outlays (*e.g.* costs of full pump set, engine, V-belts, etc.). Costs were collected from the local market. The fixed cost per year was calculated from the sum of depreciation and interest on investment. Machinery depreciation was calculated for pumps and engines according to Equation 4:

$$D = \frac{C - (C \times d)}{n} \tag{4}$$

where D is depreciation (BDT, or USD)[1], C is total capital cost (BDT or USD), d is the depreciation rate at 15% following the FAO (1992), and n is the use life of the machine (years). n was assumed to be five years for well-maintained pumps. The interest rate on average capital investment was considered to be 11% of the capital cost. As such, interest on investment was calculated following Equation 5:

$$I = \frac{C + (C \times d)}{2} x\ i \tag{5}$$

where I is interest on investment, C is the capital cost, d is the depreciation rate (15%) and i is the bank interest rate (11%). The total fixed cost per year is simply the sum of d and i (BDT or USD year^{-1}). Variable input costs for dry season *Boro* rice, wheat, and maize were calculated using Equation 6:

$$V_C = \frac{V(f) \times I_c}{Q} \tag{6}$$

where V_C is the variable cost in question, $V(f)$ is the variable cost of fuel (taken as (USD l^{-1}) according to our market research) consumed at each head level (BDT or USD h^{-1}), I_c is the measured irrigation rate for maize, wheat, or *Boro* rice (m^3 ha^{-1}), and Q is pump discharge (m^3 h^{-1}) or the head level in question.

The physical properties of Bangladesh's soils (water holding capacity, hydraulic conductivity and percolation rates) vary widely. We therefore selected observations of high and low irrigation application rates for each crop grown near attainable yield without water stress from the literature in Bangladesh. These values were then used to model the outcomes of using AFPs and CEN pumps to irrigate *Boro* rice, wheat, and maize. In this sensitivity analysis, irrigation requirements were taken as 12,800 m^3 ha^{-1} (high) (Sarkar and Ali, 2010) and 11,700 m^3 ha^{-1} (low) (Rashid et al., 1991) for *Boro* rice, 3,420 m^3 ha^{-1} (high) (Sarker et al., 2010) and 2,490 m^3 ha^{-1} (low) (Hossain, 2008) for wheat, and 5,600 m^3 ha^{-1} (high) and 3,443 m^3 ha^{-1} (low) (Islam and Hossain, 2010) for maize. In all studies, only data for conventional water management and fully tilled, flat planting of crops were considered.

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1. *Throughout this study, 1 US Dollar = 77.7 BD Taka in May of 2013* (Exchange Rates, 2013).

The variables *V(f), Ic and Q* (m^3 ha^{-1}) were calculated on yearly basis. V(f) was calculated using Equation 7:

$$V(f) = F(h) \times f \quad (7)$$

where *V(f)* is the variable cost of fuel (USD h^{-1}), *F(h)* is fuel consumption (l h^{-1}) and *f* is fuel price (USD l^{-1}). We then calculated a break-even point considering the value of fuel savings per unit of land that could be achieved through use of the AFP compared to CEN pumps for each crop and head lift requirement following the first year of fixed and variable cost investments by a hypothetical farmer in irrigation using an AFP. This break-even point for average AFP and CEN performance followed Equation 8:

$$BP = \frac{\Delta C_i}{\Delta V(h)} \quad (8)$$

where *BP* is the break-even point (ha) ΔC, is the difference in costs for the *i*th (USD), and ΔV (h) is the variable cost savings (USD ha^{-1}) per head level. Finally, we also analyzed the potential command area performance of the pumps by measuring the time needed to irrigate one hectare of *Boro* rice, wheat, and maize for high and low irrigation requirements, using the pump discharge at each lift. This was accomplished using Equation 9:

$$t = \frac{I_C}{Q(H)} \quad (9)$$

where *t* is the time required to irrigate (hours (h) ha^{-1}), I_C is the irrigation requirement of a particular crop (m^3 ha^{-1}) and *Q(H)* is pump water discharge in relation to each head level (m^3 h^{-1}).

3. Results and discussion

3.1. Experiment 1

Experiment 1 determined the different pulley configurations required for each AFP to deliver maximum water discharge at 1, 2 and 3 m heads (Figure 6). For AFP1, the 114 mm diameter pulley performed considerably better at two of three lift heights compared to the 132 and 140 mm configurations. Compared to the 132 and 140 mm pulleys, discharge increased by 4% and 18% at 1 m, 8% and 28% at 2 m, and 2% and 26% at 3 m lifts, respectively. Because irrigation service providers in Bangladesh usually purchase standardized pulley sets, we choose to use the 114 mm pulley for all lifts for AFP1 in Experiment 2. The 114 mm pulley also performed well for AFP2. When compared to 130 and 140 mm diameter pulleys, discharge was boosted by 12% and 38% at 1 m, 7% and 52% at 2 m, and 12% and 57% at 3 m lifts. A similar pattern was revealed for AFP3, though when the 114 mm pulley was compared to the 75 and 102 mm pulleys (both of which were the best-fits for the AFPs pulley receptors) discharge was only marginally higher than the 75 mm pulley (4%, 6%, and 4% improvements at lifts from 1-3 m, respectively), while discharge was much higher than the 102 mm pulley (17%, 25%, and 15% greater for 1-3 m heads). 114 mm pulleys were consequently used for AFPs 1-3 in Experiment 2. By comparison, AFP4 was designed and built

A similar pattern was revealed for AFP3, though when the 114 mm pulley was compared to the 75 and 102 mm pulleys (both of which were the best-fits for the AFPs pulley receptors) discharge was only marginally higher than the 75 mm pulley (4%, 6%, and 4% improvements at lifts from 1-3 m, respectively).

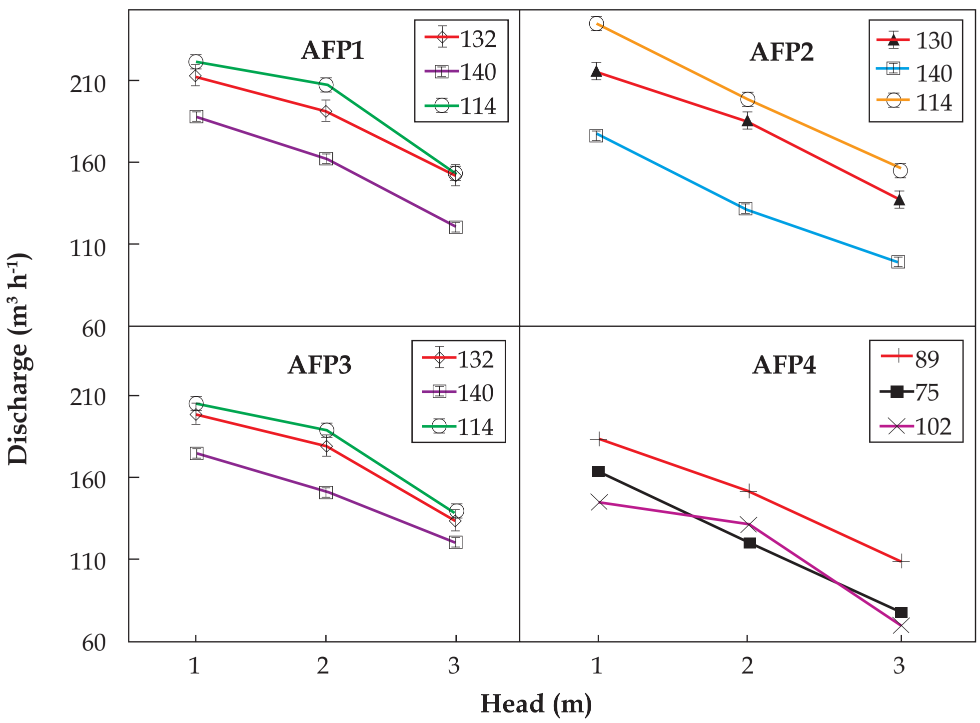


FIGURE 6.

Water discharge ($m^3 h^{-1}$) as a function of head level for AFPs 1-4 using different pulley diameters.

differently than the other AFPs. With an external rather than internal shaft, there was little space between the pump shaft and body, necessitating the use of smaller pulleys. For this reason, 89, 75, and 102 mm pulleys were compared, with the 89 mm diameter configuration giving the best general water discharge performance (26, 16 and 57%, and 26, 16, and 57% increases in discharge at 1, 2 and 3 m lifts compared to 122 and 75 mm pulleys). The 89 mm diameter was consequently chosen for Experiment 2.

These results indicate that axial flow pumps can be run utilizing standardized pulley configurations using detached engines of 12-16 HP, both of which are common for two wheel tractors in Bangladesh. Estimates are that there are between 3-400,000 two-wheel tractors (TWT) in Bangladesh (Biggs et al., 2011). Agricultural service providers typically use these tractors for tillage at the time of planting, and thereafter they are used for hauling materials or they lay idle. The compatibility of the AFP pulley arrangement with 12 and 16 HP dethatched engines indicates that service providers could utilize their TWs to power AFPs, thereby facilitating new opportunities for income generation following planting operations.

3.2. Experiment 2

3.2.1. Hydraulic performance

Water discharge from the axial flow pumps was higher than centrifugal pumps at all lift heights (Table 2), with significant differences detected at all head levels, although a negative relationship between lift height and discharge was also observed. For example, at 1-m head, average discharge of AFPs was 72% higher than CEN, whereas at 2-m and 3-m heads, discharge of AFPs was 55% and 28% higher than CEN, respectively. At 1-m head, maximum discharge obtained by AFP was 215 $m^3 h^{-1}$ compared to 125 $m^3 h^{-1}$ for the centrifugal pumps. This clearly shows that hydraulic performance of AFPs is significantly higher than centrifugal pumps at lower heads. For all pumps, significant differences (P<0.01 for AFPs, and P<0.05 for CEN) were found between lift heights and discharge.

The average discharge of the AFPs decreased by 15% between 1- and 2-m lifts whereas this decrease was only 25% between 2- and 3-m lifts. In contrast, the reduction in discharge between 2- to 3-m lift was only 0.03% for CENs. The hydraulic performance of AFPs was found to be higher at low lifts (i.e. 1 to 2-m), although it dropped significantly as head increases. Conversely, CEN hydraulic performance was low at all heads, with a significant but slight decline as head increased. Although the discharges obtained by the AFPs at 3-m lifts were significantly lower than 1-m lifts, they were still comparable with the discharges of CEN at all heights. This indicates that the hydraulic efficiency of AFPs is higher than CEN in all respects. Kathirvel (2000) found similar results while comparing the performance of AFPs at different heads in India, obtaining maximum discharges of 226, 187 and 144 $m^3 h^{-1}$ at 1-m, 2-m and 3-m heads, respectively.

Table 2. Water discharge $m^3 h^{-1}$ at different head levels by pump model, power source, and pump type.

Factor effects		Water discharge ($m^3 ha^{-1}$)			
		1 m head	2 m head	3 m head	*F*-values
Pump model	AFP1[a]	214.8 A b	205.3 B a	168.4 C b	810.56**
	AFP2	245.0 A a	202.0 B a	172.4 C a	102.27**
	AFP3	216.0 A b	190.3 B b	145.1 C c	343.88**
	AFP4	185.5 A c	149.3 B c	111.3 C e	339.19**
	CEN1[b]	102.8 A e	100.3 B e	97.7 C f	66.97*
	CEN2	147.7 A d	140.7 B d	134.9 C d	44.39*
	F-values	1528.91**	332.6**	684.28**	
LS Planned Means Contrast Pump Type					
	AFP	215.3 a	186.7 a	149.3 a	
	CEN	125.2 b	120.5 b	116.3 b	
	F-values	1427.89**	1123.77**	1106.48**	

[a] Indicates Axial Flow Pump. [b] Indicates Centrifugal Pump Values in columns not separated by rows sharing the same lower case letter are not significantly different according to Tukey's Honestly Significant Different test at α =0.05. Values in rows sharing the same upper case letter are significantly different according to the same test. Values in columns for the Least Squares (LS) Planned Means Contrasts for Horsepower and Pump Type are significantly different at α=0.05 according to the Student's T Test. ANOVA results with a * indicate significance at $P \leq 0.05$, and ** indicates significance at $P \leq 0.001$.

3.2.2. Specific speed

Specific speed is a non-dimensional parameter used by irrigation engineers to characterize the effect of impeller design, for example the shape, arrangement, and number of blades. Specific speed measurements help to characterize the work of a particular pump; such measurements can be used to determine the presence of cavitation, which can negatively affect pump efficiency. Cavitation can be defined as the development of air pockets in the internal water column within a pump. These pockets develop due to pressure differentials on the surface of the water molecules within the column of water flow. When specific speed is not within the range of 10 to 300, damage to pumps can occur (Michael, 1978). These air pockets can create 'void' spaces within the pump that can result in shockwaves when they are under high pressure, and especially when they are pushed against the inner walls of the pump or its parts. In particular, the pump's inlet and impellers are usually most sensitive to cavitation, causing cracking or disjointing. However, the pump's proximal discharge point can also be damaged, especially when water flow pressure volume and volume are high. This can result in early wear and tear that reduces pump quality.

In our experiments, pump specific speed ranged from a maximum of 473.73 for AFP2 at 1 m lift to a minimum of 110.53 of CEN1 at 3 m lift (Table 3). At 2 and 3 m heads, all measurements indicated that cavitation was minimal. In other words, there was no risk of cavitation when water was lifted within its optimal range for an AFP. This also implies that the structural and mechanical engineering of the pumps were adequate for lifting water within this range without overload. But to be safe, regular maintenance, cleaning, and correct use of pumps can assist in reducing the detrimental effects of cavitation.

Table 3. Specific speed of the pump models at 1, 2 and 3 m head[1].

Lift (m)	AFP1	AFP2	AFP3	AFP4	CEN1	CEN2
1	443.47	473.73	444.58	414.61	258.63	368.12
2	258.08	256.27	248.13	221.14	151.96	213.44
3	172.25	174.74	159.75	140.56	110.53	153.51

1. Specific is speed is a non-dimensional parameter. It can be used to characterize the geometry and design of an impeller.

3.2.3. Water horse power, fuel consumption, and water delivery per unit of fuel use

Comparing AFPs to CEN pumps, the former exhibited an asymptotic and declining trend in WHP as head increased, while the latter showed linear and increasing trend. Despite this, WHP was greater for three of the four tested AFPs at 3-m lift, with the exception of AFP 4, which was 20% lower than CEN 2 (Figure 7). Fuel consumption by AFPs was always higher and significantly different (*P*<0.001) than for CEN pumps when compared within and across pump types (Table 4). Like for WHP, CEN pumps consumed relatively the same amount of fuel when measured across the two pumps at all lifts (1.7, 1.6, and 1.8 l h^{-1} at 1-, 2- and 3-m lifts), while AFPs consumed relatively more fuel (1.9, 2.1, and 2.2 l h^{-1} at 1-, 2- and 3-m lifts) at the same head levels. The differences in fuel consumption within AFPs were related to differences in the pumps' structural and impeller designs, and in length and diameter, as well as the number of impeller blades.

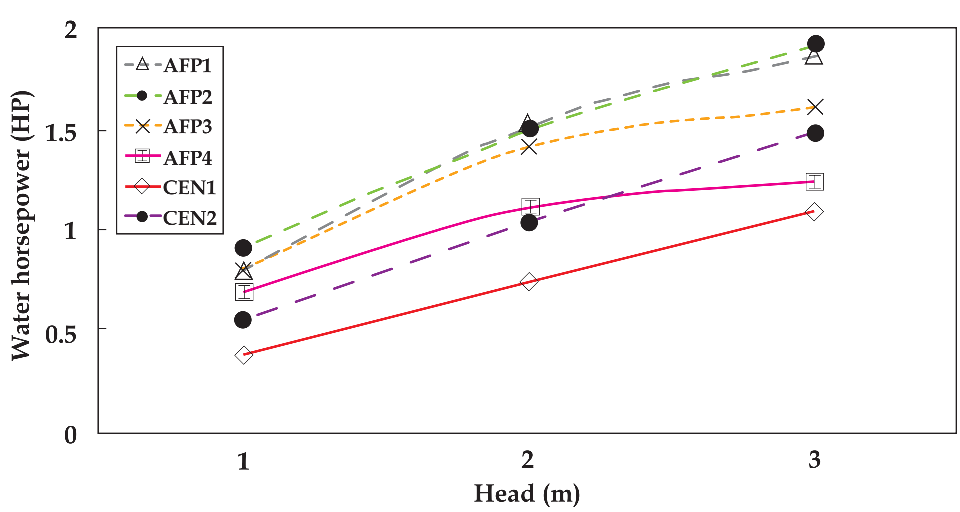


FIGURE 7. **Water horsepower (HP) described by polynomial relationships for axial flow (AFP) and centrifugal (CEN) pumps at 1, 2 and 3 m head lifts in Experiment 2.**

Considering both fuel use and water delivery, AFPs delivered more water per unit of fuel use (m^3 l^{-1}) at 1- and 2-m lifts (*P*<0.01 for both lifts), but not at the 3-m head level (*P*<0.001; Table 4). When measured across pumps, this important indicator of energy efficiency showed that AFPs were 51% and 21% more efficient at 1- and 2-m lifts in this regard, though at 1-m lift, 5% more fuel (3.8 m^3 l^{-1} on average) was required to deliver the same volume of water as the centrifugal pumps. Comparing pumps at each lift, significant differences were also found at 1-, 2- and 3-m heads ($P<0.01$ for each level). Shah (2009) examined the relationship between irrigation pump fuel consumption and CO_2 emissions in India, and found SWI to typically be low-emission. Our data indicate the potential to reduce the greenhouse gas (GHG) footprint of SWI irrigation where farmers make use of AFPs rather than CEN pumps for low lifts in Bangladesh's delta, though additional research is necessary to confirm this hypothesis. Further policy action to support the use of fuel-efficient and thus potentially lower GHG emitting pumps should be encouraged as efforts to develop SWI resources in South Asia increase (*cf.* Molden, 2007; Shah, 2009).

Table 4. Fuel consumption ($l\ h^{-1}$) at different head levels by pump model, power source, and pump type.

Factor effects		Fuel consumption ($l\ h^{-1}$)			
		1 m head	2 m head	3 m head	*F*-values
Pump model	AFP1[a]	2.1 C b	2.2 B b	2.3 A b	152.46**
	AFP2	2.3 a	2.4 a	2.5 a	6.56*
	AFP3	1.8 C c	2.1 B b	2.3 A b	228.30**
	AFP4	1.6 d	1.6 d	1.6 d	3.34 ns
	CEN1[b]	1.5 A d	1.4 B e	1.4 B e	17.35*
	CEN2	1.8 c	1.8 c	1.8 c	2.80 ns
	F-values	188.88**	654.27**	332.61**	
LS Planned Means Contrast Pump Type					
	AFP	1.9 a	2.1 a	2.2 a	
	CEN	1.7 b	1.6 b	1.8 b	
	F-values	186.85**	1345.8**	806.38**	

[a] Indicates Axial Flow Pump. [b] Indicates Centrifugal Pump Values in columns not separated by rows sharing the same lower case letter are not significantly different according to Tukey's Honestly Significant Different test at α =0.05. Values in rows sharing the same upper case letter are significantly different according to the same test. Values in columns for the Least Squares (LS) Planned Means Contrasts for Horsepower and Pump Type not sharing the same lower case letter are significantly different at α =0.05 according to the Student's T Test. ANOVA results with a * indicate significance at $P\leq 0.05$, and ** indicates significance at $P\leq 0.001$.

Table 5. Water delivery per unit of fuel consumed ($m^3\ l^{-1}$) at different head levels by pump model, power source, and pump type.

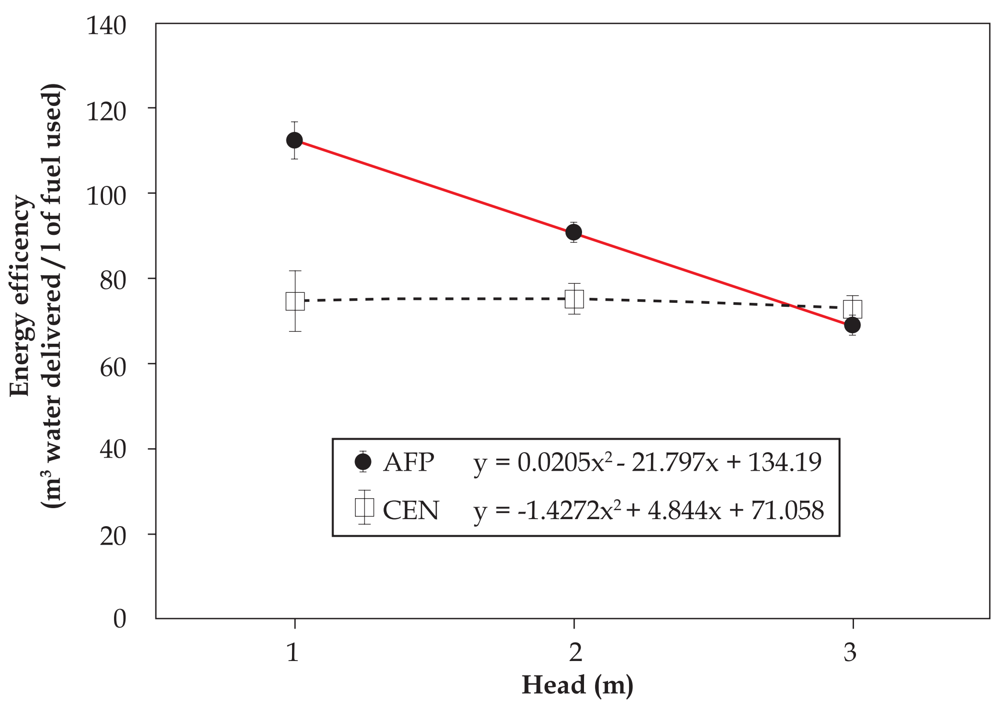
Factor Effects		Water delivery per unit of fuel consumed (m^3 water l^{-1} fuel)			
		1 m head	2 m head	3 m head	*F*-values
Pump Type	AFP1[a]	104.1 A b	94.8 B a	73. 4 C ab	1236.20**
	AFP2	105.9 A b	84.3 B bc	70.4 C bc	250.19**
	AFP3	120.0 A a	90.3 B ab	64.5 C d	484.74**
	AFP4	119.7 A a	93.3 B a	67.6 C cd	301.29**
	CEN1[b]	67.4 B d	71.5 A d	70.4 AB bc	9.05*
	CEN2	81.6 A c	78.6 B c	75.1 C a	33.32*
	F-values	332.2**	48.99**	18.85**	
LS Mean Contrast: Pump type					
	AFP	112.4 a	90.7 a	69.0 a	
	CEN AV	74.5 b	75.0 b	72.7 b	
	F-values	1421.72**	191.93**	29.63**	

[a] Indicates Axial Flow Pump. [b] Indicates Centrifugal Pump Values in columns not separated by rows sharing the same lower case letter are not significantly different according to Tukey's Honestly Significant Different test at α =0.05. Values in rows sharing the same upper case letter are significantly different according to the same test. Values in columns for the Least Squares (LS) Planned Means Contrasts for Horsepower and Pump Type are significantly different at α =0.05 according to the Student's T Test. ANOVA results with a * indicate significance at $P\leq 0.05$, and ** indicates significance at $P\leq 0.001$.

Fitting second order polynomial equations to the average performances of the different pump types across all lifts, we determined that the break-even point between the pump types for energy efficiency (as measured by the fuel consumption to discharge ratio) is 2.8-m head (Figure 8). In other words, up to a lift of 2.8-m height, the tested AFPs will use proportionally less fuel per unit of water delivered compared to CEN pumps. When exceeding 2.8-m, this efficiency is lost – while the tested AFPs continued to deliver more water (up to 33 $m^3 h^{-1}$ at 3 m, Table 2) than CEN pumps, fuel consumption becomes higher (+0.5 $l h^{-1}$ at 3-m, Table 4).

FIGURE 8.

Polynomial relationship and fuel performance (m^3 water delivered l^{-1} fuel used) use break-even point between axial flow (AFP) and centrifugal (CEN) pumps in Experiment 2. Bars indicate the standard error of the mean.



This trade-off offers important information for examining the potential performance of each pump type when used for low-lift surface water irrigation in deltaic environments like Bangladesh, where water can be lifted from rivers and canals and then directed to farmers' fields for irrigation (Figure 9). Spatial analyses that assist in the targeting of technologies to particular, and ideally suited locations based on geo-referenced landscape information (*e.g.* Chandna et al., 2012), could assist in the deployment of AFPs for efficient use in the field.

3.2.4. Ex-ante economic performance

Until the late 1980s, the Bangladeshi government was responsible for all irrigation management and deployment of pump sets to farmers. After this period, restrictions on the private sector to import small engines and irrigation equipment were removed, which ushered in the growth of an independently operated irrigation water economy (Hossain, 2009). Today, irrigation is supplied to farmers primarily by private service providers, who as local entrepreneurs invest in pump sets and supply water on a fee-for-use basis, although in some cases groundwater pumping equipment is owned by farmers in shares (Palmer-Jones, 2011). In the current study, the average fixed costs for a hypothetical service providers investing in AFPs was 21% higher than those of centrifugal pumps (Table 6). Costs ranged from 15,165–12,832 BDT (195–165 USD) year^{-1} for AFPs and 12,433–10,110 BDT (160–130 USD) year^{-1} for centrifugal pumps. In all cases, engine depreciation made up the largest proportion of the fixed costs, followed by repair and maintenance. Importantly, the unit costs of the AFPs used in this study may be slightly higher than the market price because they are prototypes and the AFP market is not yet widely developed in Bangladesh. However, over time, costs are likely to decrease if farmer uptake of the pump is widespread and manufacturers react with increased supplies and more sound models manufactured with lower production costs and higher efficiencies.

FIGURE 9.

An irrigation service provider uses an axial flow pump to provide irrigation to dry *Rabi* season in Putakhali, southern Bangladesh. Note the pulley configuration and power supply by a 16 HP two-wheel tractor engine.

Photo Timothy J Krupnik

Table 6. Capital and fixed costs (BDT) for the Axial Flow and Centrifugal Pumps. Numbers in parentheses are the US dollar rate[1].

	Axial Flow Pumps				Centrifugal Pumps	
	AFP 1	AFP 2	AFP 3	AFP 4	CEN 1	CEN 2
Capital cost (BDT)						
Pump	11,043 (142)	10.577 (136)	9,955 (128)	7,310 (94)	3,198 (41)	4,744 (61)
Engine	32,275 (415)	32,275 (415)	26,520 (341)	32,275 (415)	26,520 (341)	32,275 (415)
V-belt	467 (6)	467 (6)	467 (6)	467 (6)	467 (6)	467 (6)
Total capital costs *(BDT)*	43,785 (563)	43,318 (557)	37,019 (476)	40,052 (515)	30,175 (388)	37,485 (482)
Annual fixed costs (BDTyear^{-1})						
Engine depreciation	5,444 (70)	5,444 (70)	4,511 (58)	5,444 (70)	4,511 (58)	5,444 (70)
Pump depreciation	1,866 (24)	1,789 (23)	1,711 (22)	1,244 (16)	233 (3)	389 (5)
Interest on average capital investment (15%)	3,322 (44)	3,422 (44)	2,877 (37)	3,111 (40)	2,255 (29)	2,877 (37)
Repair and maintenance (10% of capital)	4,355 (56)	4,355 (56)	3,733 (48)	4,044 (52)	3,033 (39)	2,733 (48)
Total annual fixed costs	15,165 (195)	15,010 (193)	12,832 (165)	13,843 (178)	10,032 (129)	12,443 (160)
Total capital and fixed costs in the first year of Total investment (BDT)	58,950 (758)	58,328 (750)	49,851 (641)	53,895 (693)	40,207 (517)	49,928 (642)

1. A conversion rate of 77.7 Bangladeshi Taka to the Dollar was employed (http://www.exchangerates.org.uk/USD-BDT-exchange-rate-history.html).

We next explored the consequences of investment and irrigation via AFPs for three key irrigated dry season cereal crops in Bangladesh – *Boro* rice, wheat and maize – all of which typically have different irrigation water requirements, and which can be grown using surface water lifted from canals and rivers. The Government of Bangladesh has for decades placed attention on *Boro* rice because of its contribution to food security and political stability (see Hossain 2009; MoA and FAO, 2012). Wheat is the country's second most widely grown field crop, while maize production is now increasing more rapidly than any other cereal in response to the burgeoning poultry and fish feed sectors (Timisina *et al* 2010; Rawson, 2011). *Boro* grown in Bangladesh requires about 3,000 l of water per kg of grain produced, often applied through over 20 irrigations. In comparison, wheat requires 1–3 irrigations and 1,000 lwater kg grain^{-1}, while maize requires 850 l water kg grain^{-1} and between 2–4 irrigations (Ali *et al*, 2009). Because AFPs require 22% more investment than CEN pumps on average, we investigated the potential to break even both in terms of the number of hectares of land of *Boro* rice, wheat, and maize that would need to be irrigated to reap the benefits of fuel savings from AFPs at 1- and 2-m lifts (and the trade-off at 3-m lifts) relative to the lower investment costs in CEN pumps (Table 7), and also in terms of irrigation time savings accrued from use of AFPs (Table 8). The latter analysis is important because the reduction in time requirements for irrigation could release irrigation service providers from extended irrigation time commitments in a particular command area, allowing them to move pumps to new locations and serve larger groups of farmer-clients in different irrigated areas.

Considering a fuel cost of BDT 61 (0.78 USD) l^{-1}, and each crop's irrigation water requirement under high and low water use scenarios, fuel savings for *Boro* rice resulting from the use of an AFP were 3,111, 1,555, and -544 BDT (40, 20, and -7 USD) season^{-1} for the high requirement scenario at 1-, 2- and 3-m lifts (Table 7). This compares to 5,444, 4,588, and 2,955 (70, 59, and 38 USD) under the low water use scenario. As such, an irrigation pump owner servicing *Boro* rice farmers would need to supply water to a minimum of 3 or 5 ha at 1-m lift to break even on variable costs in the low and high scenarios, respectively, in the first year of AFP investment. By comparison, 9 and 3 ha would be required at 2-m lifts for low and high water requirements. The increase in land area required is representative of the decrease in fuel use to water delivery ratio as head increases. At 3-m lifts and under the high water use scenario, it becomes impossible to break even on the investment by irrigating *Boro* rice in the first season after purchase because of the reduced efficiency of the prototype AFPs at lifts in excess of 2.8 m. Under the low water use scenario, 5 ha would be required to break even. Because much of southern Bangladesh's delta is tidal in nature (MoA and FAO, 2012), service providers are likely to benefit the most when AFPs are used at high tide, so as to make use of lower head levels not in excess of 2.8-m (Figure 11).

Table 7. Required irrigated land surface area (ha) and value of fuel saving requirements (BDT season^{-1}, with numbers in parentheses being USD values) for *Boro* rice, wheat, and maize, to break even on the first year variable investment costs following the purchase of an Axial Flow Pump in Bangladesh.

Crop	Head lift (m)	Irrigation rate scenario High			Low		
		Variable cost (BDTseason^{-1})	Fuel saving value (BDTseason^{-1})	Required irrigated area to break even on investment (ha)	Variable cost (BDTseason^{-1})	Fuel saving value ((BDTseason^{-1})	Required irrigated area to break even on investment (ha)
Boro rice[2]	1	6,393 (82.2)	3,098 (39.84)	4.58	7,559 (97.20)	5,470 (70.34)	2.59
	2	7,881 (101.34)	1,553 (19.97)	9.14	8,342 (107.26)	4,586 (58.97)	3.10
	3	10,306 (132.52)	-551 (-7.09)	-25.75	10,399 (133.71)	2,958 (38.04)	4.80
Wheat[3]	1	1,175 (15.11)	850 (10.93)	16.70	1,614 (20.75)	1,168 (15.02)	12.16
	2	1.296 (16.67)	713 (9.17)	19.92	1,781 (22.90)	979 (12.59)	14.50
	3	1,616 (20.78)	460 (5.91)	30.88	2,220 (28.54)	631 (8.12)	22.48
Maize[4]	1	1,625 (20.89)	1,176 (15.12)	12.07	2,832 (36.41)	2,049 (26.35)	6.93
	2	1,793 (23.05)	985 (12.67)	14.40	3.124 (40.17)	1,718 (22.09)	8.27
	3	2,235 (28.74)	653 (8.17)	22.33	3,895 (50.08)	1,108 (14.25)	12.81

1. Thee value of the US dollar was employed using the September 16, 2013 Bangladesh Taka (BDT) rate of 1 USD = 77.77 BDT (Exchange Rates, 2013).
2. The high scenario water use requirement is 12,800 m^3 ha^{-1}. Low is scenario is 11,700 m^3 ha^{-1}.
3. The high scenario water use requirement is 3,420 m^3 ha^{-1}. Low is scenario is 2,490 m^3 ha^{-1}.
4. The high scenario water use requirement is 5,600 m^3 ha^{-1}. Low is scenario is 3,443 m^3 ha^{-1}.

For wheat, the area requirement to break even at 1-m head was 17 and 12 ha under the high and low scenarios. At 3-m head, 31 or 22 ha would be required, respectively. Use of AFPs on surface areas less than these would result in the pump owner's inability to break even in the initial season following investment, unless he or she differentiated crops by seeking to service farmers growing more high-water demanding crops. For maize, which requires 2,180 and 953 m^3 ha^{-1} more water than wheat under the high and low scenarios, 12, 14, and 22 ha would be required to break even for the high water requirement at 1-, 2- and 3-m lifts, compared to 7, 8, and 13 ha under the low scenario. This indicates that the AFP will be most immediately useful for irrigation pump owners who provide irrigation services to farmers growing more water demanding crops, though only at low water lift heights. Similarly, AFP owners could also find viable markets in freshwater aquaculture, where large volumes of water must be moved at low lifts from pond to pond, or to fishponds, at low lifts. Conversely, this situation could also facilitate new irrigation service provider business models that favor lower irrigation pricing due to the fuel savings accrued from use of AFPs at low lifts, especially where reduced irrigation time requirements enable service providers to move pumps to new command areas and service larger numbers of farmer clients.

Table 8. Projected total irrigation time (h ha^{-1}) required under high and low irrigation rate scenarios for *Boro* rice, wheat and maize at 1, 2 and 3 m head lifts considering the mean performance axial flow and centrifugal pumps in Experiment 2.

Lift (m)	Crop type											
	Boro rice[1]				Wheat[2]				Maize[3]			
	High		Low		High		Low		High		Low	
	AFP	CEN	AFP	CEN	AFP	CEN	AFP	CEN	AFP	CEN	AFP	CEN
1	59.4	102.2	54.3	93.4	15.9	27.3	11.6	19.9	26.0	44.7	16.0	27.5
2	68.5	106.2	62.7	97.1	18.3	28.4	13.3	20.7	30.0	46.5	18.4	28.6
3	85.7	110.1	78.3	100.6	22.9	29.4	16.7	21.4	37.5	48.2	23.1	29.6

1. High scenario is 12,800 m^3 ha^{-1}. Low is scenario is 11,700 m^3 ha^{-1}.
2. High scenario is 3,420 m^3 ha^{-1}. Low is scenario is 2,490 m^3 ha^{-1}.
3. High scenario is 5,600 m^3 ha^{-1}. Low is scenario is 3,443 m^3 ha^{-1}.

The above business model could potentially be feasible because AFPs require less time to irrigate one hectare of land as compared to centrifugal pumps (Table 8). The maximum time required to irrigate one hectare of *Boro* rice under the high water requirement scenario by an AFP was 86 hours compared to 110 hours for CEN at 3-m lift height. At 1- and 2-m heads, 43 or 38 less hours of pumping would be needed under the high scenario, while 39 and 34 hours less would be required for the low irrigation rate scenario for the same crop species. When compared to centrifugal pumps, an AFP would save about 5,444 BDT (70 USD) $season^{-1}$ at 1-m head for low water requirements for *Boro*, compared to 2,955 (38 USD) $season^{-1}$ at 3-m. Similar trends were observed for wheat and maize, though projected time savings are higher for the latter due to greater water requirements resulting from increased biomass yield (and hence evapotranspiration) under both high and low irrigation scenarios. This implies that pump operators could potentially charge less for irrigation in cases where the number of hours a pump is running is the variable that determines pumping cost, though irrigation service providers would have to make efforts to move pumps to serve more farmers to recuperate investment costs in the first year of use.

FIGURE 10.

An irrigated *Boro* rice field in Baboginj Upazilla, Barisal District, in Southern Bangladesh that is fully irrigated by the Axial Flow Pump.

Photo Timothy J Krupnik

Photo Timothy J Krupnik

FIGURE 11. An axial flow pump on Bhola Island at low tide. Note that the water in this canal is too low to be utilized for pumping, however at high tide the water level will rise up to 2.5 m higher. In coastal tidal environments like this, pumping needs to be timed with the availability of water. A centrifugal pump that was abandoned by the irrigation service provider who now uses the axial flow pump can be seen in the bottom of the photograph.

Conclusions

Compared to centrifugal (CEN) pumps, the hydraulic performance of the prototype axial flow pumps (AFPs) was higher at low lifts although it dropped significantly with increasing head and converged with CEN pumps at 2.8-m. The centrifugal pumps produced lower and more consistent (though slightly declining) discharge than axial flow pumps at all head levels. At 1-m head, the average discharge of the AFPs was 72% higher than centrifugal pumps, whereas at 2-m and 3-m heads, discharge was 55% and 28% higher, respectively. Although the discharge obtained by the AFPs at 3-m lifts were significantly lower than 1-m lifts, they remained comparable to CEN discharge all lift heights. This clearly indicates that the hydraulic efficiency of AFPs is higher than CEN in all respects at low lift levels. Further research is needed to test the endurance capacities of both pump types, especially when subjected to longer running times and increased stress.

The CEN pumps produced lower and more consistent (though slightly declining) discharge than AFPs all head levels. At 1-m head, the average discharge of the AFPs was 72% higher than centrifugal pumps, whereas at 2-m and 3-m heads, discharge was 55% and 28% higher, respectively.

Water horse power (WHP) showed a linear and increasing trend as head increased for CEN pumps, whereas AFPs exhibited an asymptotic and declining trend. Water delivery per unit of fuel was highest in AFPs at 1-m head, although this variable was inversely proportional to increasing head. This was not the case for CEN pumps where water delivery per unit of fuel use remained nearly constant. Water delivery fuel efficiency of the AFPs was on average +51% higher than centrifugal pumps at 1-m and 2-m head (+21%), but declined to–0.05% at 3-m heads, respectively. The tested AFPs used proportionally less fuel per unit of water delivered up to a head of 2.8 m compared to CEN pumps. Further research is needed to investigate the potential contribution of AFP use in the mitigation of greenhouse gasses resulting from fuel use in irrigated agriculture. After 2.8 m of head, AFPs continue to deliver more water than CEN pumps though fuel use becomes proportionally higher. Due to higher discharge, AFPs reduce the time required to irrigate *Boro* rice, wheat, and maize, with the greatest time saving benefits resulting when more water consumptive crops are irrigated. Compared to CEN and where irrigation volume requirements are low, AFPs can save between 5,444–2,955 BDT (70–38 USD) ha^{-1} $season^{-1}$ for *Boro* rice when water is lifted at 1- and 3-m heads, respectively, and 1,167–622 BDT (15–8 USD), and 2,022–1,089 BDT (26–14 USD) ha^{-1} $season^{-1}$ for wheat and maize at the same lifts. In conclusion, because AFPs can achieve fuel savings, opportunities may exist for irrigation service providers to modify their business models to reduce irrigation costs and thus the cost of production for farmers, provided that they are able to recuperate or increase the number of farmer-clients by moving pumps and/or by diversifying with water supply to more water-demanding crops. The use of more efficient technologies like the AFP can be an effective tool to mitigate the increasing energy costs derived from irrigation, and to encourage the wise use of surface water irrigation for sustainable intensification in deltaic environments like southern Bangladesh.

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The Cereal Systems Initiative for South Asia - Mechanization and Irrigation (CSISA-MI) initiative is a partnership between CIMMYT and International Development Enterprises (iDE), and is funded by USAID under President Obama's Feed the Future (FtF) Initiative. CSISA-MI seeks to transform agriculture in southern Bangladesh by unlocking the productivity of the region's farmers during the dry season through surface water irrigation, efficient agricultural machinery, and local service provision. CSISA-MI is part of the wider CSISA program in Bangladesh (CSISA-BD), which is a partnership between CIMMYT, the International Rice Research Institute (IRRI), and The World Fish Center. We are proud of the collaboration with the Bangladesh Agricultural Research Institute (BARI) that makes these aims possible.

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