Water Resources Engineering

Assessing the feasibility of a hydraulic ram pump for water supply in Mulundu water scheme.

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Abstract— *This study explored the feasibility of adopting a hydraulic ram pump for the Mulundu water supply scheme. Hydraulic ram pumps, powered solely by the kinetic energy of flowing water, offer a sustainable, cost-effective, and low-maintenance alternative, especially in areas with appropriate topography. The research focused on characterizing the Mulundu terrain, analyzing the interplay between the hydraulic ram pump's variables, and designing a pump tailored to the community's needs.*

Two distinct approaches were undertaken to evaluate the feasibility of implementing a hydraulic ram pump in the Mulundu water supply scheme. The first approach involved a theoretical design based on the unique topographical characteristics of the Mulundu area. This phase incorporated terrain analysis and computational modeling to determine the optimal specifications for a hydraulic ram pump suited to the region's conditions, including elevation, flow rate, and water demand.

The second approach focused on empirical experimentation using an existing hydraulic ram pump prototype with design features comparable to the proposed Mulundu system. Controlled experiments were conducted to assess the performance of the prototype under conditions analogous to those in Mulundu, including variations in water flow, pressure, and operational efficiency.
The results from these two approaches were then systematically compared. The theoretical predictions were validated against the actual performance data from the prototype, enabling a comprehensive evaluation of the hydraulic ram pump's viability. This approach increased the confidence level of the main design.

Hydram: a pumping device that uses part of its potential energy and a lot of water from its source to supply small amount of water at a head to about 10 times the initial

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I. INTRODUCTION

Water plays a vital role for human health, food production, and economic development (World Bank, 2006). Access to clean and safe water is an essential necessity for the well-being of all people (World Bank, 2006). One of the targets set by the United Nations in Sustainable Development Goals (SDGs) Goal 6.1, is universal and equitable access to safe and affordable drinking water for all by 2030 (United Nations, 2015). Adopted by all United Nations Member States in 2015, SDGs are a call for action by all countries to promote prosperity while protecting the planet (United Nations, 2015). With the adoption of the water supply service ladder, increased attention has been placed on providing higher levels of water service, including on-plot piped connections (WHO/UNICEF, 2020).

The sustainability of rural water supply programs in developing nations continues to be a pressing issue within the sector. Recent assessments in Sub-Saharan Africa reveal that a mere fraction of water point sources in rural locals operate reliably at any moment (RWSN, 2009). This concerning trend stems from a multitude of factors, including inadequate maintenance practices, managerial challenges, social complexities, insufficient funding, limited community involvement, and issues pertaining to ownership (Jimenez et al., 2011)

Hand pumps, a prevalent water supply technology in these regions, persistently fall short of meeting the targets set forth by Sustainable Development Goal 6.1. Hand pumps encounter ongoing criticism due to their inherent limitations, such as reliability issues, high maintenance demands, and limited functional longevity, rendering them unsuitable for achieving the sustained water access envisioned by SDG 6.1 (Whittington et al., 2009). Consequently, there is a growing impetus to explore alternative water supply solutions that can effectively address the underlying challenges hindering the sustainability of rural water supply programs

WASH implementers are increasingly moving from centrally located community water sources, like boreholes with hand pumps, toward motorized, solar, and gravity piped systems, aiming to provide service closer to users' homes (United Nations, 2015; African Union, 2015). Despite governments' commitment to the SDGs and the African Union's Agenda 2063, most countries are not on track to meet their objective of ensuring the availability and sustainable management of water and sanitation for all (United Nations, 2023; African Union, 2023). According to the 2023 Africa Sustainable Development Report, 411 million Africans still lack access to adequate water supply (United Nations, 2023).

The implementation of piped water supply systems in rural areas of low- and middle-income countries has not yielded the expected results. Piped networks are complex systems that require sophisticated design, management, and ongoing operations and maintenance (RWSN, 2010). External financing and support programs are critical for the sustainability and user satisfaction of community-managed piped water systems (Davis et al., 2008; Kayser et al., 2014; Spaling et al., 2014; Whittington et al., 2009). Various government and private maintenance models exist to complement community management and have been shown to reduce downtime of broken water points (Lockwood, 2019; Fink et al., 2022).

Despite efforts, piped systems incorporating hydro power motorized and solar systems have not been entirely successful. Jimenez (2013) showed that hand pumps had the least favorable functionality, dropping from 61% in the first five years to 6% over 25 years. Motorized systems followed a similar pattern, starting at 77% and dropping to 13%. Gravity-fed systems performed better in the long run, dropping from 66% to 20% (Jimenez, 2013). Water costs associated with motorized hydroelectric pumps pose a concern in rural communities, while solar systems, though advantageous, have their own limitations. Solar pumping systems can be less effective during periods of low sunlight, such as during cloudy days or in regions with long rainy seasons. Additionally, the initial investment cost for solar infrastructure can be high, and maintenance can be challenging in remote areas due to the need for specialized parts and technical expertise (Kabade et al., 2013).

In the Zambian context, people's aspiration in the Vision 2030 is to become "A Prosperous Middle-Income Nation by 2030". In one of the objectives, the Vision 2030 aim at providing secure access to safe potable water sources and improved sanitation facilities to 100 percent of the population in both urban and rural areas. This Vision has been operationalized through the five-year development plans starting with the Fifth National Development Plan (2006-2010) to the current the Eighth National Development Plan.

Despite such aspirations of reaching a 100% mark of providing secure access to safe potable water sources and improved sanitation facilities, The Eight National Development Plan records that the percentage of the population that had access to an improved water source increased to 72.3 percent in 2018 from 41.1 percent in 2007. From the figures it can be stated that the rate at which the country is moving is slow and might not realize certain objectives of the vision if stringent measures are not put in place

The National Water Supply and Sanitation Council (NWASCO) who are the regulators of rural water supply and sanitation, in 2018, developed the Rural Water Supply and Sanitation Service (RWSS) Provision Regulatory Framework, which outlines the provision of RWSS services by the CUs and local authorities (NWASCO, 2023). This framework was meant to improve water supply by emphasizing managing piped water systems through hydro power motorized, solar, and gravity supply systems where feasible.

Despite efforts made by various stakeholders to improve rural water supply and sanitation, sustainability remains a challenge. The focus on solar and hydro power motorized systems as primary units for piped water systems poses sustainability issues. Solar components are complex, difficult to manage, and have limited hours of availability (Kabade et al., 2013). The cost of operating motorized pumping systems is also a setback. NWASCO (2023) notes that most piped water schemes use solar power; but the complexity and lack of durability of solar components threaten the sustainability of these schemes.

To improve access to clean and safe water in rural areas, adopting gravity systems that incorporate sustainable pumping mechanisms is crucial. One such mechanism is the hydraulic ram pump, which does not require external energy for its operation. This pump operates using the kinetic energy of flowing water, making it a viable solution for sustainable water supply in rural areas (Ndache, 2007). However, hydraulic ram pumps have limitations, including the need for a sufficient and continuous flow of water to function effectively, which may not be available in all locations (Rohit, 2015). Such systems can only be implemented in areas with sufficient head.

Hydraulic ram pumps have been successfully used in several commercial applications for water supply: The island community of Palawan in the Philippines for example, uses hydraulic ram pumps to supply water to households and agricultural areas, capitalizing on the hilly terrain to generate the necessary water pressure without external energy sources (Turner, 2020). In Bermuda, hydraulic ram pumps are employed to move water from lower to higher elevations for agricultural irrigation, exploiting the island's natural gradient (Smith, 2018). Also, various rural communities in Nepal use hydraulic ram pumps to deliver water from mountain streams to villages situated on higher grounds, ensuring a reliable and sustainable water supply without relying on electricity or fuel (Bhattarai et al., 2016).

These examples demonstrate the potential of hydraulic ram pumps to provide sustainable and cost-effective water solutions, particularly in areas where the land topography enables the stream to have a relative high slope that makes the water to have high kinetic energy which is used to generate enough potential energy by the pump thereby lifting the water to higher grounds. (Hussin et al., 2017)

1.2 Statement of the problem

Access to clean and safe water is a fundamental right for every human being, essential for health, food production, and economic development (World Bank, 2006). However, many rural communities in developing countries, including those in Sub-Saharan Africa, struggle with unreliable water sources. This issue is compounded by the fact that many water points are poorly documented and suffer from operational failures due to poor maintenance, management issues, social problems, lack of financing, lack of community participation, and a lack of ownership (RWSN, 2009; Jimenez & Perez-Foguet, 2011).

Traditional water supply methods, such as hand pumps, have proven inadequate due to these systemic issues. Efforts to improve water access by transitioning to motorized hydro pumps and solar-powered systems face significant challenges. These systems are costly, require regular maintenance, and involve complex technologies that local communities often lack the skills to manage effectively (Kabade et al., 2013; RWSN, 2010). As is the case in Mulundu village, a hydroelectricity powered motorized pumping system has been deemed unsustainable by the operations committee. The complexity and the associated high costs hinder the sustainability of this system.

Gravity-fed systems, particularly hydraulic ram pumps, offer a promising alternative particularly for Mulundu Community. These pumps use the kinetic energy of flowing water to operate and do not require external energy sources, making them cost-effective and easier to maintain compared to hydroelectricity and solar-powered motorized systems (Ndache S, 2007). Successful implementations of hydraulic ram pumps in various regions, such as Fair Isle in Scotland, Bermuda, and rural Nepal, highlight their potential to provide reliable and sustainable water supply solutions (Turner, 2020; Smith, 2018; Bhattarai et al., 2016). However, there are no records that show the applications of the hydraulic ram pumps in Zambia and also to mention that these systems are only suitable for particular locations

1.3 Aim

To assess the feasibility of using a hydraulic ram pump for water supply in the Mulundu water supply scheme

1.4 Objectives

1. To characterize the topography of Mulundu area
2. To determine the interplay between the independent and dependent variables of the hydraulic ram pump
3. To design the pump that fits the demand and terrain of Mulundu community

1.5 Research questions

1. How is the terrain of Mulunda area?
2. What is the relationship between dependent and independent variables for they hydraulic ram?
3. What are the descriptions of the major components of the hydraulic ram pump that meets the demand and terrain of Mulundu?

1.6: Significance of the study

The information generated from this research will be important because:

- ✓ It will raise the need for alternative pumping mechanisms to reduce the cost of using electricity for pumping water in some rural areas.
- ✓ It may be used by different stakeholders especially policy makers to make informed decisions
- ✓ It may provide an alternative approach to pumping irrigation water by small scale farmers in some rural areas thereby improving crop production where water is the limiting factor.

Chapter two

2. Literature review

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. (Joseph K. O. a et al., 2023)

Therefore, as the world's technology shifts to green energy, hydraulic ram pumps need to be re-invented. In the late twentieth century, studies on hydraulic ram 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 hydraulic ram pump technology. (Joseph K. O. a et al., 2023)

Figure 1. Fabrication of hydraulic ram pumps for irrigation (source. West Pokot County Kenya)

In Zambia, where hydropower shortages have become increasingly prevalent, hydraulic ram pumps offer a promising solution. These devices, which harness the energy of flowing water to pump water uphill, are inherently green, requiring no external power source. By optimizing their design and performance, hydraulic ram pumps can provide a reliable and sustainable alternative to traditional pumping methods.

This literature review explores recent advancements in hydraulic ram pump technology, focusing on design improvements, efficiency enhancements, and real-world applications.

2.1 What is a hydraulic ram pump?

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). The water hammer effect generates waves that open the delivery valve and water is delivered to a higher head (Verspuy, et al. 2019). The operation of a hydraulic ram pump 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 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).

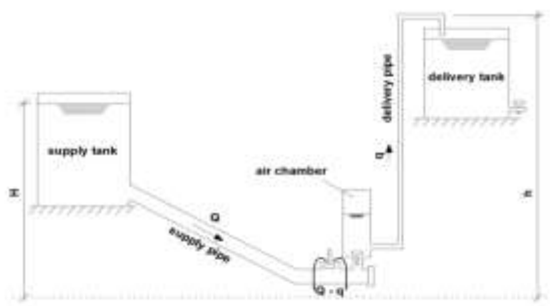

Figure 2. Schematic diagram – Hydraulic ram pump

According to Mahmud & Rahman (2020), for a better output performance of a hydraulic ram pump, the drive length should be designed sufficiently to suit the site conditions. This is because the performance of the hydraulic ram pump 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 achieved (Shende et al. 2015).

In summary successful execution of the hydraulic ram pump undergoes four main sequencies; the first sequence is where water from source (most cases weir dam) enters the drive pipe (A) as shown below. In sequence 2, water entering the pump through the drive pipe (A) has its velocity and pressure directed out of waste valve (B) as illustrated. In sequence 3, water stopps flowing through the drive pipe (A) as a “shock wave” created by the “water hammer” travels back up the drive pipe to the source. The waste valve (B) is then closed by the hydraulic for built in the ram body. Air volume in the pressure tank (D) continues expanding to equalize pressure, pushing a small amount of water out of the delivery pipe (E). Finally in sequence 4, the shock wave reaches the source causing a “gasp” for water in the drive pipe (A). The waste valve (B) opens and the water in the drive pipe (A) flows into the pump and out of the waste valve (B). The check valve (C) remains closed until the air volume in the pressure tank (D) has stabilized and water has stopped flowing out of the delivery pipe (E). At this point, sequence I begins all over again (Ndache, 2007).

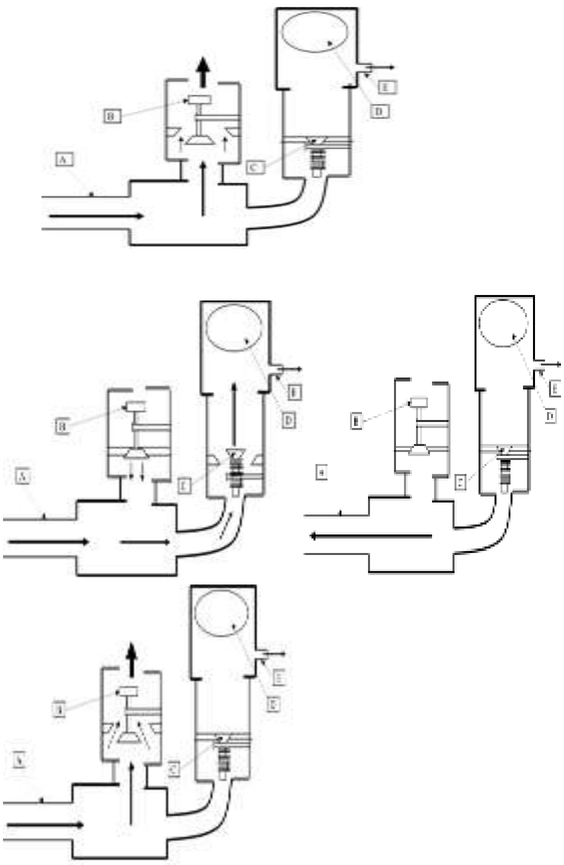

Figure 3.Sequences of hydraulic ram operation (source; Shaibu Ndache Journal)

The performance of a hydraulic ram pump is heavily influenced by the specific characteristics of its installation site. To optimize efficiency and maximize output, it is essential to carefully consider the topography of the area. This review explores a range of topographic determination methods that have been employed in the design of hydraulic ram pumps and water reticulation systems.

2.2. Determination of topography for water supply

Determining the topography of the site is crucial in the design of hydraulic ram pumps, as it significantly impacts the pump's performance, efficiency, and overall functionality. Topography influences the static head, which is the vertical distance the water must be lifted, directly affecting the required total system head for effective operation. Accurate topographical assessments help identify elevation changes, slopes, and potential obstacles in the water flow path, allowing for optimal placement of the pump and associated piping systems. Below is a list of case studies on various methods of topography determination for the purpose of hydraulic ram pump installation

Traditional Leveling and Stadia Method in Ethiopia; In the Amhara Region, Ethiopia, Tesfaye, G., & Gebremedhin, A. (2018). relied on traditional leveling and stadia methods to determine the topography for hydraulic ram pump installations. While this approach is labor-intensive and time-consuming, it can be effective in areas where modern technologies are not readily available. The leveling and stadia method involves using a theodolite and leveling rod to measure elevation differences between points. Traditional leveling and stadia methods can be time-consuming and labor-intensive, especially for large-scale projects. They may not provide the same level of accuracy as modern technologies like LiDAR or GNSS.

Figure 4. surveyors performing traditional leveling in the Amhara Region, Ethiopia

Remote Sensing and GIS in Mountainous Nepal; In the Mustang District, Nepal, a study by Shrestha, B., & Pradhan, B. (2017) utilized remote sensing techniques, such as satellite imagery and LiDAR, in conjunction with GIS software to evaluate potential hydraulic ram pump sites in a mountainous region. The high-resolution data captured by remote sensing allowed for precise identification of suitable locations with adequate elevation differences and minimal obstacles. GIS analysis facilitated the visualization and analysis of topographic features, aiding in the design of efficient and cost-effective systems.

The limitation to this study could be attributed to the fact that remote sensing data may be affected by cloud cover or atmospheric conditions, limiting its accuracy in certain regions. Also, LiDAR data can be relatively expensive to acquire and process, especially for large-scale projects which could call for massive data acquisition

Drone-Based Photogrammetry in Kenya; A study by Otieno, F. O., & Awange, J. O. (2019) in the Turkana County, Kenya, demonstrated the effectiveness of drone-based photogrammetry for topographic mapping in support of hydraulic ram pump projects. Drones equipped with high-resolution cameras captured aerial images, which were then processed using photogrammetry software to create detailed digital elevation models (DEMs). This method provided accurate topographic information at a relatively low cost and with minimal disruption to the surrounding environment.

Figure 5. Simulation of drone flying over the arid landscape of Turkana County, Kenya,

However, drone flight restrictions by weather conditions, regulations and airspace limitations limited the scope of this study. Challenges in photogrammetry processing were also reported

Ground-Based LiDAR in South Africa; Ground-based LiDAR was employed in the Eastern Cape Province, South Africa, to obtain precise topographic data for hydraulic ram pump installations. LiDAR technology uses laser pulses to measure distances to the ground, resulting in highly accurate elevation measurements. This method was particularly useful in areas with dense vegetation or complex terrain, where traditional surveying techniques might be challenging.

Ground-based LiDAR can be expensive and requires specialized equipment. It may be impractical for large-scale projects or areas with difficult terrain. (Van der Merwe et al., 2021).

Global Navigation Satellite Systems (GNSS) in India; Rao, P. V., & Reddy, K. R. (2023). conducted a study in the Karnataka State, India, using GNSS receivers to determine the topography of potential hydraulic ram pump sites. GNSS technology provides real-time positioning data, allowing for accurate measurements of elevation and coordinates. This method is well-suited for large-scale projects or remote areas where access to topographic maps or other data sources may be limited. GNSS signals can be affected by atmospheric conditions, obstructions, or multipath errors, which can reduce accuracy. GNSS receivers may require specialized equipment and software.

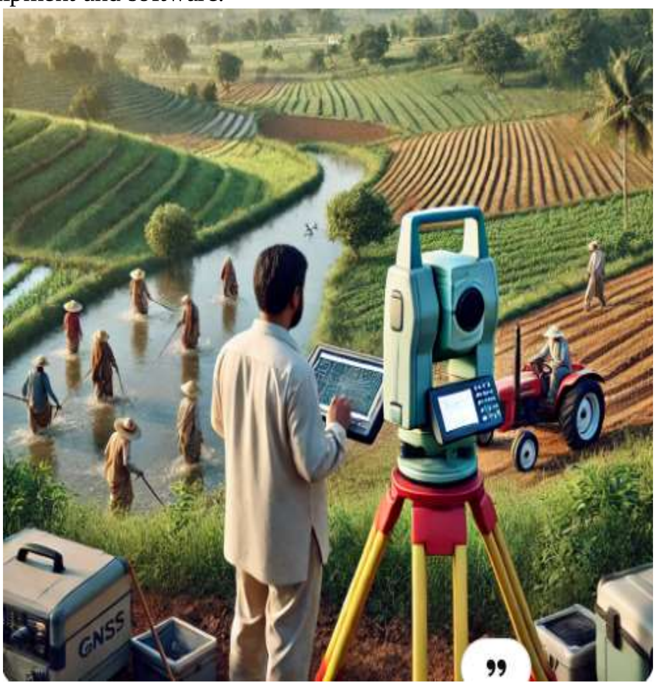

Figure 6. Simulation of GNSS receivers for topographic mapping to identify potential hydraulic ram pump sites Karnataka State, India

2.3 Independent and Dependent Variables

Understanding independent and dependent variables in hydraulic ram pump design is vital for optimizing performance and ensuring suitability for specific applications. Independent variables, such as drive head, delivery head, and input flow rate, directly influence dependent variables like pump efficiency, output flow rate/head, and operational frequency. By analyzing these relationships, the pump can be tailored to site-specific conditions, maximize energy transfer, and minimize losses. This understanding also aids in predicting performance, troubleshooting issues, and making informed design adjustments, ultimately ensuring the pump operates effectively and meets its intended purpose

2.3.1 Independent Variables

Supply Head

Supply head is a crucial term in understanding the operation of a hydraulic ram pump. It refers to the vertical distance between the water source (supply tank or reservoir) and the inlet of the ram pump. This distance, measured in meters, is a key factor in determining the pump's efficiency and the height to which it can lift water. (Jedsada, J. 2019)

In an experiment for the Determination of Hydraulic Ram Pump Performance, Jedsada, J. (2019) noted that an increase in the supply head tends to increase the supply flow rate, delivery flow rate, delivery head, and the overall efficiency of the pump

Drive pipe length

The drive pipe length in a hydraulic ram pump is a critical independent variable that significantly influences its performance. This pipe carries the incoming water from the source to the ram body, and its length directly affects the velocity and pressure of the water. A longer drive pipe can increase the velocity and pressure of the water, leading to a more powerful impact on the ram's valve and ultimately a higher pumping efficiency (Shende et al. 2015).

According to Mahmud & Rahman (2020), for a better output performance of a hydraulic ram pump, the drive length should be designed sufficiently to suit the site conditions. This is because the performance of the hydraulic ram pump 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).

Supply Discharge

Supply flow rate is a critical independent variable in a hydraulic ram pump. It refers to the volume of water that enters the pump per unit time. Joseph K.O. et al. (2023) in their study of Performance evaluation of hydraulic ram pumping systems for small-scale farmers noted that a higher supply flow rate generally led to increased power output. This is because the pump has more kinetic energy available to drive the piston and lift water. While a higher flow rate can increase power output, it may not always lead to increased efficiency. Excessive flow rates can cause water hammer effects, which can reduce the pump's overall efficiency and even damage its components. (Pawlick et al. 2018)

Pawlick et al. (2018) in their design showed that, the supply flow rate together with the supply head has an influence on the lift height achieved by a hydraulic ram pump. A higher flow rate can increase the lift height, but this effect is often limited by other factors such as the pump's design and the water hammer effects.

Swing Check Valve

It is defined as the number of times the waste valve opens and closes per unit time of the hydraulic ram pump. A study by Philip J. S. et.al., (2022) suggested that each swing check valve beat corresponds to the water delivered and water spilled out of the waste valve. In their experiment conducted, they showed that; An increase in waste valve stroke variations from 75 beats/min to 95 beats/min for 1:3 design ratio and 84 beats/min to 103 beats/min for 1:4 design ratio increased the water spilled.

2.3.2 Dependent Variables

Delivery Flow Rate

Delivery flow rate is the volume of water delivered by the pump per unit time. Studies conducted by Mondol (2017) showed that a higher flow rate indicates better pump performance, as more water can be transported to desired locations. He established that Factors like drive pipe diameter, drive pipe length, and air chamber volume influence flow rate. A larger drive pipe diameter allows more water to enter the pump, leading to higher flow rates. Similarly, a longer drive pipe can increase water pressure, resulting in higher flow rates. The air chamber volume also plays a crucial role in regulating flow rate. An appropriately sized air chamber can help maintain a consistent flow by absorbing and releasing water as needed (Mondol, 2017)

Delivery Head

The vertical distance the water is lifted by the pump. A higher head indicates the pump's ability to lift water to greater heights, which is essential for applications like irrigation and water supply to elevated areas. Kesharwani et al. (2021) used a hydraulic ram pump for agricultural farming in a remote village in Taipadar, Central-East India. It had an 8-inch ram inlet and 4-inch ram outlet, manufactured by Rife Incorporated, using the river as the water source. They developed a ram scaling law that provides a criterion of head-discharge-diameter ratios. The predicted dimensionless characteristics of head ratios, discharge ratios and velocity ratios were identified as the governing parameters when optimizing how high a hydraulic ram pump would pump water

Efficiency

The ratio of the output power to the input power. A higher efficiency indicates that the pump is converting more of the input energy into useful work, reducing energy consumption. Studied conducted by Philip J, et. al, (2022) found out that. Factors like drive pipe diameter, drive pipe length, water source head, and air chamber volume influence efficiency. A well-designed drive pipe with appropriate diameter and length can minimize energy losses due to friction, leading to higher efficiency. Higher water source head can also improve efficiency by reducing the pump's energy requirements. The air chamber volume plays a role in regulating the pump's operation, ensuring efficient energy transfer (Philip J, et al)

Power

The rate at which work is done by the pump. Higher power output indicates the pump's ability to deliver more water or lift it to greater heights. Factors such as flow rate, head, and efficiency influence power. A higher flow rate and head require more power to drive the pump. A pump with higher efficiency can produce more power output for a given input power. Therefore, optimizing factors like drive pipe diameter, drive pipe length, water source pressure, and air chamber volume can lead to higher power output. (Sarip.S., 2020)

Wastewater flow rate at the waste valve

Wastewater flow rate in a hydraulic ram is a crucial parameter that significantly impacts its overall efficiency and performance. It represents the volume of water that is diverted away from the output line and lost during the operation of the pump (Sarip.S. et al., 2020). This wasted water is typically returned to the source or disposed of elsewhere. In an experiment conducted by Sarip.S. et al., (2020) showed that an increased inlet flow rate resulted in a higher wastewater flow rate and this continued for as long as the water flow rate increased, He used the following equation to model the waste water flow from the hydraulic ram pump

$$Q_w = Q_s - Q_d \quad \text{------------------------------------}1$$

Where Q_s = Water supply flow rate and;

Q_d = is delivery water flow rate

2.4 Design of Hydraulic Ram Pumps

Typically, a Hydraulic ram is a pumping device that allows rising water uphill without using any external power source (Hussin et al., 2017). It uses the water hammer effect to develop pressure from the elevated source, which pushes a certain amount of water to higher elevations in a periodic operating cycle (Fatahi-Alkouhi and Lashkar-Ara, 2019). It has a simple water pumping system consisting of an elevated water source supply, drive pipe, ram pump body with two moving parts (i.e., waste valve and delivery valve), pressure chamber and delivery pipe (Sarma et al., 2016; Hatipoğlu et al., 2018; Asvapoositkul et al., 2019). Water source flow rate and head are very critical in hydraulic ram pump design as shown by S. Sarip, (2022) in his studies

$$Q_s = \frac{N\pi L r^2}{60} \quad \text{-----------------------------------}2$$

Where; N = Number of beat cycle/per minute

L = Length of drive pipe

r = Radius of drive pipe

Recently, the necessity to use hydraulic ram pumps has been recognized to address renewable energy and sustainable technology needs (Kumar, 2022). Thus, the continuous development of this pump provides more interest to other researchers because of its contribution to rural communities and remote areas. Owing to its simplicity and eco-friendly process, the hydraulic ram pump is most suitable in mountainous areas for farmers and low-income earning citizens with abundant water sources. In fact, this pump can be used for irrigation and domestic water supply (Sampath et al., 2015).

Recently, Kesharwani et al. (2021) used a hydraulic ram pump for agricultural farming in a remote village in Taipadar, Central-East India. It has an 8-inch ram inlet and 4-inch ram outlet, manufactured by Rife Incorporated, using the river as the water source. They developed a ram scaling law that provides a criterion of head-discharge-diameter ratios. The predicted dimensionless characteristics of head ratios, discharge ratios and velocity ratios were identified as the governing parameters when optimizing large rams. Similarly, Li et al. (2020) identified the flow passage of head ratios as the main factor influencing the hydraulic ram pump performance. They created a novel waste valve that could decrease the head loss coefficient, optimize the delivery heads with relatively high efficiency and provide more water outputs. Hence, the head ratios were derived from establishing the design of the drive pipe and the delivery pipe. On the other hand, a small-scale hydraulic ram pump decreases back-head pressure due to the water hammer effect from the drive pipe length and its moving parts. The pressure shock in the delivery pipe was due to an increase in the air in the chamber, which resulted in a strong vibration of the drive pipe (de Carvalho et al., 2016). These findings also agreed with Inthachot et al. (2015) wherein a small-scale hydraulic ram with a 1-inch ram inlet and 1/2- inch ram outlet was installed in the stream for irrigation in Northern Thailand. Aside from differing the check valves, varying the drive pipe lengths also influenced the water production because the actual setup of this pump is installed in different terrain elevations.

Previous literature for large-scale and small-scale rams pointed out that the drive and delivery pipes were among the parameters that must also be considered in designing an effective hydraulic ram pump. Analytically, the drive pipe length must be kept between four to 12 times the drive head (Maw and Htet, 2014). Moreover, Mondol (2017) suggested a range of design ratios of the drive pipe from elevated source supply to the ram pump placement from 1:3 to 1:7 head-to-distance ratio to produce a water hammer effect. On the other hand, the Permaculture Research Institute in Australia provided a conservative estimate of drive pipe to its delivery pipe head-to-head ratio of 1:7 so that the moving parts would uninterruptedly function in an open and close manner (Roberts, 2017). It also allows the delivery head to reach up to 12 times from the supply elevation (de Carvalho et al., 2011).

Existing studies and manufacturers only provide a range of values for the drive head to its delivery head ratios (Watt, 1974; Corps, 1981; Brown, 2006; Browne, 2009; Practical Action, 2010; de Carvalho et al., 2011; Kumar, 2022; Jocags, 2017; Mondol, 2017; Roberts, 2017) as a reference in designing the water pumping system of the hydraulic ram pump.

The abovementioned studies only discussed the ranges of design ratios of head-to-head for the drive pipe and delivery pipe. The studies by de Carvalho et al. (2011), Mondol (2017) and Roberts (2017) did not emphasize the existence of the critical elevation for the delivery pipe in which the moving parts of the hydraulic ram pump could function uninterruptedly. Therefore, one needs to perform trial tests to be able to determine the critical delivery head, which can be tedious and time-consuming when constructing a water pumping system using a hydraulic ram pump. In general, no other related studies have emphasized the importance of determining the critical head of the delivery pipe in designing a functional and effective hydraulic ram pump. Critical delivery head is significant in ascertaining weather the newly designed pump is strong enough to overcome head requirements of the system.

2.5 Determining Total System Head (TSH) requirement

In a pumping system, the objective, in most cases, is either to transfer a liquid from a source to a required destination, e.g. filling a high level reservoir, or to circulate liquid around a system, e.g. as a means of heat transfer in heat exchanger. A pressure is needed to make the liquid flow at the required rate and this must overcome head 'losses' in the system. Losses are of two types: static and dynamic head. (Karassik, I. J. et.al, 2008)

System head curves are constructed by computing the heads required by the system to deliver different volumes of water per unit time. System Head curve is given by the following Equation:

TSH = He + PH + FH + VH + ML + DD-----------------2

TSH = Total System Head, m

He = Elevation difference

PH = Operating head

FH = Head loss due to pipe friction in the system, m

VHs = Velocity Head in the system, m

MLs = Minor Losses through fittings in the system

The total system head is a critical factor in the design and operation of hydraulic ram pumps, as it directly impacts the efficiency, reliability, and overall performance of these systems. Total system head encompasses both the static head, which is the vertical distance the water needs to be lifted, and the dynamic head, which accounts for the energy losses due to friction in pipes and fittings, as well as the velocity head associated with the flow of water (Iruña-Montes, A., 2022). Accurately determining the total system head is essential for selecting the appropriate size and type of ram pump, as an undersized pump may not meet the required flow rates, while an oversized pump can lead to unnecessary energy consumption and increased wear (Iruña-Montes, A., 2022).

Furthermore, a properly designed system that accounts for total head can maintain stable flow rates, which is crucial for applications such as irrigation and water supply (Iruña-Montes, A., 2022). The design must also consider friction losses, which can vary significantly based on pipe material, diameter, and flow rate, and changes in elevation throughout the system to ensure that the pump can overcome these losses and deliver the required flow (Iruña-Montes, A., 2022).

Integration of hydraulic ram pumps into water distribution systems can enhance energy recovery, and by optimizing total system head, these pumps can effectively manage excess pressure and reduce energy losses in the system, contributing to more efficient water use and reduced environmental impact (Iruña-Montes, A., 2022).

3. Methodology

The research methodology was crafted in alignment with the objectives and research questions outlined in Chapter 1. Initially, a theoretical design of a hydraulic ram pump tailored for Mulundu was developed. This was subsequently followed by a prototype simulation conducted on a real-world stream to validate the accuracy and suitability of the designed pump for the Mulundu context

3.1 Determination of the topography for the water source

A detailed topographic survey of Mulundu was conducted using advanced surveying techniques and applications i.e. GPS, Google Earth, GPX visualizer and Safer. This included gathering data on the elevation, slope, and geographical features of Luapula river near Mulundu water scheme. Then an analysis of the collected data to create a comprehensive topographic map of the area was conducted. Below is an outline on the methodology used in obtaining a 2D elevation map

3.2.1 Procedure for generating a topographical profile

Google Earth was launched on the computing device, providing an interactive platform for geographical exploration. Using the search functionality within Google Earth, the Mulundu Water Scheme along the Luapula River was identified as the area of interest. Employing the path tool provided by Google Earth, a path was traced along the course of the Luapula River near the Mulundu Water Scheme.

This path accurately represented the stretch of interest for the topographic profile. The traced path was saved as a Keyhole Markup Language (KML) file format. This file contained the geographical coordinates delineating the path along the Luapula River. The saved KML/KMZ file was converted to the GPS Exchange Format (GPX), a format compatible with GPX Visualizer. The GPX file obtained from the previous step was uploaded to a GPX visualizer tool. Utilizing the functionalities provided by the GPX visualizer, a topographic profile was generated along the traced path. This profile depicted the elevation changes along the Luapula River near the Mulundu Water Scheme. The figures below show the topographic profile for Luapula river in Mulundu

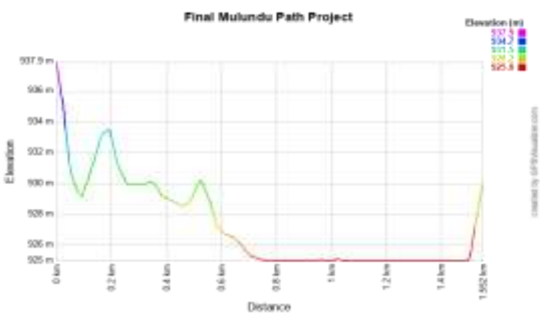

Figure 7.Profile for Luapula river from source to proposed installation site-Gpx visualiser

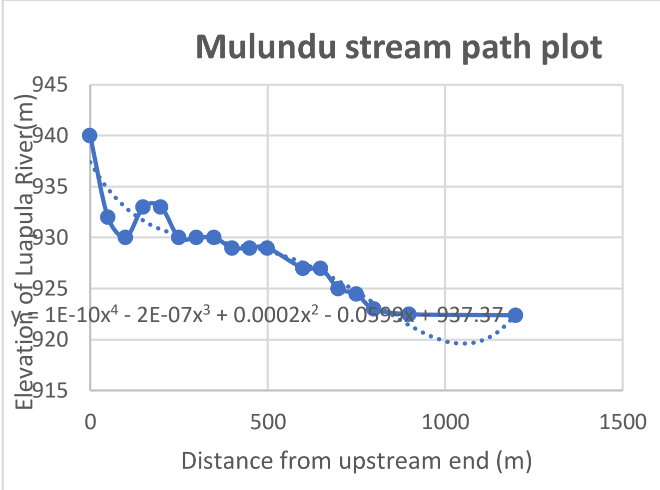

Figure 8.Profile for Luapula river from source to proposed installation site-Excel

3.2.1.1 Selecting possible pump installation site

The profile presented above was used to determine the best possible installation point. A number of factors were considered

A. Length of drive pipe to supply head ratio

To optimize the performance of a hydraulic ram pump, careful considerations for the ratio between drive pipe length and supply head (the height difference between the water source and the pump inlet) were made. This ratio significantly influences the pump's efficiency and overall operation. As reviewed before, empirical studies have shown that a range of ratios of 4:1 to 12:1 is generally recommended. Higher ratios can lead to decreased efficiency due to excessive energy loss in the drive pipe on the other hand, ratios that are too low may also result in suboptimal performance.

In this study, the optimal supply head to drive pipe ratio for the purpose hydraulic ram pump design and installation was determined to be at a horizontal distance of 100 meters from the water source. The mean elevation of the water source was 940m while the proposed installation position was at an elevation of 930 m. This finding was based on a detailed examination of various data points and a graphical representation of the relationship between these two variables. While the remaining data sets did not produce the expected results, the identified optimal ratio provides valuable insights for future installations and performance optimization of hydraulic ram pumps

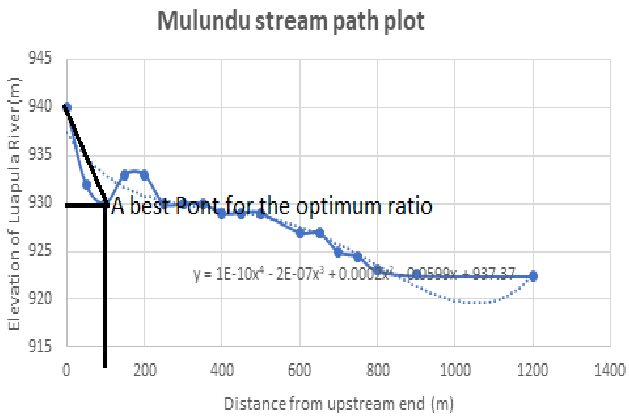

Figure 9. Optimum pump installation point

B. Drive pipe length to diameter of drive pipe ratio

To ensure optimal performance of the hydraulic ram pump, the ratio between the drive pipe length (L) and the drive pipe diameter (D) must be carefully considered. Previous studies, such as those conducted by S. B. Watt in 1974, have established recommended guidelines for this ratio. The ideal L/D ratio should fall within a specific range to minimize energy losses and maximize the pump's efficiency

$$150 < \frac{L}{D} 1000 \text{---} 4$$

Where L is the length of drive pipe and D is the diameter of the drive pipe

In othe analysis, only three of the 19 potential installation points met the recommended L/D ratio criteria. The proposed installation point, selected based on the criteria outlined above, also fell within the acceptable range, exhibiting an L/D ratio of approximately 659. The remaining points deviated from the recommended design ratios, suggesting that their performance may be compromised

C. Type of pipe to be used

The type of pipe used for the drive pipe in a hydraulic ram pump installation can significantly influence the selection of the optimal site, particularly in terms of the supply head to drive pipe length ratio. Metal pipes are generally durable and resistant to corrosion. They can withstand higher pressures and are suitable for long drive pipe lengths. However, they can be heavy and relatively expensive to install. On the other hand, plastic pipes (e.g., PPR, PVC, HDPE) are lightweight, corrosion-resistant, and relatively inexpensive. They are often preferred for shorter drive pipe lengths due to their flexibility and ease of installation. However, they may have limitations in terms of pressure resistance and long-term durability.

Considering the current higher price for metal pipes, plastic pipes where chosen and they influenced the selection of the installation site as discussed above.

3.2. Determination of variables

3.2.1 Supply discharge

The theoretical supply discharge for the proposed hydraulic ram pump was determined based on following parameters and assumptions

Number of swings per cycle (N); This parameter as stated earlier is significant in the sense that, it can either increase the efficiency of pump performance or reduce it. In this study a value of 90 beats was selected as an optimum number of beats per minute that would produce best results for the pump (Asvapoositkul et al., 2019)

Length of drive pipe (L); The length of drive pipe to be used in the determination of theoretical hydraulic ram pump discharge was determined based on criteria discussed in 3.2. A-C. The value which was theoretically calculated was 100.2. This value was deemed as that which would give optimum pump performance (Sarip S., 2020)

Diameter of drive pipe (D); The diameter of drive pipe to be used in the determination of theoretical hydraulic ram pump supply discharge was determined based on criteria discussed in 3.2. A-C which proposed that for best hydraulic ram pump performance, the ratio of drive length pipe to diameter of pipe should be in the range $150 < \frac{L}{D} 1000$ (S. B. Watt in 1974). Based on this range a diameter of 150 mm (6") for the pipe was sufficient (Sarip S., 2020)

Based on above parameters, the supply discharge was determined using the following expression

$$Q_s = \frac{N\pi L r^2}{60} \text{--} 5$$

Where N is number of beats per minute by waste check valve, L is the length of supply pipe length and r is the radius of supply pipe (D/2)

3.2.2 Velocity of fluid flow (Vs) at supply

The velocity of fluid flow in the supply pipe was determined using the following expression

$$V_s = C_v\sqrt{2gH_s} \text{--} 6$$

Where Cv = 0.96

3.2.3 Theoretical velocity in the delivery pipe (Vd)

In order to determine the velocity of flow in the delivery pipe, it is important to first determine the delivery pipe diameter. According to Sarip S., (2020), for a long delivery pipe, an optimal size is recommended to maintain the steady flow with less friction. Basically, a ratio of 1:3 (Supply pipe diameter – Delivery pipe diameter) could be sufficient. In this study a pipe diameter of 50 mm was used as delivery pipe. The velocity however was determined using the equation below.

$$V_d = C_v\sqrt{2gh_d} \text{--} 7$$

Note that h_d = 10 H_s this equation assumes losses in the system*

3.2.4 Theoretical discharge at the delivery pipe

The theoretical discharge at the delivery pipe was determined using the equation below

$$Q_d = A_d V_d \text{--} 8$$

Where A_d is cross section area of delivery pipe

Alternatively, the delivery head was determined using the following equation

$$Q_d = \varepsilon * Q_s \text{--} 9$$

Where ε is water loss coefficient (on average a value of 0.1 is often used)

3.2.5 Discharge through waste valve (Qw)

The discharge at the waste valve is significant for the determination of pump efficiency. In this study, It was determined using the following equation

$$Q_w = Q_s - Q_d \text{-------------------------------} 10$$

3.2.6 Velocity of flow at the T-Junction (Vt)

The velocity of flow at the T-Juntion is important for it is used in determining the Head loss due to sudden contraction at the T junction of a hydraulic ram pump

$$V_t = \frac{Q_d}{A_t} \text{------------------------------} 11$$

Where At is the cross section area at the T – Junction

3.2.7 Determination of Total System Head (TSH)

The Total System Head i.e. the amount of energy in terms of head required to transport water from the pump to the reservoir.

TSH = He + PH + FH + VH + ML + DD

1. **Elevation Difference (He)**

The elevation difference is the difference between the position of a hydraulic ram pump and the eventual point of water usage. In this study the elevation from proposed pump installation site was plotted as shown in the figure below. Plots where done both in gpx visualizer and Microsoft excel. An average value of 30 m was determined

Figure 10.Profile from pump position to reservoir

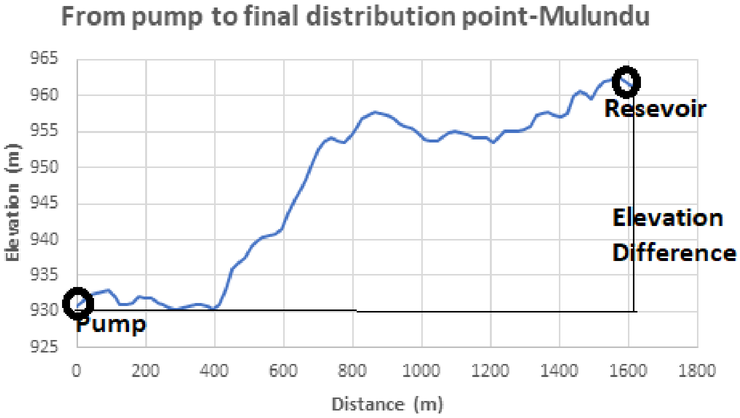

Figure 11.Profile from pump position to reservoir

2. **Pressure head (PH)**

It is assumed that the pump will deliver into a reservoir where the pressure is equivalent to atmospheric pressure. In this case the Pressure Head (PH) was taken as

3. **Friction Head loss (FH)**

To determine the friction head loss in the 50 mm plastic pipe that was used, Hazen-Williams's Equation shall be used

$$FH = \frac{KC_1LQ_d{}^m}{d^{2m+n}}$$

Where C1, m and n are Hazen William's Constants, K if the friction coefficient dependent on pipe type, Qd is delivery flow in l/m and d is diameter of delivery pipe (50 mm) in mm

K was determined using the following equation ,

$K = (0.285 * C_2)^{-1.852}$ *where* C_2 *is roughness coefficient*

Table 1. Friction Head Loss Constants

	C_1	m	n
Darcy weisbach's	277778	2	1.0
Hazen-williams	591722	1.85	1.17
Scobey	610042	1.9	1.10

Table 2. Values of C_2 for various types of pipes

Type of Pipe	Hazen-Williams Coefficient, C_2
Asbestos cement	140
Concrete	100 – 130, use 100
Copper	130 – 140, use 130
Plastic	130 – 150, use 130
Glass	130
New welded steel	120
New riveted steel	110
Corrugated steel	60
Ductile Iron:	
Cement Lined	130 – 150, use 140
New, unlined	130
5-year old, unlined	120
20-year old, unlined	100

4. Velocity Head

Velocity head was determined using the following equation

$$VH = \frac{Q^2}{435.7d^4}$$

Where d is delivery pipe diameter in cm

5. Minor Losses

In this study the network did not have a lot of appurtenances. Therefore, loss due to installed appurtenances was neglected

3.3 Design Parameters

The design parameters where selected based on the findings as per objectives. The raw data which was used to arrive at the following design parameters is documented in the Annexes (i-vi)

Table 3. Design parameters for the proposed hydraulic ram pump for Mulundu

SN	Component	Specification	Comment
From Source to pump			
1	Weir	Concrete weir with a minimum height of 1.5 m	
2	Supply drive pipe	Type of pipe: Polyvinyl Chloride Length: 100 m Diameter of pipe: 150 mm Class: Minimum Class 4	
3.	Control valve	Ball Plastic valve 6”	
4.	Hydram specification	Ram body length: 80 cm Elbow: 150 mm Ram body pipe diameter: 150 mm Non-Return Waste Valve Diameter/Type/Orientation: 6”/Flap/upright Non-Return Delivery Valve/Type: 4”/Flap/upside down Air Chamber volume: 31 ltrs Air Chamber Diameter: 200 mm Air Chamber Depth: 1000 mm	
From pump to reservoir			
1	Delivery Pipe	Type of pipe: Polythene pipe Diameter of pipe: 50 mm Length of pipe: 1602 m Class of pipe: Class 6 minimum	

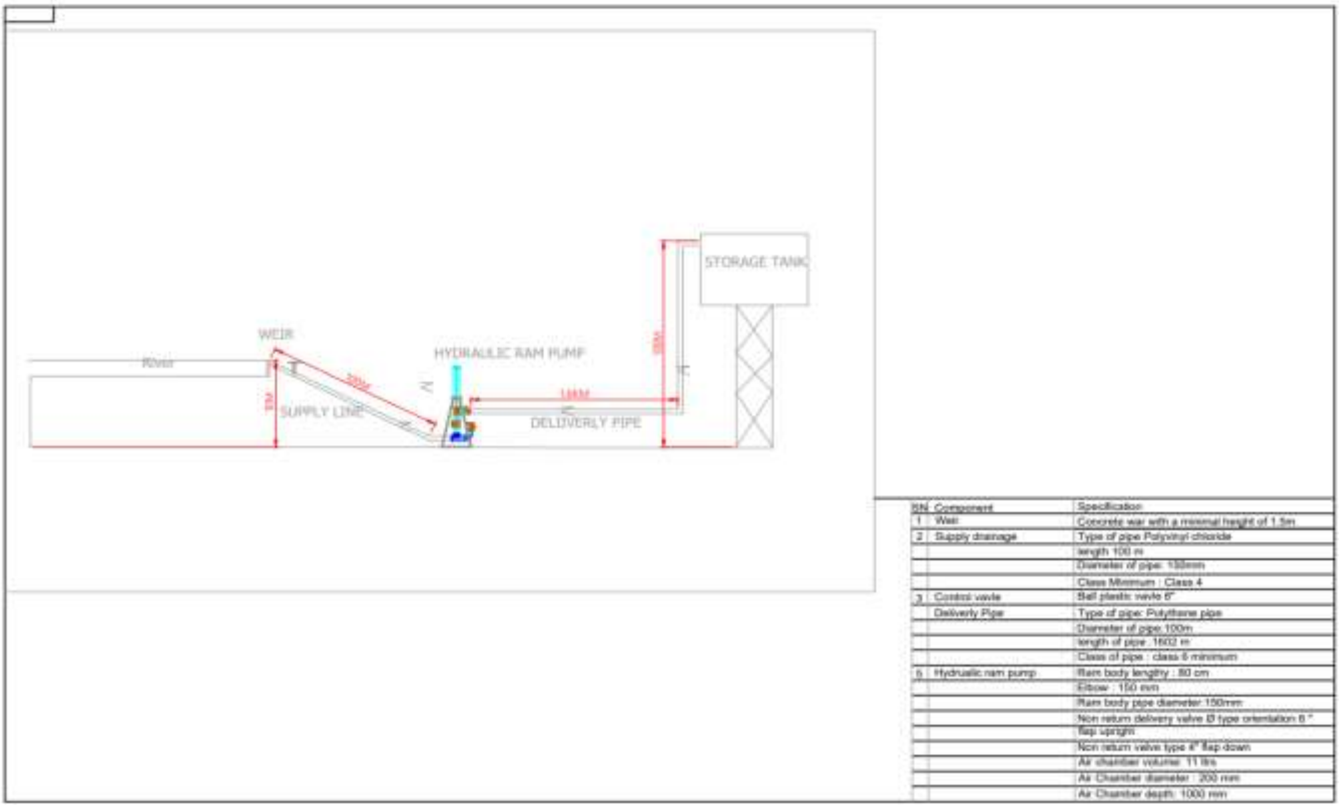

Figure 12. Sketch of proposed design

3.4 Simulation of hydraulic ram pump

To thoroughly evaluate the potential functionality of the designed hydraulic ram pump for Mulundu, an existing prototype of a hydraulic ram pump was selected and tested under real-world conditions in a natural stream. During the testing process, various operational parameters of the prototype were carefully observed and recorded. The supply flow and head to be specific where kept constant while the height to which the pump should lift the water was varied. The whole essence of doing this was to observe the variation in flow as the delivery height is increased. This was also used to determine the critical delivery head which is the maximum height of delivery beyond which a pump may not function

Table 4. Experimental delivery height positions vs fixed supply head

SN	Height for pump to deliver flow	Constant supply head
1	1.2	0.5
2	1.4	0.5
3	1.6	0.5
4	1.8	0.5
5	2	0.5
6	2.2	0.5
7	2.4	0.5
8	2.6	0.5
9	2.8	0.5
10	3	0.5
11	3.2	0.5
12	3.4	0.5
13	3.6	0.5
14	3.8	0.5
15	4	0.5
16	4.2	0.5
17	4.4	0.5
18	4.6	0.5
19	4.8	0.5

Simultaneously, theoretical output parameters were calculated using the design specifications of the prototype and relevant hydraulic principles. These theoretical values provided a baseline for understanding the pump's expected performance. The results from the theoretical analysis were then systematically compared to the actual performance data obtained during the prototype's operation. This comparative approach enabled a comprehensive assessment of the pump's efficiency, reliability, and alignment with the expected performance outcomes, providing valuable insights into its practical functionality

Figure 13. Proto-type hydraulic ram pump

3.4.1 Specifications of prototype hydraulic ram pump

An existing hydraulic ram pump with the following specification was used. The parameters listed below were used to theoretically and practically determine the performance of the hydraulic ram.

Table 5. Prototype Hydraulic ram pump specifications

SN	Component	Specification	*Comment*
From Source to pump			
1	Weir	Rectangular plate weir equipped with 2” filtration system	
2	Supply drive pipe	Type of pipe: Polyvinyl Chloride Length to pump: 15 m Diameter of pipe: 40 mm Class: Class 6	
3.	Control valve	Ball Plastic valve 2”	
4.	Hydram specification	Ram body length: 40 cm Elbow: 40 mm Ram body pipe diameter: 40 mm Non-Return Waste Valve Diameter/Type/Orientation: 2”/Flap/upright Non-Return Delivery Valve/Type: 1.5”/Flap/upside down Air Chamber volume: 2.5 ltrs Air Chamber Diameter: 75 mm Air Chamber Depth: 1000 mm	
From pump to reservoir			
1	Delivery Pipe	Type of pipe: Polythene pipe Diameter of pipe: 15 mm Length of pipe: 35 m Class of pipe: Class 6	

3.5 VBA application for updating hydraulic ram data

The current pump design under study is specifically for a certain terrain (Mulundu) which has its unique and specific parameters which may be different from other sites. Zambia has a number of potential sites that could be used for this purpose. A lot of isolated areas within the country could be potential sites for hydraulic ram installation. A quick example could be the various water Falls available

Table; Some selected waterfalls and their potential fall heads

SN	Waterfall Name	Province	Fall Height (meters)
1	Kundalila Falls	Central Province	70
2	Victoria Falls	Southern Province	108
3	Kalambo Falls	Northern Province	221
4	Ngonye Falls	Western Province	5
5	Chishimba Falls	Northern Province	60
6	Lumangwe Falls	Northern Province	35
7	Ntumbachushi Falls	Luapula Province	30
8	Nyambwezi Falls	North Western Province	20
9	Mumbuluma Falls	Northern Province	25
10	Mambilima Falls	Luapula Pronvnce	30

To address the need for efficient and specialized design processes, a unique VBA-based design application was developed. This application is equipped with four primary design features, each tailored to meet specific aspects of hydraulic system design and analysis:

1. **Hydraulic Ram Pump Design Form**: A user-friendly design form is included to display key parameters of hydraulic ram pump systems. This feature allows users to input data for any given location and instantly view the corresponding design outputs, enhancing usability and efficiency.

2. **Design Code Module for Mulundu**: The application incorporates a dedicated module that houses the design code for Mulundu. This module serves as the foundational framework for generating precise and location-specific hydraulic designs.
3. **Head Loss Calculation Code for Mulundu**: To facilitate detailed analysis, the application provides

a separate code module specifically for calculating head loss in the Mulundu system. This ensures accurate and reliable performance assessments tailored to the unique characteristics of this location.

4. **System Head Loss Determination Form**: Completing the suite of features is a form dedicated to determining the system head loss for any site. This versatile tool enables users to assess and optimize hydraulic performance across diverse scenarios and locations

This User Form facilitates user interaction with essential parameters. This User Form has features labeled Text Boxes for input variables such as supply head, supply flow, length of supply pipe, number of swing bits etc. and other relevant metrics, alongside a Command Button to trigger calculations. The expected output being delivery flow, Delivery Head, Waste valve flow ete.

In parallel, a separate module was created to be handling the core calculations and data management logic (design). This module will contain subroutines for performing the hydraulic calculations based on the input values from the UserForm, ensuring that all inputs are validated for numeric values with clear error messages for any invalid entries.

When the CommandButton is clicked, the code in the module retrieves values from the TextBoxes, execute the necessary calculations using established hydraulic formulas, and return the results to the UserForm for display. Additionally, the application incorporates functionality for users to save and load data, enabling easy updates and retrieval of previous entries.

To further enhance usability, the application includes preset default values in the TextBoxes, tooltips for user guidance, and robust error handling to ensure a seamless user experience. Finally, extensive testing was conducted to verify the accuracy of calculations and the reliability of the application before it is made available for use.

```
Sub CalculateHydraulicRamPump()
    ' Declare input variables
    Dim n As Double ' Number of beats
    Dim L As Double ' Length of supply pipe
    Dim r As Double ' Radius of supply pipe
    Dim Hs As Double ' Supply head
    Dim Cv As Double ' Velocity coefficient
    Dim g As Double ' Acceleration due to gravity

    ' Declare output variables
    Dim Qs As Double ' Supply flow
    Dim Vs As Double ' Velocity of supply flow
    Dim Qd As Double ' Delivery discharge
    Dim Hd As Double ' Delivery head
    Dim Qw As Double ' Waste

    ' Assign values to input variables
    n = 40                              ' Number of beats
    L = 1                               ' Length of supply pipe in meters
    r = 0.075                           ' Radius of supply pipe in meters
    Hs = 10                             ' Supply head in meters
    Cv = 0.96                           ' Velocity coefficient
    g = 9.81                            ' Acceleration due to gravity in m/s^2

    ' Calculate Supply Flow (Qs)
    Qs = (n * Application.WorksheetFunction.Pi() * L * r ^ 2) * 60000 / 60

    ' Calculate Velocity of Supply Flow (Vs)
    Vs = Cv * Sqr(2 * g * Hs)

    ' Calculate Delivery Discharge (Qd)
    Qd = 0.1 * Qs

    ' Calculate Delivery Head (Hd)
    Hd = 10 * Hs

    ' Calculate Waste (Qw)
    Qw = Qs - Qd

    ' Output results
    MsgBox "Supply Flow (Qs): " & Qs & " m³/s" & vbCrLf & _
           "Velocity of Supply Flow (Vs): " & Vs & " m/s" & vbCrLf & _
           "Delivery Discharge (Qd): " & Qd & " m³/s" & vbCrLf & _
           "Delivery Head (Hd): " & Hd & " m" & vbCrLf & _
           "Waste (Qw): " & Qw & " m³/s"
End Sub
```

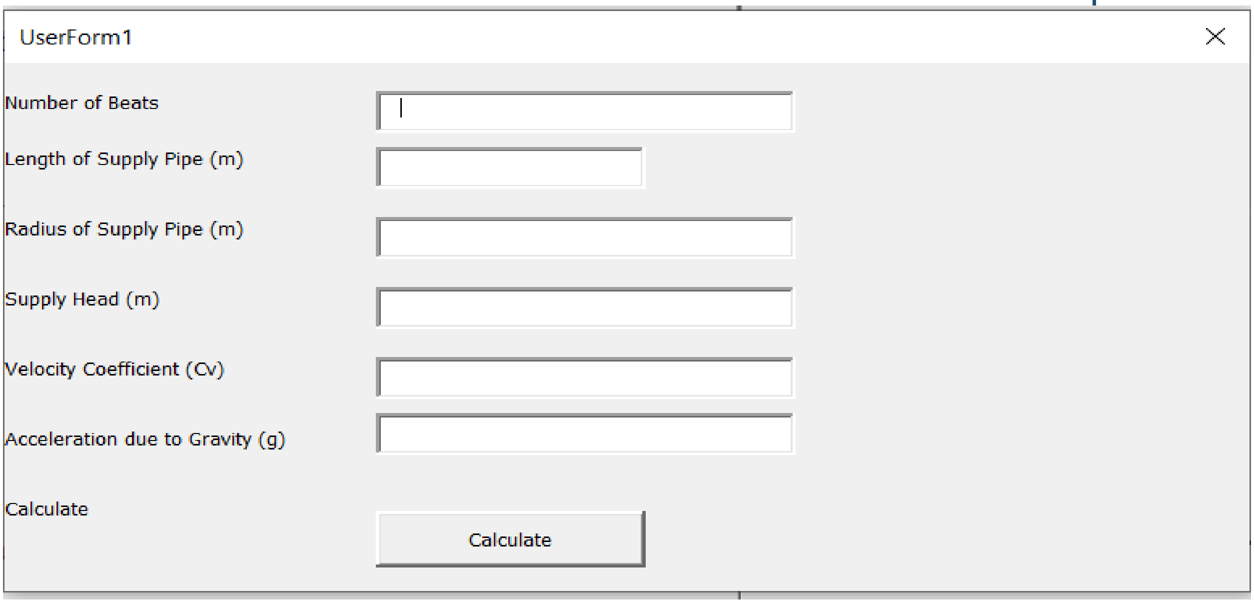

Figure 15. Form for updating parameters for any potential site

Input Data Validation checks

The newly designed VBA-based application incorporates an in-built code that effectively detects the type of data entered into the system, ensuring robust input data validation checks. For instance, if a user mistakenly enters a letter in a cell designated for numeric values, the system promptly displays an error message, guiding the user to provide the appropriate input data. This mechanism is crucial for maintaining data integrity and ensuring that calculations are based on valid entries. Once the user corrects the input, the system continues processing as intended. This seamless interaction enhances user experience by preventing errors before they can affect the application's functionality. The accompanying figure illustrates the code responsible for data entry validity detection, showcasing how the application ensures that only acceptable data types are processed, thereby reinforcing the reliability and accuracy of the application

3.6. Ethical considerations

The researcher followed the following ethical issues

- ✓ Obtained ethical clearance from Natural and Applied Sciences Research Ethics Committee (NASREC)
- ✓ Showed respect and maintained integrity for participants.
- ✓ Obtained consent from participants and ensure confidentiality

4. Results and Discussion

In designing a hydraulic ram pump, the results demonstrated significant efficiency in water lifting capabilities, particularly in low-flow scenarios. The pump effectively utilized the kinetic energy of flowing water to generate sufficient pressure, allowing it to lift water to considerable heights without the need for an external power source. The analyses showed that the pump could achieve a lift ratio of up to 10:1, meaning it could elevate water ten times higher than the source's original level. Additionally, the design's simplicity and minimal maintenance requirements were highlighted, making it an ideal solution for rural areas with limited access to electricity. Overall, the successful design of the hydraulic ram pump not only provided a sustainable water source but also showcased the potential for renewable energy applications in water management systems. Below are summaries of results achieved in this study

4.1 Supply Discharge, Delivery Discharge and Waste discharge

The calculations indicated a theoretical supply discharge of 706.950 liters per minute, which serves as the maximum supply flow rate of the system for the proposed pump in Mulundu. The calculated waste discharge of 636.255 liters per minute was recorded. This value of waste water highlights a significant loss, representing approximately 90% of the total supply. This indicates that only a small fraction of the water is being effectively utilized, as the delivery discharge stands at just 71 liters per minute, accounting for roughly 10% of the total supply. This however is a common trend for typical hydraulic ram pumps

When projecting the total discharge over a 24-hour period, the cumulative volume of 101,800.8 liters illustrates the pump's capability to provide a substantial amount of water. However, the stark contrast between the supply and the delivery raises concerns about efficiency and waste management. Improving the system to minimize waste could significantly enhance the overall effectiveness of the pump. However hydraulic ram pumps are known for low efficiencies

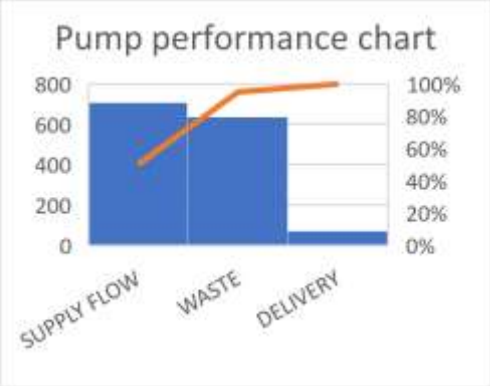

Figure 16. Pump performance chart

The current hydroelectric-based pump serving the Mulundu small scheme water community supplies water at a rate of 120,000 liters per day, which is marginally higher than the proposed hydraulic ram pump's capacity of 101,800.8 liters per day, resulting in a narrow difference of 18,199.2 liters, or approximately 15%. However, it is important to consider the operational costs associated with these two systems; while the hydroelectric pump incurs ongoing expenses due to its continuous consumption of electricity and may experience interruptions in service due to load shedding, the hydraulic ram pump, once installed, operates with almost zero cost. This stark contrast in operational efficiency and economic sustainability highlights the potential advantages of transitioning to a hydraulic ram pump system, particularly in terms of long-term maintenance and reliability, as it does not rely on external power sources and can provide a more consistent water supply for the community without the additional financial burden associated with energy consumption

4.2 Supply head, Delivery head and System head requirements

The results derived from the hydraulic ram pump calculations indicated a complex interplay between the supply head, theoretical delivery head, and friction or system head loss, which collectively influence the pump's efficiency and operational viability. With a supply head of 10 m, the pump has a limited energy source to draw from, which is crucial for its functioning. In contrast, the theoretical delivery head is set at 100 m, representing a significant lift requirement that far exceeds the available energy from the supply head. This disparity highlights a potential challenge, as the pump must overcome a total dynamic head of about 46.2074m. Specifically, a head loss of 46. 2074 m suggests that a considerable amount of energy is lost due to resistance from the fluid flowing through the pipe, which can significantly hinder the overall performance of the pump. In practical terms, this means that while the pump may be designed to lift water to a height of 100 m, the effective lift capability is diminished by the system head losses, which are substantial relative to the supply head. Consequently, the effective head that the pump can actually utilize for delivery becomes a critical factor. To enhance the pump's efficiency and ensure adequate water delivery, it may be necessary to implement design modifications, such as increasing the diameter of the delivery pipe which is currently at 50 mm to reduce losses. Minimizing the length of the delivery system, or selecting materials that promote smoother flow. These adjustments are essential to bridge the gap between the theoretical delivery head and the limitations imposed by the friction losses, ultimately allowing the hydraulic ram pump to operate more effectively and achieve its intended performance goals

4.

3 Theoretical and actual results from the simulated hydraulic ram pump

To ensure the effective functionality of the primary theoretical hydraulic ram pump designed for the Mulundu scheme, a separate prototype hydraulic ram pump's was used. This prototype was rigorously tested in a real-world setting, specifically on a local stream, to evaluate its operational capabilities and efficiency and then results compared to the main hydraulic ram pump design for Mulundu. During the testing phase, various performance metrics, such as flow rate and energy efficiency, were quantitatively monitored and recorded, allowing for a statistical comparison between the theoretical predictions and the actual performance observed in the field. This comparative analysis was essential for verifying the accuracy of the theoretical model and for identifying any variances attributable to environmental factors or design limitations. The insights derived from this performance assessment were invaluable for enhancing the overall design, contributing to a more robust understanding of the system's behavior under real-world conditions and informing future implementations within the Mulundu scheme. Results collected from the simulated pump are tabulated below

Table 6. Theoretical and actual results from a prototype hydraulic ram pump

sn	Theoretical		Actual		Percentage error (%)
	Parameter	**Quantity**	**Parameter**	**Quantity**	
1	Supply head	0.5m	Supply head	0.5 m	
2	Theoretical supply discharge	36.4l/min	Supply discharge	34.285 l/min	5.4
3	Theoretical delivery discharge	2.9 l/min	Delivery flow at critical head	2.5 l/min	13.8
4	NA		Critical delivery head	5m	
5	Theoretical pump efficiency	63.7%	Actual pump efficiency	58.3%	8.5

4.3.1 Findings from prototype

The table above is a summary of results recorded from a prototype. It involves both theoretical and the actual analysis

Supply Head

As can be seen from the above table, supply head used was consistent across both theoretical and actual measurements at 0.5 m, indicating that the pump is operating at the intended elevation. The researcher had no full control over this parameter as that was the maximum the terrain could provide

Supply Discharge

For the supply discharge, the theoretical value determined was 36.4 l/min, while the actual measurement was 34.285 l/min, resulting in a percentage error of 5.4%. This relatively small error indicates that the pump was performing close to its expected capacity. Such discrepancies can be quantified as absolute error (the difference between theoretical and actual values) and can be attributed to factors like minor leaks, friction losses, or turbulence, which may not have been fully accounted for in the theoretical model. The low percentage error suggests that the pump design is robust, but it also highlights the need for further investigation into the flow dynamics to pinpoint potential losses.

Delivery Flow at Critical Head

In contrast, the delivery flow at critical head exhibited a more pronounced deviation, with a theoretical discharge of 2.9 l/min compared to an actual delivery of 2.5 l/min, resulting in a percentage error of 13.8%. This larger error suggests significant hydraulic losses, potentially due to factors such as changes in the system's geometry, including bends or fittings that increase resistance. The discrepancy can also indicate that the pump may not be operating under optimal conditions, which could affect its overall performance. The error however was within the acceptable range

Critical Delivery Head

The critical delivery head, which is measured, is not merely a theoretical value but rather represents the maximum height to which the pump can effectively deliver water, and it can only be accurately determined through experimental methods. This understanding of the critical delivery head is essential for evaluating the pump's performance across various operational conditions, as it directly influences both the pump's operational limits, known as head, and its overall efficiency. In the context of this study, a supply head measured at 0.540 meters resulted in a critical delivery head of approximately 4.8 meters. This critical head was able to deliver a discharge 0.4ltrs/min. The relationship between the supply head and the delivery head is significant, as it provides insight into the pump's functionality, yielding a ratio that is indicative of performance; this ratio of 8.8:1 is particularly noteworthy as it aligns closely with the design guidelines outlined in the hydraulic ram pump handbook, which recommends a maximum Delivery head: Supply head ratio of 10:1. This close adherence to established guidelines underscores the importance of design validation in various applications as the case for Mulundu, ensuring that the pump once installed will meet the design expectations. The table below show field data collected during an experiment for determining critical delivery head

Table 7. Determination of critical head data

SN	ELEVATION	Volume ltrs	Time(s)	Time(min.)	Flow rate(ltrs/min.)	Comments
1	1.2	0.33	9	0.2	2.2	
2	1.4	0.33	13.5	0.2	1.5	
3	1.6	0.33	14	0.2	1.4	
4	1.8	0.33	15	0.3	1.3	
5	2	0.33	17.6	0.3	1.1	
6	2.2	0.33	19.1	0.3	1.0	
7	2.4	0.33	19.7	0.3	1.0	
8	2.6	0.33	20.1	0.3	1.0	
9	2.8	0.33	21	0.4	0.9	
10	3	0.33	21.5	0.4	0.9	
11	3.2	0.33	22	0.4	0.9	
12	3.4	0.33	22.5	0.4	0.9	
13	3.6	0.33	24	0.4	0.8	
14	3.8	0.33	24.6	0.4	0.8	
15	4	0.33	26	0.4	0.8	
16	4.2	0.33	28	0.5	0.7	
17	4.4	0.33	32.5	0.5	0.6	
18	4.6	0.33	40	0.7	0.5	
19	4.8	0.33	45	0.8	0.4	

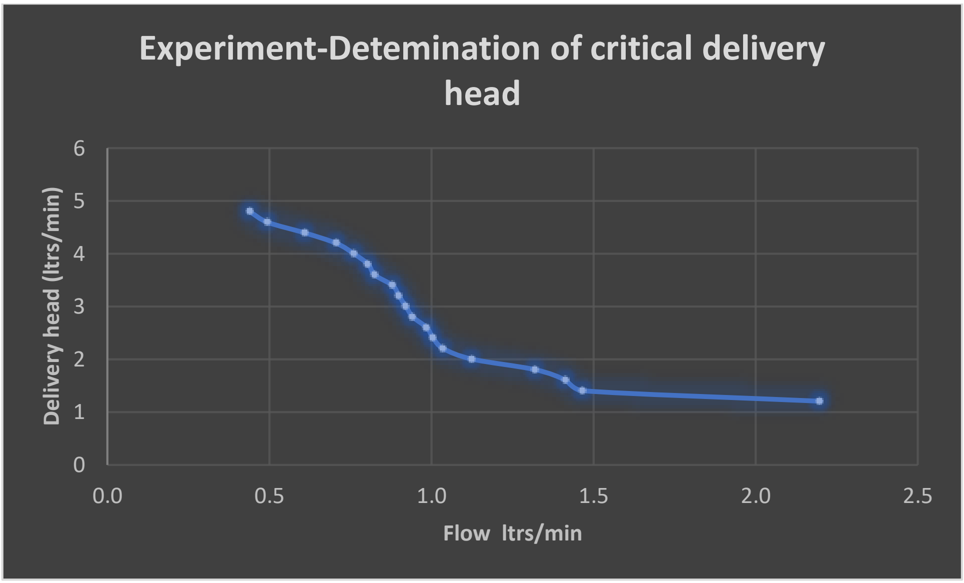

Figure 17. Critical delivery head determination

The results indicate that flow decreases as the delivery head increases, which aligns with the guidelines outlined in the hydraulic ram pump design handbook. At a delivery head of approximately 1.2 meters, the pump discharged around 2.2 liters per minute. However, as the delivery head increased, the discharge rate dropped significantly, eventually reaching 0.4 liters per minute

Pump Efficiency

The efficiency of the pump is another critical parameter which was assessed. The theoretical efficiency was 63.7% compared to an actual efficiency of 58.3%. This resulted into an efficiency loss of 8.5%. This reduction in performance can be quantified through energy balance equations and reflects the ratio of useful work output to total energy input. The differences in efficiency can be traced back to mechanical losses (due to wear or misalignment) and hydraulic losses (due to friction and turbulence). Understanding these losses through methods such as sensitivity analysis could provide further insights into which factors most significantly impact efficiency.

5. Conclusions and Recommendations

5.1 Conclusions

In conclusion, the successful design of the hydraulic ram pump for the Mulundu small scheme water community present a promising alternative to the existing hydroelectric pump system, particularly in terms of operational efficiency, cost-effectiveness, and sustainability. Operational efficiency in the sense that little effort is required to obtain high loads. A hydraulic ram pump once installed runs remotely and may demand minima to zero supervision. The pump is also sustainable in the sense that it is made out of local and readily available materials as opposed to the current hydro-electric based pump which has parts that may be scarce

The results of this study demonstrate that the hydraulic ram pump can effectively utilize the kinetic energy of flowing water to deliver substantial volumes, from a theoretical supply discharge of 706.950 liters per minute this pump is capable delivering 71 litres/min of delivery flow to the community which translates to 101,800 ltrs per day.

However, the contrast between the existing hydroelectric pump's daily supply of 120,000 liters and the hydraulic ram pump's capacity of 101,800.8 liters, the narrow deviation illustrates the potential for a transition to a system that operates at minimal ongoing costs, especially considering the reliability of the hydraulic ram pump, which is not subject to load shedding and does not require external power sources.

The study also reveals critical insights into the relationship between supply head, delivery head, and system head losses, indicating that optimizing design elements—such as these including pipe diameter and material, could enhance the pump's overall performance and also increase the capacity of the entire pumping system

5.2 Recommendations

To ensure the ongoing success of this project once implemented, several aspects must be considered. Firstly, and foremost, it is essential to form dedicated committees responsible for the maintenance and oversight of the hydraulic ram pump system, ensuring that all stakeholders, including local community members and non-governmental organizations (NGOs), are actively engaged in the process. Regular meetings should be scheduled to discuss system performance, address any operational challenges, and explore potential enhancements based on performance data and user feedback. Furthermore, fostering a sense of ownership among community members and active collaboration with NGOs can provide additional resources and support, ensuring that the hydraulic ram pump system is not only effectively managed but also sustainable in the long term. By addressing these factors and leveraging the insights gained from this study, the Mulundu water management system can enhance its efficiency, reduce waste, and provide a reliable water supply that meets the needs of the community, ultimately contributing to better water management practices in rural areas.

Lastly, Zambia has a potential of improving small scale farmers based by used of hydraulic ram pump especially in the northern part of the country where almost in each and every village, there is a natural stream with a considerable magnitude of a head. If such places are exploited, then mini hydraulic ram pumps could be designed and be installed for rural farmers

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