

# Performance Characteristics of a Small Hammer Head Pump

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## Abstract:

Many rural farming areas are located far from reliable electricity supply, hence, having a reliable source of water for crops and livestock can prove to be an expensive venture. A water pump operating on the water hammer effect requires no external power source and can serve as an effective means of pumping water to a higher altitude once a reliable supply is available. ~~The~~ A low-cost small hammer-head pump was designed to operate on the hammer head effect created by the sudden stoppage of a flowing fluid. This design consisted of an inlet section followed by the pump body, a pressure section and an outlet. The experimental set-up for testing the hammer head pump was designed with a variable head input and an adjustable head output. For each test configuration, ten samples of pump supply water and pump ~~waste~~ exhausted water were collected. The water samples were collected for 30s in each case. The results showed ~~delivered~~ a non-linear variation of water flow ~~rate varied according to a cubic variable~~ with respect to pump outlet height. The pump was capable of delivering water to a maximum height of 8 to 10 times the height of the input head. The pump operated at average efficiencies of 26%, 16% and 6% when the delivery height was twice, four times and six times the input head, respectively. There was a 5% incremental decrease in pump efficiency as the delivery height increased in increments of the corresponding input head height.

## Keywords:

~~Pump characteristic, hammer~~ Hammer head, hydraulic ram, water pump.

## Introduction

The first type of pumps to use the water hammer effect was the hydraulic ram pump which was reported in 1775 and was built by John Whitehurst [1]. His design was not automatic and was controlled by manually opening and closing a stopcock which resulted in the device only being able to raise water to a height of 4.9 meters. This involved a significant amount of work and consumed a lot of time to operate. However, in 1797 the design was improved and the first reported automatic hydraulic ram was developed by Joseph and Etienne Montgolfier to raise water to a paper mill [2]. Although this was an improved design it still contained design flaws which caused the air in the pressure chamber to dissolve or drop. In 1816 this problem was eliminated when Pierre Montgolfier designed the sniffer valve that reintroduced air into the chamber. This valve was 15 cm in radius and it was reported that the pump was able to raise water to 48 meters in height [3]. The automatic hydraulic ram has been used for centuries to lift water to heights over 100 meters and was considered an effective and highly reliable machine for pumping water once certain conditions are satisfied. The pump construction was simple and consisted of a pump chamber fitted with two moving parts, an impulse valve through which the driving water was wasted and a delivery valve through which the water was delivered [4]. It worked solely on the power supplied from the water

40 head in the source. This source could be a spring, streams, river, ponds, dam, lakes and even some wells, once the conditions existed for these water sources to create a hydraulic flow head, either by forming a dam or a naturally existing head. Basically, once a hydraulic head can be created, the pump can operate, however, the source must provide a steady and reliable supply of water [5]. The ram pump must be installed at a location lower than the water source which was used to create the flow giving the fluid (water) some velocity.

45 In many rural farming areas, having a reliable source of water for crops and livestock can prove to be an expensive venture. ~~Especially in developing countries, farmland are located far from any reliable source of electricity, however, situated close to a water source.~~ In developing and under-developed countries, farmlands are ideally located close to a reliable water source to ensure viability [6, 7]. However, in many instances these locations are far from any reliable source of electricity and the cost can be prohibitive [6, 8]. The alternative of diesel-driven pumps create high operation costs and are prone to service gaps due to insufficient fuel supply and technical defects. A reliable and cost-effective supply of irrigation water is therefore a core problem in many rural areas in developing and emerging countries [9]. In cases where ~~The~~ the water source is ~~usually~~ situated below the level of the farmlands, ~~and~~ getting the water to where it is needed can be challenging [7]. Under these circumstances, ~~A~~ a water pump operating on the water hammer effect and requires no external power source ~~and~~ can serve as an effective means of pumping water to a higher altitude once a reliable source is available. Also, in under developed countries, such as 55 Haiti, the feasibility of using small hammer head pumps to provide clean water for citizens were explored by Prude University [10]. The ram pump can operate 24/7 and hence a water storage facility, such as storage tanks, at the water delivery end will be needed. This will serve as the reservoir to supply the needs when required. The major hindrance in using this established technology in third world countries is the exorbitant cost of the commercially available units. For a UK built pump the cost is US\$ 1800 [11] and cheaper china made pumps range between US\$500 to US\$1300 [12]. One of the objectives of the Prude University project in Haiti was to develop a cheaper alternative, however, the cost was US\$100 60 [10]. Therefore, there is the need to develop a low cost alternative that can be easily built from readily available construction materials and requires minimal technical skills.

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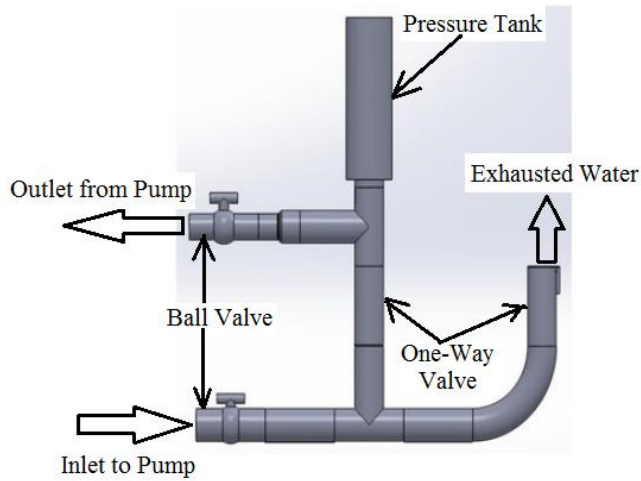
however, the source must provide a steady and reliable supply of water [5]. The ram pump is ideally installed at a location lower than the water source which is used to create the flow giving the fluid (water) some velocity.

80 Given the long history of the hydraulic ram pump, the design and manufacture has improved considerably with time and efficiency of operation increased. For commercial ram pumps the typical energy efficiency is about 60%, but can reach up to 80% [13]. This is different from the volumetric efficiency, which relates the volume of water delivered to total water taken from the source. The amount of water delivered will be reduced by the ratio of the output head to the supply head. For example, if the source is 2 meters above the ram pump and the water is lifted to 10 meters above, only 20% of the supplied water will be available and the other 80% being spilled via the exhaust valve [14]. These ratios assumed 100% energy efficiency. 85 The actual water delivered will be reduced further by the energy efficiency. Hence, for an energy efficiency of 70%, the water delivered will be 70% of 20%, which yields 14% [14, 15]. Suppliers of ram pumps often provide tables giving expected volume ratios based on actual tests. The amount of water delivered to the end for use will depend on source flow, height of supply reservoir above pump, height of delivery site above pump, length and size of delivery pipe and drive line, pump efficiency, and size of pump [15, 16, 17]. Considering the many combinations of these variables, the amount of water that can be delivered vary significantly. For example, delivery output from a single 2" ram pump system can range from a low of 17 gallons per day to 4,000 gallons per day or more [17].

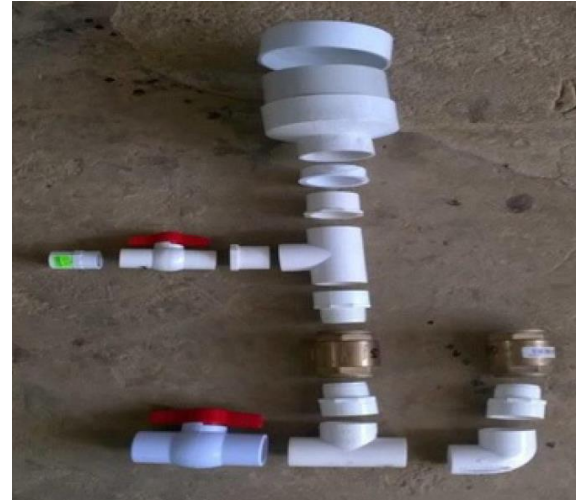
95 Apart from the delivery output of the hydraulic ram pump depending on many variables the design itself is complicated by the three pipe flow system and the hydraulic ram effect [18]. The delivery output is a non-linear relationship with variables of input head and output head. Therefore, for a specific hydraulic ram pump, determining the delivery output at variable input and output head heights will be a critical factor in determining the applicability, suitability and effectiveness for use. This study investigates the performance characteristics of a low cost hydraulic ram pump with input and delivery head height variation and quantify the change in efficiency of delivered water. 100

### **Pump Design and Construction**

105 The small hammer-head pump was designed to operate on the hammer head effect created by the sudden stoppage of a flowing fluid. The main components of the pump operation involved two one-way valves and a pressure tank. The one-way valves were arranged such that when one closes the other opened and vice-versa. This design consists of an inlet section followed by the pump body, a pressure section and finally an outlet. A 24.5mm PVC ball valve was installed at the inlet section which allowed control of the water entering the body of the pump and facilitated priming of the pump. The pump was constructed using 32mm diameter PVC pipe and valves. The advantages of this material were the low cost, low coefficient of friction and the resistance to corrosion. The Brass one-way swing valves were used in the design of brass construction. Another 13mm PVC ball valve was placed on the outlet pipe of the pump to prevent back-flow and drainage of the supplied water when the pump was not operating. Figure 1 is a schematic showing the main components of the pump design. 110

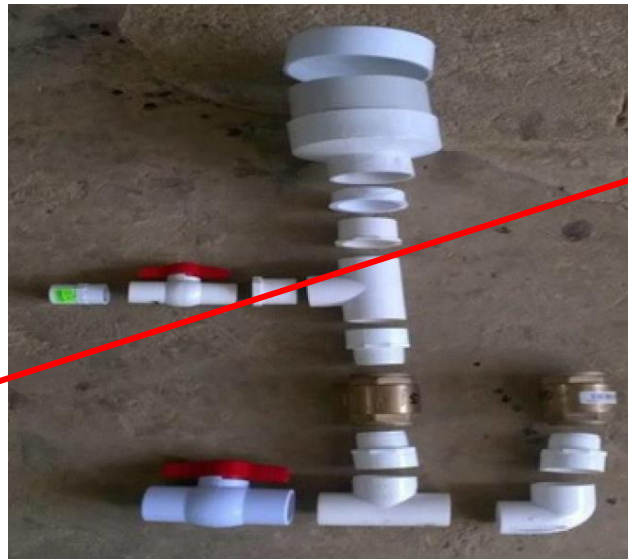


**Fig. 1** Schematic of Hammer Head Pump



**Fig. 2** Picture of pump components

The pressure tank was constructed using a 127mm long 75mm diameter PVC pipe. A PVC end caps was used on one end of the pipe and reduction PVC fittings on the other end attached to the 32mm pipe. Figure 2 is a picture of the pump components in the position for assembly.



**Fig. 2** Picture of pump components

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The materials/components required for the pump construction were obtained from the local hardware store. The cost of the components for the pump construction are shown in table 1. The total cost of the pump components was TT\$178, equivalent to US\$ 26.

Table 1: Cost of Pump Components

Component	TT\$ (Trinidad and Tobago dollars)
2 One way swing valve (brass)	70
1 25.4mm PVC ball valve	15
50cm PVC pipe (32mm diameter)	5
1 13mm PVC ball valve	10
50cm PVC pipe (75mm diameter)	10
2 PVC end caps (75mm diameter)	12
1 PVC reducer 75mm to 32mm	8
1 PVC reducer 25.4mm to 13mm	3
3 male adapters 32mm	9
1 PVC elbow 32mm	4
2 PVC 'T' 25.4mm/32mm	20
1 PVC male adapter 13mm	2
1 PVC glue 50 ml	10

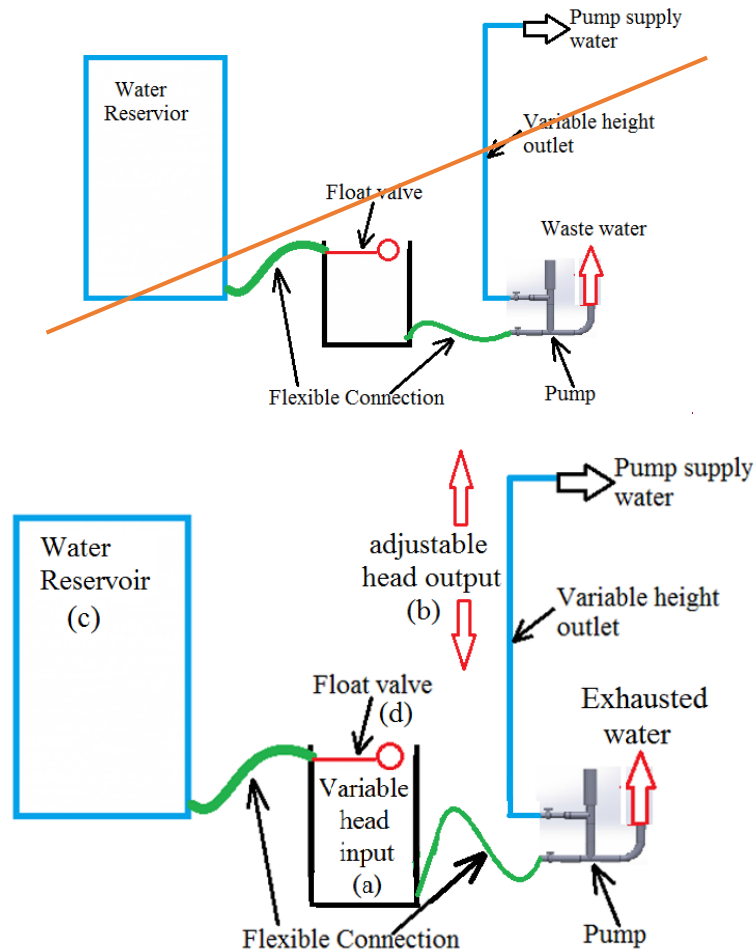
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### Experimental Set-Up

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Figure 3 shows a schematic of the experimental apparatus. The experimental set-up for testing the hammer head pump was designed with a variable head input (a) and an adjustable head output (b). The water supply ~~of water~~ was from a 5000L ~~storage tank~~ water reservoir (c). The constant head supply tank was designed with a float (d) that maintained the constant water level as water was supplied to the inlet of the pump. The input head was the difference in height between the inlet of the pump and the water level at the top of the constant head supply tank. The outlet side of the pump used variable length of 13mm diameter PVC pipe to adjust the delivery height (b). ~~Figure 3 shows a schematic of the experimental apparatus.~~

145



**Fig. 3** Schematic of Experimental Set-up

150 The water supplied by the pump was collected at fixed time intervals during operation and the volume measured with a 2000ml measuring cylinder with an accuracy of  $\pm 20\text{ml}$  to determine the pump supply flow rate. The ~~waste-~~ exhausted water from the pump ~~-exhaust~~ was also collected at fixed time intervals during operation and the volume measured with a 2000ml measuring cylinder with an accuracy of  $\pm 20\text{ml}$  to determine the pump ~~waste-~~ exhausted water flow rate.

155 **Experimental Results**

Experiments were conducted by varying the input head of the water at between 30 cm to 150 cm in increments of 30cm ~~intervals~~. At each corresponding input head the pump outlet height was varied between 60cm to 600cm in increments of 60cm ~~intervals~~. For each test configuration, ten samples of pump supply water and pump ~~waste-~~ exhausted water were collected. The water samples were collected for 30s in each case. The volume of water for each sample was measured and the average volume flow rate for the ten samples calculated. This procedure was repeated for each combination of supply head and pump outlet height. The calculated results were tabulated and shown on Tables ~~1~~ 2 and ~~2~~ 3.

Table 2: Pump output water flow rate variation with input head and outlet height

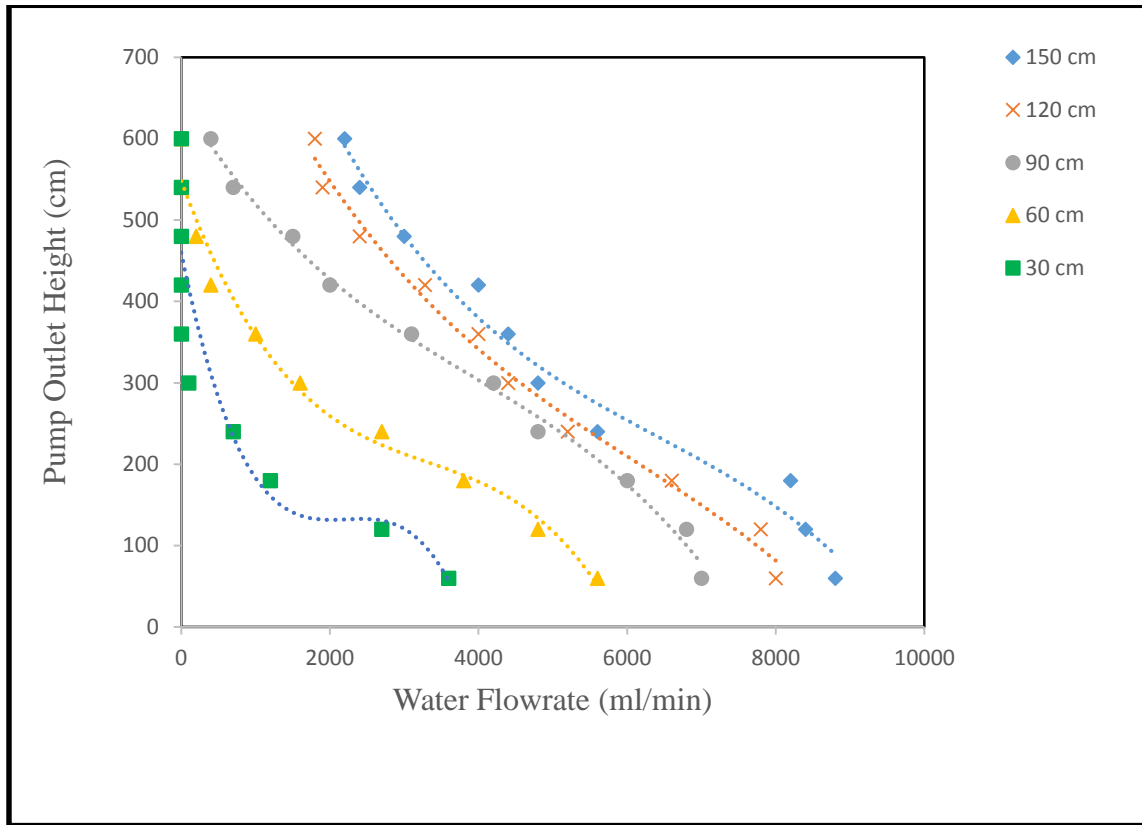
Input Head (cm)	Pump Outlet Height (cm)									
	60	120	180	240	300	360	420	480	540	600
	Water Flow Rate at Pump Outlet (Pump Supply Water) (ml/min)									
30	3600	2700	1200	700	100	0	0	0	0	0
60	5600	4800	3800	2700	1600	1000	400	200	0	0
90	7000	6800	6000	4800	4200	3100	2000	1500	700	400
120	8000	7800	6600	5200	4400	4000	3280	2400	1900	1800
150	8800	8400	8200	5600	4800	4400	4000	3000	2400	2200

Table 3: Pump ~~waste~~ exhausted water flow rate variation with input head and outlet height

Input Head (cm)	Pump Outlet Height (cm)									
	60	120	180	240	300	360	420	480	540	600
	Water Flow Rate at Pump Exhaust (Pump Waste Water) (ml/min)									
30	11600	11200	16400	10600	10500	0	0	0	0	0
60	12800	12800	15000	12600	12600	12600	12400	12400	12400	12400
90	13800	13800	13600	13600	13600	13400	13400	13200	13200	13200
120	14800	15200	12800	15000	14800	14800	14400	14400	14400	14400
150	16000	16000	11000	16400	16000	15600	15200	15000	14800	14400

### Analysis and Discussion

The simple construction low cost water hammer pump showed that as the delivery head increased the rate of water delivered decreased for the five input head height tested. For the lowest input head of 30 cm, the pump operated up to a maximum height of 300 cm. No water was delivered beyond this height. For input head of 60 cm, the pump operated up to a maximum height of 480 cm. No water was delivered beyond this height. For input head of 90 cm, 120 cm and 150 cm, the pump delivered water up to the maximum test height of 600 cm. A plot of the data points indicated a non-linear relationship between pump outlet height and delivered water flow rate and the regression analysis are as shown on the graph in Figure 4. This observation is in agreement with published literature [16, 18, 19].



**Fig. 4** Graph of supply water flow rate vs pump outlet height for various input head

The regression equations indicated the rate at which water was delivered with pump outlet height followed an  $x^3$  variation. This corroborated the experimental data which showed that as pump outlet height decreased, there was a slow increase in delivered water flow rate. This was followed by an increase in delivered water flow rate with a close-to a linear variation. This observation is in agreement with published literature [17, 18]. As the pump outlet height dropped lower than 120 cm, there was a decrease in the delivered water flow rate. The regression equations corresponding to the various input head heights are given in equations 1 to 5.

Input head; 150 cm:  $y = (-2 \times 10^{-9})x^3 + (4 \times 10^{-5})x^2 - 0.2999x + 1082.80$   $R^2 = 0.9772$  .....(1)

Input head; 120 cm:  $y = (-1 \times 10^{-9})x^3 + (3 \times 10^{-5})x^2 - 0.2247x + 900.54$   $R^2 = 0.9882$  .....(2)

Input head; 90 cm:  $y = (-2 \times 10^{-9})x^3 + (2 \times 10^{-5})x^2 - 0.1513x + 648.43$   $R^2 = 0.9946$  .....(3)

Input head; 60 cm:  $y = (-7 \times 10^{-9})x^3 + (7 \times 10^{-5})x^2 - 0.2493x + 548.37$   $R^2 = 0.9820$  .....(4)

Input head; 30 cm:  $y = (-3 \times 10^{-8})x^3 + 0.0002x^2 - 0.4515x + 460.20$   $R^2 = 0.8242$  .....(5)

The regression equations with the exception of the 30 cm input head equation indicated an  $R^2$  fit of more than 0.97.



190 The pump efficiency was determined from the ratio of the water delivered to the total water flow. The values were calculated and tabulated on Table 3 4.

Table 3 4: Pump efficiency variation with input head and outlet height

Input Head (cm)	Pump Outlet Height (cm)									
	60	120	180	240	300	360	420	480	540	600
	Pump efficiency (%)									
30	23.7	19.4	6.8	6.2	0.9	0	0	0	0	0
60	30.4	27.3	20.2	17.6	11.3	7.4	13.0	1.6	0	0
90	33.7	33.0	30.6	26.1	23.6	18.8	13.0	10.2	5.0	2.9
120	35.1	33.9	34.0	25.7	22.9	21.3	18.6	14.3	11.7	11.1
150	35.5	34.4	42.7	25.5	23.1	22.0	20.8	16.7	14.0	13.3

195 From the data for the 60 cm and 30 cm input head, the pump was capable of delivering water be between 8 to 10 times the input head with efficiencies of 1.6% and 0.9%, respectively. This was within the range of 5 to 25 times as published by U.S. department of agriculture natural resources conservation service [17]. The difference in delivery height capacity may be due to the shorter pipe length of 300 cm compared to 480 cm associated with the 30 cm and 60 cm input head, respectively. For the increased pipe length there would be increased frictional resistance to flow and the also increased gravitational force due to the higher water column. For input head ranging between 30 cm to 150 cm, the efficiency of the pump delivering water twice the input head height ranged from 23.1% to 30.6% with an average efficiency of 26%. For input head ranging between 30 cm to 150 cm, the efficiency of the pump delivering water four times the input head height ranged from 19.4% to 13.3% with an average efficiency of 16.6%. From the three sets of data available for input head ranging between 30 cm to 90 cm, the efficiency of the pump delivering water six times the input head height ranged from 5.0% to 7.4% with an average efficiency of 6.4%. The trend indicated that as the delivery height increased in increments of twice the corresponding input head, there ~~is~~ was a 10% decrease in efficiency. This observation is in conformity with the operation of the hydraulic ram pumps [19].

## Conclusions

- ~~A small scale hammer head pump operated effectively without any external energy input.~~
- The delivered water flow rate ~~varied according to a cubic variable~~ showed a non-linear variation with respect to pump outlet height.
- The pump was capable of delivering water to a maximum height of 8 to 10 times the height of the input head.
- The pump operated at average efficiencies of 26%, 16% and 6% when the delivery height was twice, four times and six times the input head, respectively.
- There was a 5% incremental decrease in pump efficiency as the delivery height increased in increments of the corresponding input head height.

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## Point-by-point reply to the comments

290 *The comments from reviewer 1 were constructive and served to improve the quality of the manuscript. The comments are addressed below.*

295 **Referee comment:** *However, it lacks some (scientific) reasoning, which should be addressed in a next version of the manuscript. General comments: - A clear objective (and knowledge gap) at the end of the introduction is missing. It should be stated what the drawbacks of the previous designs was, what the research gap is and thus the research question*

**Author response:** (marked up manuscript lines 95-101)

300 Apart from the delivery output of the hydraulic ram pump depending on many variables the design itself is complicated by the three pipe flow system and the hydraulic ram effect [17]. The delivery output is a non-linear relationship with variables of input head and output head. Therefore, for a specific hydraulic ram pump, determining the delivery output at variable input and output head heights will be a critical factor in determining the applicability, suitability and effectiveness for use. This study investigates the performance characteristics of a low cost hydraulic ram pump with input and delivery head height variation and quantify the change in efficiency of delivered water.

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**Referee comment:** *A clear objective (and knowledge gap) at the end of the introduction is missing. It should be stated what the drawbacks of the previous designs was, what the research gap is and thus the research question –*

310 **Author response:** (marked up manuscript lines 54-63)

315 Also, in under developed countries, such as Haiti, the feasibility of using small hammer head pumps to provide clean water for citizens were explored by Prude University [9]. The ram pump can operate 24/7 and hence a water storage facility, such as storage tanks, at the water delivery end will be needed. This will serve as the reservoir to supply the needs when required. The major hindrance in using this established technology in third world countries is the exorbitant cost of the commercially available units. For a UK built pump the cost is US\$ 1800 [10] and cheaper china made pumps range between US\$500 to US\$1300 [11]. One of the objectives of the Prude University project in Haiti was to develop a cheaper alternative, however, the cost was US\$100 [9]. Therefore, there is the need to develop a low cost

320 alternative that can be easily built from readily available construction materials and requires minimal technical skills.

Also, above - marked up manuscript lines 95-101

**Referee comment:** *do not use words like “perfect”*

Author response: (marked up manuscript lines 33-35)

325 The automatic hydraulic ram has been used for centuries to lift water to heights over 100 meters and was considered an effective and highly reliable machine for pumping water once certain conditions are satisfied.

330 **Referee comment:** *explain how with “ponds”, “lakes”, and “wells”, “a form of flow can be created”*

Author response: (marked up manuscript lines 38-41)

335 This source could be a spring, streams, river, ponds, dam, lakes and even some wells, once the conditions existed for these water sources to create a hydraulic flow head, either by forming a dam or a naturally existing head. Basically, once a hydraulic head can be created, the pump can operate, however, the source must provide a steady and reliable supply of water [5].

**Referee comment:** *delete “construction”*

Author response: (marked up manuscript line 110)

Brass one-way swing valves were used in the design

340 **Referee comment:** *Figure 1 the word “exhausted water” and in Figure 3 “waste water” is used. Please synchronize and avoid the word “waste water” since this has another connotation. –*

Author response:

345 In the marked up manuscript version; the word **waste water** was replaced with **exhausted water** throughout the manuscript.

**Referee comment:** *explain to what reference the “input head” is related.*

**Author response:** (marked up manuscript lines 139-141)

350 The constant head supply tank was designed with a float (d) that maintained the constant water level as water was supplied to the inlet of the pump. The input head was the difference in height between the inlet of the pump and the water level at the top of the constant head supply tank.

**Referee comment:** *117-127, not of interest, so please delete.*

**Author response:** (marked up manuscript lines 178-189)

355 The equations were deleted from the revised marked up manuscript

**Referee comment:** *"explain if this was to be expected (and give reference) - 140-141,*

**Author response:** (marked up manuscript lines 194-196)

360 From the data for the 60 cm and 30 cm input head, the pump was capable of delivering water be between 8 to 10 times the input head with efficiencies of 1.6% and 0.9%, respectively. This was within the range of 5 to 25 times as published by U.S. department of agriculture natural resources conservation service [16].

**Referee comment:** *explain if this was to be expected (and give reference)"*

365 **Author response:** (marked up manuscript lines 204-206)

The trend indicated that as the delivery height increased in increments of twice the corresponding input head, there ~~is~~ was a 10% decrease in efficiency. This observation is in conformity with the operation of the hydraulic ram pumps [18].

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*The comments from reviewer 2 were constructive and served to improve the quality of the manuscript. The comments are addressed below.*

**Referee comment:** *The topic of affordable technology for farmers, that deliver certain services or benefits to them, is of interest. As such, new designs are more than welcome, as long as they are able to show why they are worth being pursued. I am sorry to say that this aspect is missing from the current paper. Experience with hydro-powered pumps is rather extensive already, and as such one can certainly argue that any new design needs to clarify why its newness brings added value - which could be financial, because it is cheap, or functional, because it delivers water in a specific way, or relate to maintenance, as the pump is easy to repair. None of these aspects are discussed.*

Author response: (marked up manuscript lines 54-63)

Also, in under developed countries, such as Haiti, the feasibility of using small hammer head pumps to provide clean water for citizens were explored by Prude University [9]. The ram pump can operate 24/7 and hence a water storage facility, such as storage tanks, at the water delivery end will be needed. This will serve as the reservoir to supply the needs when required. The major hindrance in using this established technology in third world countries is the exorbitant cost of the commercially available units. For a UK built pump the cost is US\$ 1800 [10] and cheaper china made pumps range between US\$500 to US\$1300 [11]. One of the objectives of the Prude University project in Haiti was to develop a cheaper alternative, however, the cost was US\$100 [9]. **Therefore, there is the need to develop a low cost alternative that can be easily built from readily available construction materials and requires minimal technical skills.**

(marked up manuscript lines 108-110)

The pump was constructed using 32mm diameter PVC pipe and valves. The advantages of this material were ~~the~~ low cost, low coefficient of friction and the resistance to corrosion. ~~The~~ Brass one-way swing valves were used in the design ~~of brass construction~~.

(marked up manuscript lines 95-101)

Apart from the delivery output of the hydraulic ram pump depending on many variables the design itself is complicated by the three pipe flow system and the hydraulic ram effect [17]. The delivery output is a non-linear relationship with variables of input head and output head. Therefore, for a specific hydraulic ram pump, determining the delivery output at variable input and output head heights will be a critical factor in determining the applicability, suitability and effectiveness for use. This study investigates the

405 performance characteristics of a low cost hydraulic ram pump with input and delivery head height variation and quantify the change in efficiency of delivered water.

410 **Referee comment:** *The design, the analysis and the numerical statements that are presented remain rather difficult to value when we do not find any information about user prospects, robustness in daily practices, etcetera. I do not want to suggest that the authors need to engage in full-scale field tests first before they can present their own designs. However, just dropping a design with some numbers without explaining why this particular design would be of interest for any target group, is not really appropriate.*

**Author response:** above section (marked up manuscript lines 54-63)

415 **Referee comment:** *Are the different test settings in any way realistic, when we would consider farming practices? Is the discharge in any way useful? What type of use do the authors assume? What additional equipment would a farmer need to make the pump a viable asset on a farm? As long as these question are not at least considered, the information in the paper remains obscure.*

**Author response:** (marked up manuscript lines 54-58)

420 Also, in under developed countries, such as Haiti, the feasibility of using small hammer head pumps to provide clean water for citizens were explored by Prude University [9]. The ram pump can operate 24/7 and hence a water storage facility, such as storage tanks, at the water delivery end will be needed. This will serve as the reservoir to supply the needs when required.

(marked up manuscript lines 96-101)

425 The delivery output is a non-linear relationship with variables of input head and output head. Therefore, for a specific hydraulic ram pump, determining the delivery output at variable input and output head heights will be a critical factor in determining the applicability, suitability and effectiveness for use. This study investigates the performance characteristics of a low cost hydraulic ram pump with input and delivery head height variation and quantify the change in efficiency of delivered water.

430 **Referee comment:** *A final comment may relate to the number of references. In general, one cannot easily decide what six references mean, but in this case - given the rather high number of documents available on hydro-powered pumps - one would expect a few more references.*

**Author response:** (marked up manuscript lines 218-270)

The number of references were increased to 1

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435 *The comments from reviewer 3 were constructive and served to improve the quality of the manuscript. The comments are addressed below.*

440 **Referee comment:** *General Comments: Hydrams, since their invention more than two centuries ago, have been attracting many researchers around the world. Therefore it is a relevant topic, but at the same time challenging while pursuing for innovation. In this sense, I suggest the authors to highlight as much as possible the actual contribution of their article to this specific field of knowledge. Maybe that contribution is more focused on the easiness of construction and installation, perhaps to its size or maybe to the ratio size / efficiency.*

**Author response:** (marked up manuscript lines 58-63)

445 The major hindrance in using this established technology in third world countries is the exorbitant cost of the commercially available units. For a UK built pump the cost is US\$ 1800 [10] and cheaper china made pumps range between US\$500 to US\$1300 [11]. One of the objectives of the Prude University project in Haiti was to develop a cheaper alternative, however, the cost was US\$100 [9]. Therefore, there is the need to develop a low cost alternative that can be easily built from readily available construction materials and requires minimal technical skills.

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(marked up manuscript lines 128-133)

The materials/components required for the pump construction were obtained from the local hardware store. The cost of the components for the pump construction are shown in table 1. The total cost of the pump components was TT\$178, equivalent to US\$ 26.

Component	TT\$ (Trinidad and Tobago dollars)
2 One way swing valve (brass)	70
1 25.4mm PVC ball valve	15
50cm PVC pipe (32mm diameter)	5
1 13mm PVC ball valve	10
50cm PVC pipe (75mm diameter)	10
2 PVC end caps (75mm diameter)	12

1	PVC reducer 75mm to 32mm	8
1	PVC reducer 25.4mm to 13mm	3
3	male adapters 32mm	9
1	PVC elbow 32mm	4
2	PVC 'T' 25.4mm/32mm	20
1	PVC male adapter 13mm	2
1	PVC glue 50 ml	10

455 **Referee comment:** *On the other hand, a main part not explicitly addressed in the introduction is the research gap and the consequent research objective. Therefore it is difficult to link the C1 DWESD Interactive comment Printer-friendly version Discussion paper concluding remarks to the general work.*

**Author response:** (marked up manuscript lines 46-59)

460 In developing and under-developed countries, farmlands are ideally located close to a reliable water source to ensure viability [6, 7]. However, in many instances these locations are far from any reliable source of electricity and the cost can be prohibitive [6, 8]. –In cases where ~~The~~ the water source is **usually** situated below the level of the farmlands, ~~and~~ getting the water to where it is needed can be challenging [7]. Under these circumstances, ~~A~~ a water pump operating on the water hammer effect and requires no external power source ~~and~~ can serve as an effective means of pumping water to a higher altitude once a reliable source is available. Also, in under developed countries, such as Haiti, the feasibility of using small hammer head pumps to provide clean water for citizens were explored by Prude University [9]. The ram pump can operate 24/7 and hence a water storage facility, such as storage tanks, at the water delivery end will be needed. This will serve as the reservoir to supply the needs when required. The major hindrance in using this established technology in third world countries is the exorbitant cost of the commercially available units.

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475 **Referee comment:** *Moreover, it is highly recommended to keep the traditional structure of a scientific article: Introduction, Materials and methods, Results, Discussion, Conclusion. That aside, it makes more sense to have the "Pump Design and Construction" and "Experimental Set-Up" sections being part of Materials and methods.*

Author response: In my opinion, I would prefer to leave the manuscript in the format presented, unless it is a mandatory requirement of the journal format.

480 **Referee comment:** L. 26: *Not all the farmlands in the world meet the condition of being far from an electricity source yet close to a water source. Maybe a word like "usually" or "mostly" could fit, as long as evidence is provided for such an affirmation.*

Author response: (marked up manuscript lines 44-51)

485 In many rural farming areas, having a reliable source of water for crops and livestock can prove to be an expensive venture. ~~Especially in developing countries, farmland are located far from any reliable source of electricity, however, situated close to a water source.~~ In developing and under-developed countries, farmlands are ideally located close to a reliable water source to ensure viability [6, 7]. However, in many instances these locations are far from any reliable source of electricity and the cost can be prohibitive [6, 8]. The alternative of diesel-driven pumps create high operation costs and are prone to service gaps due to insufficient fuel supply and technical defects. A reliable and cost-effective supply of irrigation water is therefore a core problem in many rural areas in developing and emerging countries [9].

490 **Referee comment:** L. 26: *It is better to explain why the relevance of being far from electricity sources, i.e. why is it a challenge/problem for farming. Besides, please think of what happens with diesel-based pumps, which do not rely on electricity.*

495 Author response: (marked up manuscript lines 44-51) above

**Referee comment:** L. 27: *Is there evidence for stating "The water source is usually situated below the level of the farmlands"? Or perhaps it is better to say something more general, such as "there are cases where the water source..."*

Author response: (marked up manuscript lines 51-52)

500 In cases where ~~The~~ the water source is ~~usually~~ situated below the level of the farmlands, ~~and~~ getting the water to where it is needed can be challenging [7].

505 **Referee comment:** L. 28: *There is the need of an introductory / transition sentence before "A water pump operating on the water hammer effect...". I suggest to introduce the reader why it is a challenge being far from electricity, and what can be done using hydropower. Then the explanation of the hydraulic ram pump will fit better in the storyline.*

Author response: (marked up manuscript lines 44-54)

510 In many rural farming areas, having a reliable source of water for crops and livestock can prove to be an expensive venture. ~~Especially in developing countries, farmland are located far from any reliable source of electricity, however, situated close to a water source.~~ In developing and under-developed countries, farmlands are ideally located close to a reliable water source to ensure viability [6, 7]. However, in many instances these locations are far from any reliable source of electricity and the cost can be prohibitive [6, 8]. The alternative of diesel-driven pumps create high operation costs and are prone to service gaps due to insufficient fuel supply and technical defects. A reliable and cost-effective supply of irrigation water is therefore a core problem in many rural areas in developing and emerging countries [9]. In cases where ~~The~~ the water source is ~~usually~~ situated below the level of the farmlands, ~~and~~ getting the water to where it is needed can be challenging [7]. Under these circumstances, ~~A~~ a water pump operating on the water hammer effect and requires no external power source ~~and~~ can serve as an effective means of pumping water to a higher altitude once a reliable source is available.

520 **Referee comment:** *Ls. 31-38: The historic introduction, particularly if it does not go beyond the work done by Pierre Mongolfier, must be briefly summarized. Its constructive details are not relevant for the scope of the paper.*

Author response: (marked up manuscript lines 24-35)

525 The first type of pumps to use the water hammer effect was the hydraulic ram pump which was reported in 1775 and was built by John Whitehurst [1]. His design was not automatic and was controlled by manually opening and closing a stopcock which resulted in the device only being able to raise water to a height of 4.9 meters. This involved a significant amount of work and consumed a lot of time to operate. However, in 1797 the design was improved and the first reported automatic hydraulic ram was developed  
530 by Joseph and Etienne Montgolfier to raise water to a paper mill [2]. Although this was an improved design it still contained design flaws which caused the air in the pressure chamber to dissolve or drop. In 1816 this problem was eliminated when Pierre Montgolfier designed the sniffer valve that reintroduced air into the chamber. This valve was 15 cm in radius and it was reported that the pump was able to raise water to 48 meters in height [3]. The automatic hydraulic ram has been used for centuries to lift water to  
535 heights over 100 meters and was considered an effective and highly reliable machine for pumping water once certain conditions are satisfied.

**Referee comment:** *L. 39: In principle, no machine can be considered "perfect". Furthermore, what are the criteria to be considered as such? I recommend to use expressions like "highly reliable", or any other that reflects its degree of development. In addition, hydrams, compared to other similar technologies, are*

540 *subject to constant wearing due to the aggressiveness of the water hammer effect, which is in turn their main drawback.*

Author response: (marked up manuscript lines 33-35)

545 The automatic hydraulic ram has been used for centuries to lift water to heights over 100 meters and was considered an effective and highly reliable machine for pumping water once certain conditions are satisfied.

**Referee comment:** *L. 41: It mentions "water was wasted", whereas the Fig. 1 refers to "exhausted water". It is important to keep consistency in the nomenclature, and making sure it matches with the usual terminology in the literature (e.g. "A Manual On The Hydraulic Ram For Pumping Water" by S.B. Watt, or "Hydraulic Ram Pumps: A guide to ram pump water supply systems" by Jeffrey et al.)*

Author response:

In the marked up manuscript version; the word waste water was replaced with exhausted water throughout the manuscript.

555 **Referee comment:** *L. 43: About "once any form of flow can be created", it will be good to provide an insight on how this flow can be created after the different water sources, i.e. what kind of extra infrastructure it might need: dam, weir, drop, etc.*

Author response: (marked up manuscript lines 38-40)

560 This source could be a spring, streams, river, ponds, dam, lakes and even some wells, once the conditions existed for these water sources to create a hydraulic flow head, either by forming a dam or a naturally existing head.

**Referee comment:** *L. 44: The ram pump installed at a lower location than the water source is not an ideal scenario but a mandatory one. Otherwise the pump will not operate whatsoever.*

565 Author response: (marked up manuscript lines 41-43)

The ram pump must be installed at a location lower than the water source which was used to create the flow giving the fluid (water) some velocity.

570 **Referee comment:** L. 48-41: *This paragraph describes the generic structure of a Hydrum. I suggest to put that in the introduction, so in this section the specific parts and assembly methods of your prototype are directly described.*

**Author response:** In my opinion, I would prefer this paragraph to remain as is.

**Referee comment:** L. 61: *Figs 1 and 2 could be put side to side, so the reader can make a quick correspondence between the scheme and the actual prototype.*

575 **Author response:** This change was made.

**Referee comment:** L. 73-76: I recommend to match the parts of the experimental set-up, as described in this paragraph, with those of the Fig. 3, to make sure all of them can be identified in both graphic and text. A good way of achieving it could be by assigning letters or numbers to each part.

580 **Author response:** (marked up manuscript lines 137-142)

585 Figure 3 shows a schematic of the experimental apparatus. The experimental set-up for testing the hammer head pump was designed with a variable head input (a) and an adjustable head output (b). The water supply ~~of water~~ was from a 5000L ~~storage tank~~ water reservoir (c). The constant head supply tank was designed with a float (d) that maintained the constant water level as water was supplied to the inlet of the pump. The input head was the difference in height between the inlet of the pump and the water level at the top of the constant head supply tank. The outlet side of the pump used variable length of 13mm diameter PVC pipe to adjust the delivery height (b).

Figure 3 (marked up manuscript line 148)

590 **Referee comment:** L. 93: *I wonder if it would be more convenient to combine both tables 1 and 2 in a single one, due to their similar structure. In that case, each cell must be divided in two parts, for the pumped flow and wasted flow, respectively. Moreover, this can give the chance to include a third part: the pumped/wasted ratio; it can be eventually related to the pumping efficiency.*

595 **Author response:** An attempt was made to combine the tables, however, the data was too much to fit properly side-by-side on one table. Hence, the tables were left as is.

**Referee comment:** *L. 100 and next ones: The discussion part must be enriched by comparing your study with other ones, perhaps using similar prototypes in sizes and conditions. Of course, the respective literature and references must be taken into account while doing so.*

600 Author response: (marked up manuscript lines 169-206)

The findings from the study were compared with published literature and the appropriate comparison were made with respect to references [16] to [19] in the discussion section of the marked-up manuscript.

605 **Referee comment:** *L. 134: The first conclusion might be too obvious, after so many years of continuous and ubiquitous use of the hydrams, to be considered as such after the present study.*

Author response: (marked up manuscript line 209)

This conclusion was removed

➤ ~~A small scale hammer head pump operated effectively without any external energy input.~~

610 **Referee comment:** *Keywords: "Pump characteristic" is not a so accurate keyword for this study, since it does not suggest any possible topic*

Author response: (marked up manuscript lines 21-22)

**Keywords:**

~~Pump characteristic, hammer~~ Hammer head, hydraulic ram-, water pump.

615 **Referee comment:** *L. 26: Farmlands are (missing plural).*

Author response: (marked up manuscript line 46)

In developing and under-developed countries, farmlands are

620 **Referee comment:** *L. 37: The name of the son of Joseph Michel de Montgolfier, who improved his father's model, is Pierre (or Pierre François).; L. 37: "Montgolfier designed the sniffer valve that reintroduce..." It must be "reintroduced"*

Author response: (marked up manuscript line 31)

1816 this problem was eliminated when Pierre Montgolfier designed the sniffer valve that reintroduced

625

**Referee comment:** *L. 40: "The pump construction was simple and consisted of a pump chamber...". Do you refer to "chamber" perhaps?*

**Author response:** (marked up manuscript line 32)

air into the chamber.