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Performance evaluation of hydraulic ram pumping systems for small-scale farmers: a case study of West Pokot county, Kenya

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ABSTRACT

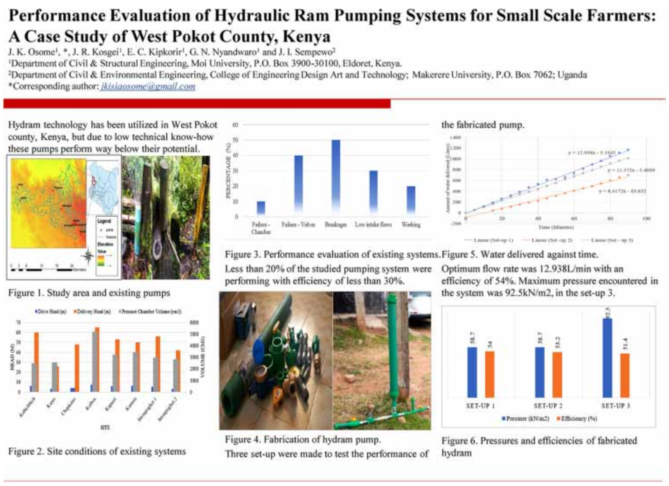
Hydraulic ram (hydram) pump has been in existence for more than two centuries. However, these pumps have been on the verge of extinction since the invention of motorized pumps, which are more powerful and efficient. Unfortunately, motorized pumps are expensive to acquire, operate, and maintain. Their contribution to climate change and environmental degradation has steered the need for an alternative pumping technology. Therefore, as the world's technology shifts to green energy, hydram pumps need to be re-invented. In the late twentieth century, studies on hydram pumps have been revived with the aim of making them more efficient and economically competitive. Small-scale farmers in West Pokot County, Kenya, have embraced the hydram technology, but due to low technical capacity; installed low-performing hydram that operated under low efficiencies of less than 30%, with the majority having operational failure due to inadequate designs. Hence, this study investigated the design and operation of these pumps. Thereafter, designed and assembled a hydram pump, using locally available materials, to supply water for domestic and small-scale agricultural use. The optimum efficiency achieved by the pump was 54%, with an optimum delivery flow rate of about 13 L/min.

Key words: efficiency, green energy, hydram, motorized pump, operational failure, optimum delivery flow rate

HIGHLIGHTS

- The locally installed hydraulic ram pumping system performs way below its potential due to low technical know-how.
- The study assesses the performance, thereafter, designs a prototype pump that can cheaply be fabricated by local farmers for irrigation.
- The fabricated pump exhibits higher efficiency compared to the existing hydraulic ram pumping systems.
- The study aims to make the pump economically competitive.

GRAPHICAL ABSTRACT



INTRODUCTION

Water is a basic commodity essential for human, industrial, and agricultural development (Januddi *et al.* 2018). The need for water has been the key motivation that drives humankind to venture ways of ensuring easy access to it through various pumping mechanisms (Mishra *et al.* 2018). The first self-pumping machine (hydram) that did not require external energy was invented in 1796 by the Montgolfier brothers (Mohammed 2007). These pumps were modified and utilized until the late nineteenth century after the invention of oil and electric-driven pumps (motorized pumps). Recently, the need for sustainable technology and renewable energy, especially in developing countries, has revived the interest in hydram technology (Kherde *et al.* 2020).

A hydraulic ram pump is a simple pump consisting of a pressure chamber, two main valves (impulse and delivery valves), and interconnecting pipes (Sheikh *et al.* 2013). The pump, with its simplicity, does not require external energy, either mechanical or electrical, to pump water (Harith *et al.* 2017). It utilizes the energy of water falling from a higher head, the drive head, to pump a portion of the same water to a higher head, the delivery head (Veljko *et al.* 2003). The operation of hydraulic ram pumps depends on the water hammer phenomenon that results from the sudden closure of the impulse valve (Tacke 1988) (see Figure 1). The water hammer effect generates waves that open the delivery valve and water is delivered to a higher head (Verspuy & Tijsseling 1993; Than *et al.* 2019) (see Figure 2). The operation of a hydram is intermittent due to the cyclic opening and closing of the waste and delivery valves (Januddi *et al.* 2018). The closure of the waste valve creates a high-pressure rise in the drive pipe. An air chamber is required to transform the high intermittent pumped flows into a continuous

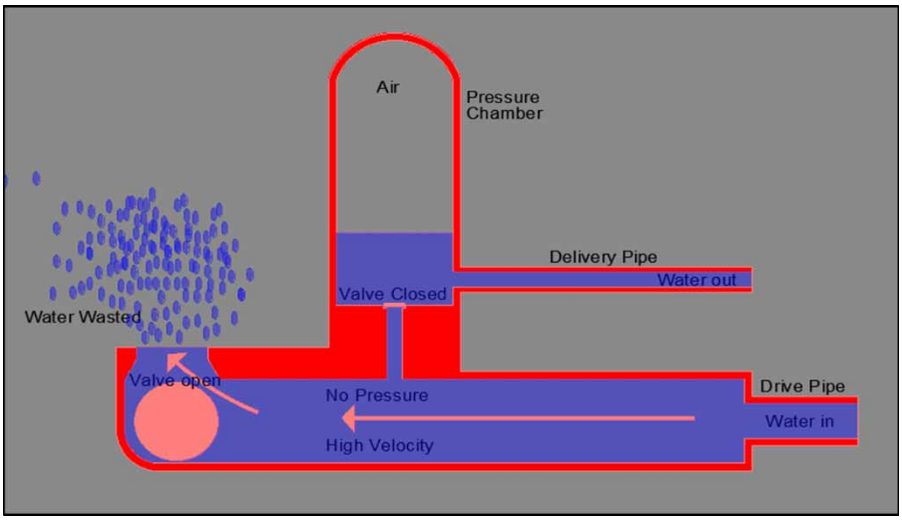


Figure 1 | Flow of water into the hydram.

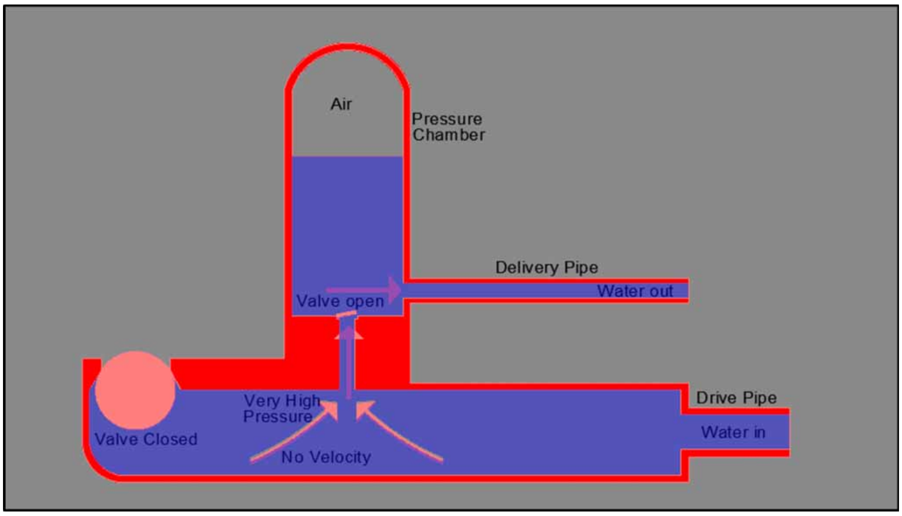


Figure 2 | Flow of water after sudden closure of the impulse valve.

stream of flow (Rajaonison & Rakotondramiarana 2019). The air valves allow air into the hydram to replace the air absorbed by the water due to the high pressure and mixing in the air chamber (Laxmi *et al.* 2015).

The effect of climatic change and global warming has adversely affected the water supply for domestic and agricultural use. The small-scale farmers who depend on rain-fed agricultural systems have incurred losses due to unreliable rainfall patterns (Ochieng *et al.* 2016). These farmers are unable to irrigate their farms due to their limited financial capabilities to acquire and operate oil or electric-powered pumping systems. The solution is to look for an alternative that is cheaper and more self-efficient, the hydraulic ram pumping system (Hussin *et al.* 2017). Therefore, a more reliable and cost-effective system for irrigation during unfortunate events and also to act as a water supply is required. The most appropriate system will be hydraulic ram pumps.

The hydram pumping system is not a new technology in West Pokot County, Kenya. The farmers have embraced the technology because the area is endowed with a good river network system with a good potential drive head for the pumping systems. The pumping systems in West Pokot are mainly used to supply water from the flowing rivers and streams for the purpose of domestic use and small-scale livestock farming. Unfortunately, the locals lack the technical know-how capacity of the hydram technology and therefore have fabricated and installed hydram pumps that were performing with low efficiencies. Therefore, this study investigated the existing hydraulic ram pumping systems in West Pokot County, Kenya, to assess these systems' design and performance characteristics. A low-cost hydram was designed and fabricated using locally available materials. The pump was tested by varying the drive and delivery head and its performance was assessed. The major limitation of the study was the behaviour of the existing pumps for different drive and delivery heads where they were installed. Similarly, the designed pump was observed for a limited number of drive and delivery heads with the assumption that the pump will simulate the actual site conditions.

Dhanwat *et al.* (2021) observed that hydram technology is the cheapest and most economical pump that can easily be fabricated since it consists of simple components which are readily available in the market suggesting that this technology is appropriate and sustainable for remote locations.

According to Mahmud & Rahman (2020), for a better output performance of a hydram pump, the drive length should be designed sufficiently to suit the site conditions. This is because the performance of the hydram strongly depends on the drive length. Since losses in the system can easily be predicted, one needs to effectively design the pump to suit the site conditions to ensure higher efficiencies are being achieved (Shende *et al.* 2015).

Inthachot *et al.* (2015) investigated the effect of different valves and pressure chamber sizes on pump performance. An off-shelf valve achieved an optimum efficiency of 30%. The larger pressure chamber achieved a higher efficiency. An overall optimum efficiency of 44% was achieved in the field. Iddi *et al.* (2018) found out that a larger pressure chamber with an additional weight on the drainpipe results in higher pump efficiency, while a smaller pressure chamber without additional weight achieved even higher efficiencies. According to Sethi *et al.* (2015), higher efficiency is obtained at higher drive heads with a lower delivery head than at lower drive heads. They concluded that the terrain conditions have an impact on the efficiencies of the pump.

METHODOLOGY

Existing hydraulic ram pumping systems

The investigation was conducted on eight hydraulic ram pumping systems identified in West Pokot County, Kenya. These sites were chosen based on their availability and accessibility. Figure 3 shows the existing sites that were studied. These sites include Karas, Kaibos, Chepkono, Kabichbich, Imonpoghet 1, Imonpoghet 2, Kamsis, and Kapsait. These systems were owned by individual members except the one found in Chepkono area which was a community-owned system. These systems were used to supply water for domestic purposes and for small-scale livestock farming.

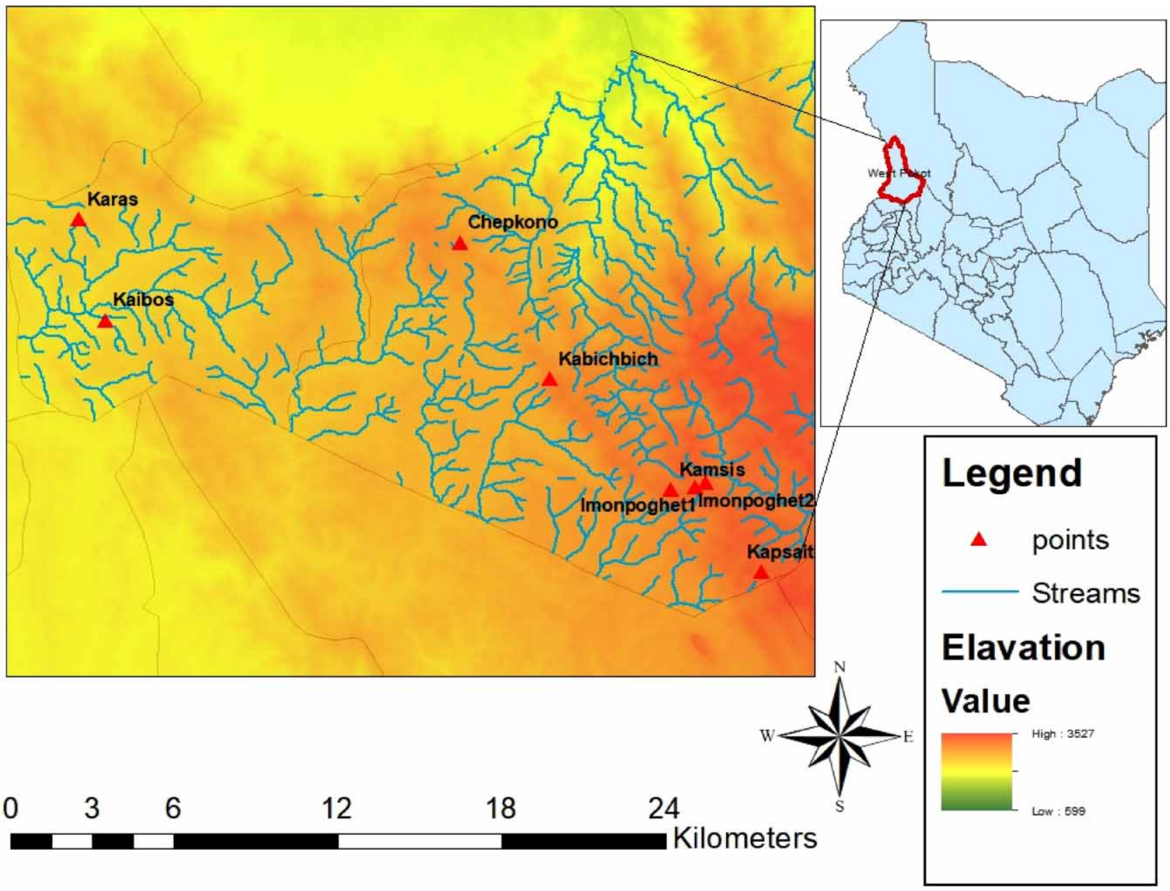


Figure 3 | Location of the existing eight hydram pumping systems that were studied.

The evaluation focused on the design and performance criteria of the eight pump systems. On design criteria, the following components were assessed: materials used for the system, the size of pump and pipe components, and the site conditions (stream flow rates, drive, and delivery head). The performance criteria included the efficiency of the system, failures, and breakages.

The existing pump was locally designed and fabricated by artisans. The process of determining the design and performance criteria of the eight existing hydram systems was as follows:

- Direct interview and interrogation of the owners of the sites.
- Observations and basic measurements.

Design criteria

The key components of design criteria that were necessary for this study were:

- Size of the pump which was determined by measuring the pressure chamber, the impulse, and the delivery valve. Tools used were the measuring tape and rope.
- Size of the drive and delivery pipes (both diameter and length) were measured using measuring tapes and rope.

- The drive and delivery heads were measured using GPS/GIS android applications.
- Stream flows were measured using a time–volume basis approach, by using a container of known volume and the time taken to fill the container measured.
- The material used for fabricating the system was determined through observation and interrogations.

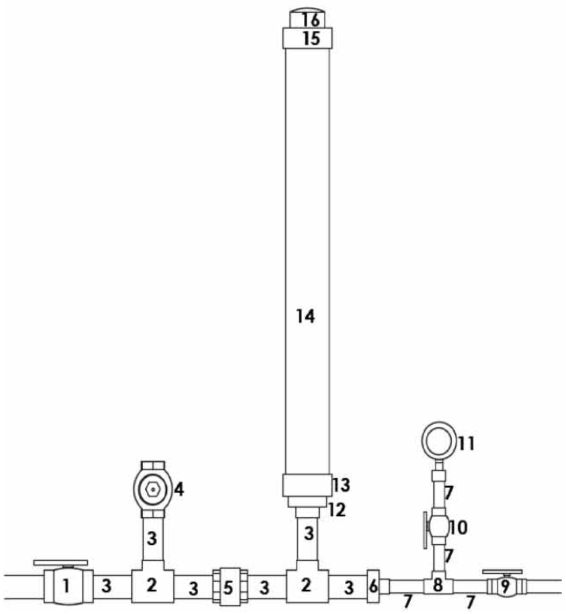
Performance criteria

The key components of performance criteria that were necessary for this study were:

- The pump efficiency was calculated after measuring the delivery flow rate using the time–volume basis approach. This was measured for a period of 1 hour for 3 days to establish the consistency of the results obtained.
- Amount of water delivered was determined by interrogating the individual owners.
- Failures and breakages were determined through observations and interrogation of the individual owners.

Construction and experimentation of the hydram pump

The hydram pump was designed following Pawlick *et al.* (2018) and Watt (1975) guidelines. Figure 4 shows a set-up of the hydram pump as done by Hussin *et al.* (2017). The designed system was fabricated using PP-R pipes and fittings and GI fittings, as shown in Figure 5 since these materials are cheaply available and they have similar strength capacity as steel to resist the pressures generated within the pump.



PIPE FITTINGS SCHEDULE

ITEM	DESCRIPTION	DIA (mm)	LENGTH (mm)	CLASS	QTY (No.)
1	VALVE	32		PN 16	1
2	ALL EQUAL TEE	32		PN 16	2
3	GI NIPPLE	32	100	PN 16	6
4	BRASS SWING CHECK VALVE	32		PN 25	1
5	SPRING CHECK VALVE	32		PN 16	1
6	REDUCER	32/20		PN 16	1
7	PPR PIPE PIECE	20	70	PN 16	2
8	ALL EQUAL TEE	20		PN 16	1
9	VALVE	20		PN 16	1
10	VALVE	12		PN 16	1
11	PRESSURE GAUGE (21 BAR)	12		PN 16	1
12	REDUCER	50/32		PN 16	6
13	REDUCER	90/63		PN 16	1
14	PPR PIPE PIECE	90	1000	PN 16	1
15	REDUCER	90/63		PN 16	1
16	PPR END CAP	63		PN 16	1

Figure 4 | Hydram schematic drawing for the designed hydram pump.

The drive head and the delivery head were the key parameters for investigation. The variation of both heads significantly affects the quantity of water delivered by the pump (Than *et al.* 2019).

Table 1 shows the drive heads and delivery heads used for the experimentation of the fabricated hydram.

RESULTS

The investigation of the existing eight hydram pumping systems showed that 87.5% of hydram pumps are made up of steel. The majority of the pumps were of size 80/40 mm configuration (i.e., the inlet pipe size 80 mm and outlet pipe size 40 mm) and 80/25 mm configuration (i.e., inlet pipe size 80 mm and outlet pipe size 25 mm) that constitute 50 and 37.5%, respectively, of the investigated pumps in West Pokot.

Figure 6 shows the distribution of the commonly used hydram sizes in the region under the study. Figure 7 shows the site conditions (drive and delivery heads) and the pressure chamber sizes of the existing systems.

Figure 5 | Fabrication of the hydram pump: (a) components and (b) complete hydram pump.

Table 1 | Experimental set-up parameters

Experimentation	Drive head (m)	Delivery head (m)
1	2.4	4.2
2	2.4	6.0
3	2.8	10.0

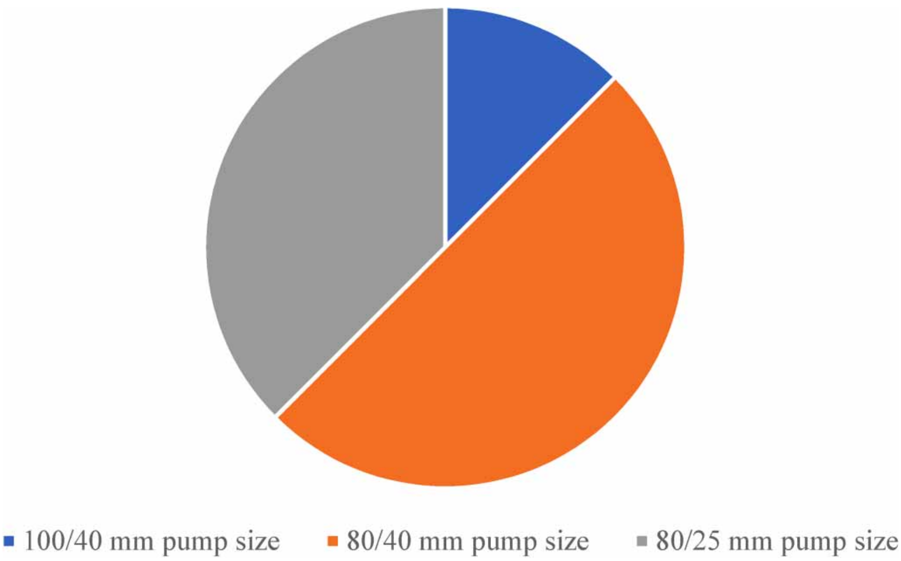


Figure 6 | Pump size commonly used in the study area.

All sites had drive heads less than 10 m with delivery heads of more than 40 m and pressure chamber volume of greater than 2,500 cm^3.

The performance criteria investigated the number of operational hydram pumps during the investigation, the failure mode (pressure chamber or impulse valve), intake flows, and breakages, as shown in Figure 8.

It was observed that 25% of the pumps were in working conditions, while 75% of the pumps were not working, of which 12.5% resulted from the failure of a pressure chamber, and 37.5% resulted from the failure of the valves.

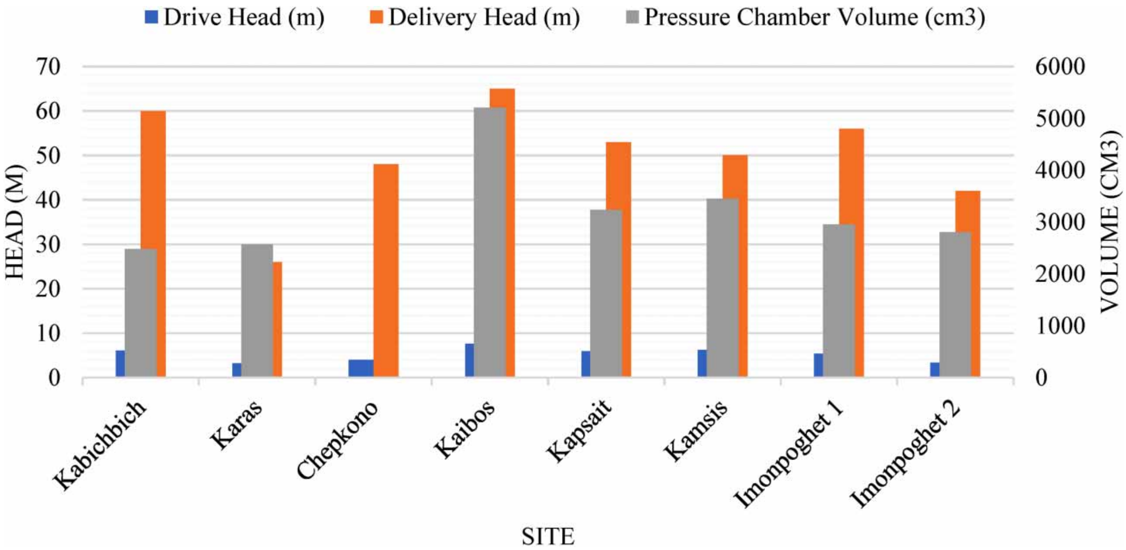


Figure 7 | Relationship between drive head, delivery head, and pressure chamber volume of existing eight hydram pumping systems.

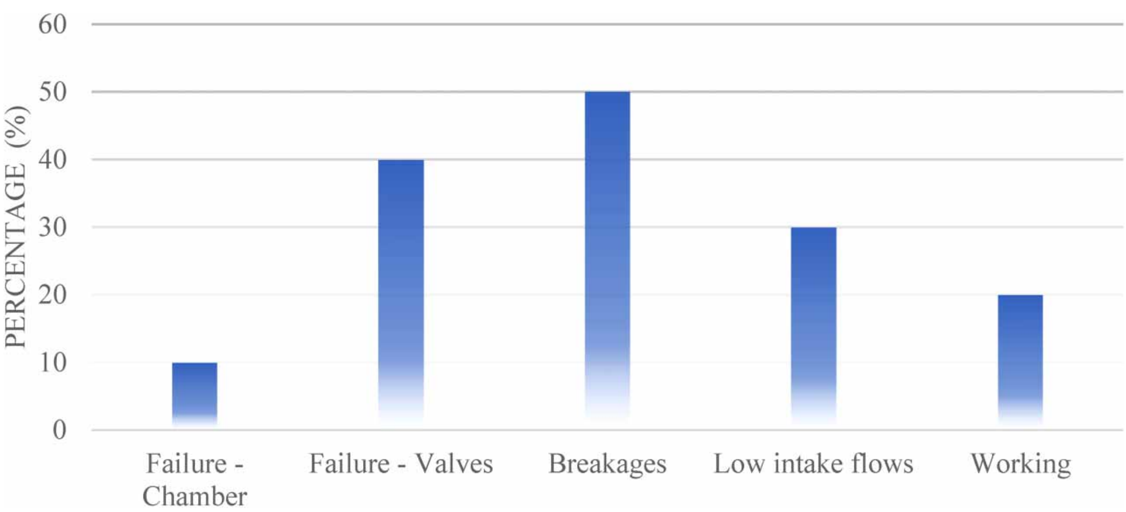


Figure 8 | Performance evaluation of existing eight hydram pumps.

These pumps had lower efficiencies of less than 30% due to inadequate design of the system meaning, their designs are not tailor-made to ensure pumps will be working as per site conditions (such as the drive head and the anticipated delivery heads) and pumping requirements that are the flow rates, build-up pressures, and the water velocities within the pump as a result of site conditions.

The designed and fabricated hydram pump was able to obtain higher delivery flow rates, as shown in Figure 9. For the three experiments, a higher flow rate of 12.938 L/min was obtained on set-up 1 with a drive head of 2.4 m and a delivery head of 4.2 m. For a higher drive head of 2.8 m and delivery head of 10 m, a flow rate of 11.372 L/min was obtained.

The rate of the amount of water wasted by the pump was higher at higher heads as compared to the lower heads. Figure 10 shows the amount of water wasted by the pump measured against time. A flow rate of 67.579 L/min was obtained at set-up 3 for the water wasted. This resulted from higher pressure generated in the pump hitherto required to pump water to higher delivery heads.

Figure 11 shows the average pressures and the efficiencies of the three experimental set-ups carried out using the designed and fabricated hydram pump.

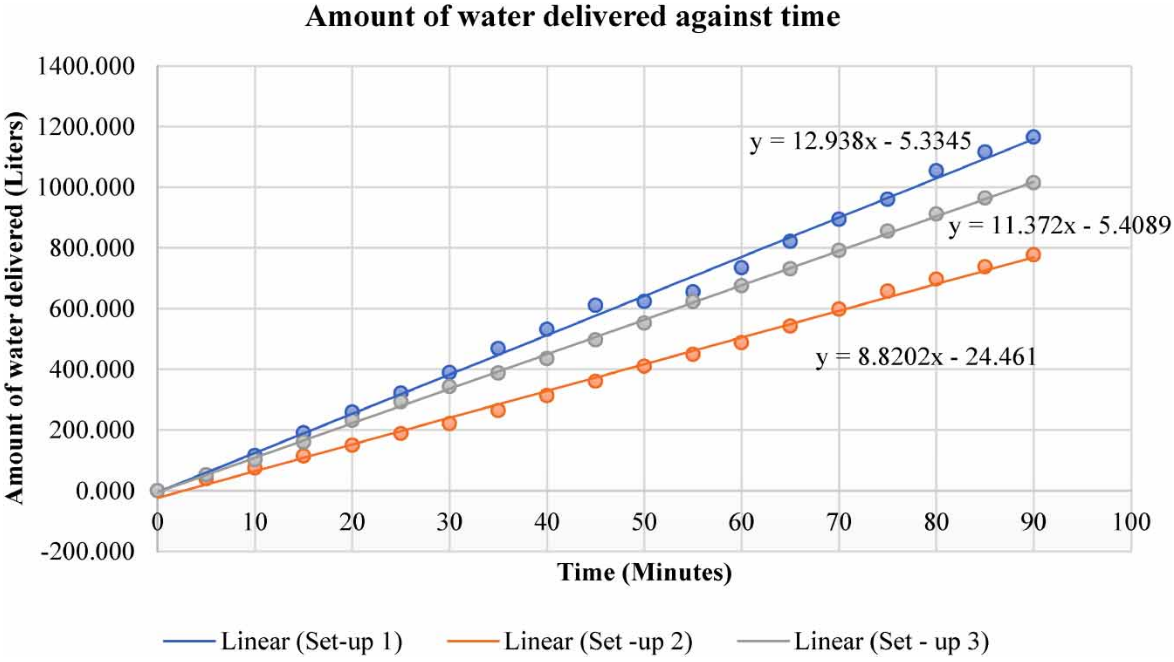


Figure 9 | Amount of water delivered against the time of the designed prototype hydram pump.

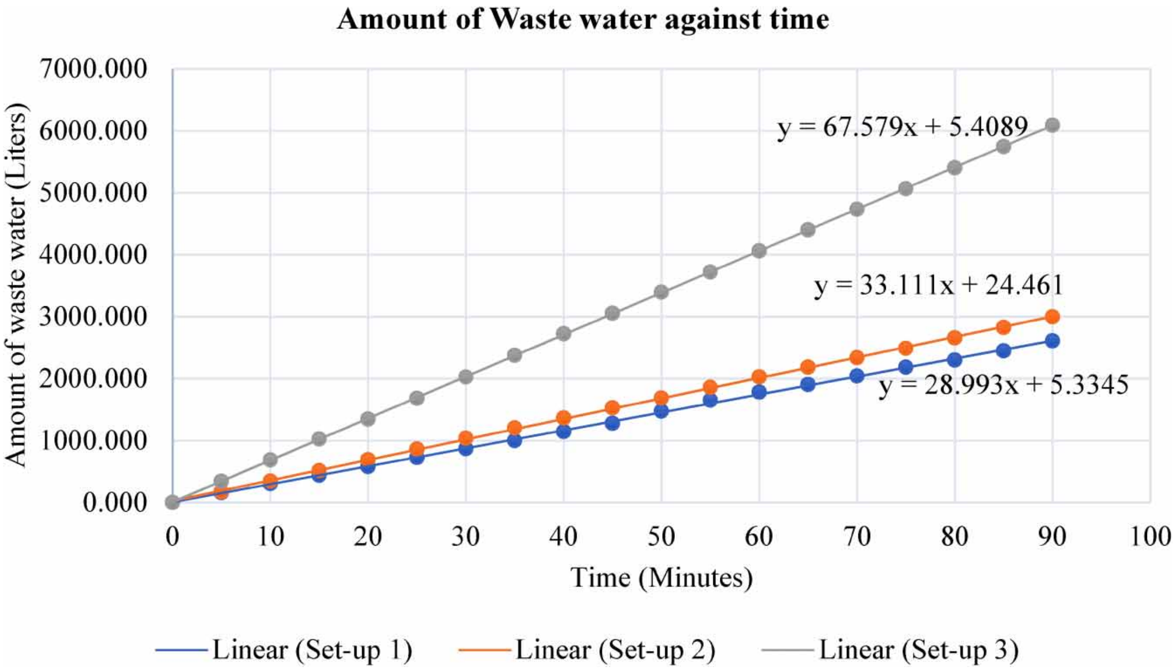


Figure 10 | Amount of water wasted by the pump against the time of the designed prototype hydram pump.

An average pressure of 92.5 kN/m^2 was obtained in set-up 3 while an average of 58.7 kN/mm^2 was obtained in set-ups 1 and 2. Therefore, it is observed that pressure in the hydram increases with an increase in delivery and drive heads. The pressures in the hydram are due to the water hammer effect that results to pressure waves that cause the intermittent closure and opening of impulse and delivery valves that enables water to be delivered. Optimum efficiency of 54% was obtained in set-up 1 and a minimum of 51.4% in set-up 3. The drop in efficiency results from the increase in the delivery/drive head ratio, thereby the hydram pumps lesser water with a great amount of water wasted as a result of an imbalanced delivery head-to-drive head ratio.

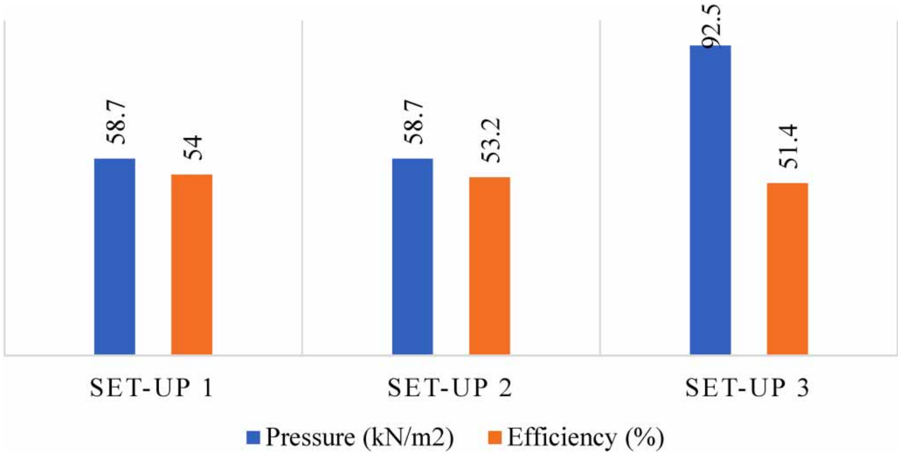


Figure 11 | Pressures and efficiencies of the hydram set-up of the designed prototype hydram pump.

DISCUSSIONS

The existing systems exhibited low efficiencies of less than 30%, with 25% of the investigated pumps working. The major cause of failure was the imbalance of the pressure within the pump as a result of an improper design of the valves and pressure chamber. The efficiency of the pump depends on the proper design of the valves and the pressure chamber, since these are key controllers of the pressures and the velocities of the system, which thereafter affects the pump's efficiency (Kimaro 2018).

The site conditions, drive and delivery heads, and stream flows are key components when installing the pumps (Asvapoositkul *et al.* 2019). The existing systems failed due to inadequate designs of the head ratio to flow ratio. The higher head ratio results in high-pressure build-up in the pump. This pressure is due to the water hammer effect of the pump that causes a portion of water to be pumped to the delivery tank (Inthachot *et al.* 2015). The higher pressure generated in the pump can destroy the pump components, that is the valves, pressure chamber, and pipes. Therefore, a pressure chamber should be designed to absorb the pressure within the pump (Mishra *et al.* 2018).

The prototype pump designed and constructed was able to achieve a higher efficiency of 54% compared to an efficiency of less than 30% for the existing systems, this was possible by ensuring the components of the pump have been designed to perform well under the prevailing site conditions (Januddi *et al.* 2018). According to Iddi *et al.* (2018), pressure chamber design with weight alterations can significantly improve the pump's efficiency. When the delivery head and supply head varied, it was observed that both the amount of water supplied and water wasted through the waste valve increased linearly as in Figures 9 and 10, respectively. This is because when the supply head increases, the velocity and momentum of the water in the drive pipe also increase the pump flow rate, delivery power, and pump efficiency.

CONCLUSIONS

Hydraulic ram pumps have great potential in providing alternative pumping solutions to rural populations for domestic and agricultural use. The investigation carried out showed that hydram technology is well utilized in West Pokot County, Kenya. This is because it is cheaper and easy to fabricate and install as compared to motorized pumping systems. The investigated systems, however, performed with low efficiencies of less than 30%. The study, therefore, tries to sensitize and improve the locals' designed systems by providing a simplified designed prototype that they can use to develop new systems and also highlights how they can improve their existing systems. From the study, the pump was able to achieve an optimum efficiency of 54% with an optimum delivery flow rate of 12.938 L/min, further studies can be carried out to improve the efficiency of the pump by modifying the pump, that is the valves and pressure chamber.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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