Experimental Performance Evaluation of Low-Cost Hydraulic Ram Pump in Bhutan

Sangey Pasang[1], Chimi Chezom[2*], Dependra Prasad Bhandari[3], Ugyen Tshomo[4], Chimi Wangmo[5], Lhundup Tshomo[6]

Civil and Environmental Engineering Department, College of Science and Technology, Royal University of Bhutan

E-mail: sangeypasang.cst@rub.edu.bt[1], 02230002.cst@rub.edu.bt[2*],02230007.cst@rub.edu.bt[3] , 022400061.cst@rub.edu.bt[4] , chimiwangmo.cst@rub.edu.bt[5], lhunduptshomo.cst@rub.edu.bt[6]

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Abstract

A water supplying technique where a portion of water is used to lift the water from rivers to agricultural land or any location where required and for any purpose is the hydraulic ram pump, one of the oldest mechanical devices for water lifting, invented centuries ago and still commercially available today. The first hydraulic ram was constructed by Whitehurst in 1772 (Whitehurst, 1775), and had to be operated manually. The hydraulic ram pump has not found popularity in Bhutan. According to Kubota (2020), Bhutan possesses one of the highest per capita water availabilities in the world. With an average river flow of about 2,238 cubic metres per second, the country produces approximately 70,572 million cubic metres of water annually, equivalent to around 94,500 cubic metres per person per year. Hydraulic ram pumps provide a sustainable and energy-free solution for lifting water in mountainous regions where conventional pumping systems are often impractical. This study developed and experimentally evaluated a low-cost hydraulic ram pump fabricated from locally available materials to assess its suitability for water supply applications in Bhutan. The prototype was tested under varying supply heads of 3.4 m to 4.3 m and delivery heads of 9 m and 10 m. Pump performance was evaluated in terms of discharge rate, hydraulic power and efficiency. Experimental results showed that increasing the supply head significantly improved pump performance. At a 9 m delivery head, the discharge increased from 0.225 to 0.338 m³/h, while the efficiency improved from 6.67% to 10% as the supply head increased from 3.4 m to 4.3 m. At a 10 m delivery head, the discharge ranged from 0.208 to 0.240 m³/h, with efficiencies increasing from 7.18% to 8.30%. The findings demonstrated a positive relationship between supply head and pump performance, confirming that higher available hydraulic energy enhances water delivery and system efficiency. The developed prototype operated successfully without any external energy source, showing its potential as an economical and environmentally sustainable water lifting technology suitable for Bhutan's terrain.

Keywords: *Hydraulic ram pump, valve, heads, Sustainable water supply, Experimental performance, Pump efficiency*

1. INTRODUCTION

1.1 Background and Working Principle

The hydraulic ram pump, also known as a hydram, lifts water without using external power input. Its historically lower performance combined with the affordability of fuels put this technology in the backburner of science and research for a long time. However, growing concerns about the impacts of fossil fuel use on the environment and the rising price of electricity have generated a renewed interest in such technology, consistent with the broader global push toward sustainable water resource development (UNESCO, 2021). Invented in the late 18th century, the self-acting hydraulic ram was developed by Joseph Montgolfier in 1796, building on John Whitehurst's manually operated precursor from 1772 (Whitehurst, 1775). The pump operates based on the water hammer effect, where the momentum of flowing water is suddenly stopped by a valve, generating a pressure surge that lifts water through a delivery pipe.

A pipe connected at one end to a tank containing water and the other end to a valve to regulate water flow. When the valve is completely open the water is flowing with velocity V in the pipe. However, if the valve is suddenly closed, the momentum of the water is disturbed and a high wave of pressure will be built up. This wave of high pressure will be transmitted along the pipe with a velocity equal to the velocity of a sound wave. This wave of pressure has the effect of hammering action and hence is called water hammer.

Estimation of the pump efficiency using theoretical calculation.

$$P_h = \frac{q * \rho * g * h}{3.6 * 10^6}$$

Where,

P_h=hydraulic power in kW
q=fluid flow in m^3/hour
ρ=density of fluid (1000 kg/m^3)
g=acceleration due to gravity (9.81 m/s^2)
h=total dynamic head
$3.6*10^6$ is the conversion of hours to seconds and watts to kilowatts

Input hydraulic power from drive head and drive pipe,

$$P_{in} = \frac{q_{drive} * p * g * h_{drive}}{3.6 * 10^6}$$

Output hydraulic power from delivery flow and delivery head,

$$P_{out} = \frac{q_{deliver} * p * g * h_{deliver}}{3.6 * 10^6}$$

Pump efficiency,

$$\eta = \frac{p_{out}}{p_{in}} * 100$$

1.2 Review of Contemporary Developments

Locally fabricated hydraulic ram pumps built from low-cost, off-the-shelf plumbing fittings have been documented in several construction guides (John, 2003; Mohammed, 2007), with subsequent work evaluating discharge and efficiency under varying waste-valve designs and low-head conditions (Ismail et al., 2018; Aqib et al., 2019). Recent advancements in localized hydram manufacturing emphasize the substitution of expensive, commercially cast-iron alloys with standard polyvinyl chloride (PVC) and galvanized iron (GI) plumbing fittings. While contemporary global studies (Suarda et al., 2020) have mathematically isolated the impacts of valve stroke length and air chamber volumes on volumetric efficiency, few empirical models capture these dynamics within micro-head configurations common to Himalayan Mountain streams. Furthermore, current literature lacks standardized empirical frameworks capable of predicting localized performance variations without relying on highly complex computational fluid dynamics (CFD) software. This study bridges the gap by synthesizing localized fabrication workflows with accessible, statistically validated empirical performance equations.

1.3 Problem Statement

Bhutan is a landlocked country with abundant water resources, mostly in the form of rivers, and a dense network of tributaries that flow down the steep slopes and side valleys, as shown in Fig. 1(a) (National Center for Hydrology and Meteorology [NCHM], 2018). While most human settlements in Bhutan are on rough terrains and mountainous slopes (Fig. 1(b)), the farmlands are scattered, which makes water accessibility limited for irrigation, agriculture, and drinking. The elevation difference of waterbodies and farmlands makes the development of irrigation and other modern farm structures very difficult. Therefore, there is a pressing need to design and test a self-operating pumping system that can function reliably in Bhutan's unique geographical and environmental conditions.

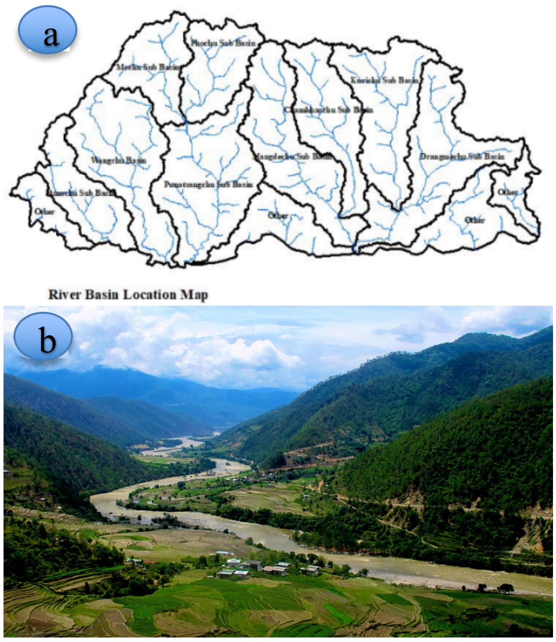


Fig. 1: *Distribution of river basins in relation to human settlement and farmland in Bhutan: (a) river basin location map showing the major basins and their tributary drainage networks (Source: NCHM, 2018); (b) terrain of Bhutan, illustrating the steep slopes and deep valleys that separate water sources from settlements and cultivated land*

1.4 Aim and Objectives

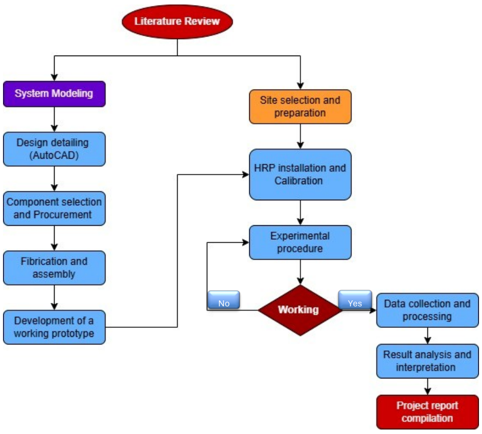
To develop a working prototype of hydraulic ram pump from locally available materials for sustainable water lifting.

The objectives of this research are as follows:

- To develop a low-cost, easy-to-assemble, user-friendly and sustainable hydraulic ram pump which every individual can assemble from the parts available in the local market.

- To enhance pump efficiency and delivery head by optimizing air chamber capacity.
- To check its suitability in practical applications.

2. MATERIALS AND METHODOLOGY



2.1 Experimental Set Up of Prototype

The study was conducted in the gym area of the College of Science and Technology, selected primarily for its reliable and sufficient water supply and topographic suitability (Fig. 2), with the pump installed at the site shown in Fig. 3. The experimental prototype was fabricated using locally procured materials.

The primary components of the setup included:

- Inlet/Drive Pipe (1): A 32 mm HDPE pipe that carried water from the source tank to the pump, providing the driving flow set 3 m above the pump.
- Waste Valve (3): A modified 32 mm brass check valve was utilized. To ensure smooth operation and appropriate timing for the water hammer cycle under the specific head conditions, the spring was intentionally removed from this waste valve. When the valve closes suddenly, the momentum of water creates a pressure surge.
- Air Chamber (4): A 75 mm diameter, 300 mm height PVC air chamber was installed to store compressed air, helping smooth out the flow and maintaining continuous delivery.
- Delivery Pipe (6): A 20 mm diameter HDPE pipe carried the pumped water from the air chamber to the higher elevation.

Fig. 2: *Gym area of the College of Science and Technology (CST) campus, the experimental site selected for its reliable year-round water supply and favourable topography*

Fig. 3: *Ram pump set-up site, showing the supply tank, the drive pipe alignment and the elevation difference between the water source and the pump*

2.2 Experimental Procedure

The hydraulic ram water pumping system operates automatically, converting a small amount of the water's potential energy into kinetic energy to lift a smaller portion of that water to a greater height. The sequence began when water flowed through the drive pipe from a set elevation, gaining velocity. As water exited through the open waste valve, the momentum increased until the valve suddenly closed, causing the high-pressure surge. This pressure forced the delivery valve to open, allowing a portion of the water into the air chamber, compressing the trapped air, which then pushed the water through the delivery pipe. Measurements were systematically recorded for discharge volume, time, and hydraulic power across varying supply heads for fixed delivery heads of 9 m and 10 m.

2.2.1 Mechanism of hydraulic ram pump

The hydraulic ram water pumping system operates automatically without requiring any external energy source. It has the unique ability to lift water to a higher elevation by utilizing only the potential energy of flowing water from a spring, stream, or river, which is driven by gravitational force (Rennie & Bunt, 1990). Essentially, the hydraulic ram pump converts a small amount of water's potential energy into kinetic energy to lift a smaller portion of that water to a greater height.

The system mainly consists of two basic valves: the waste valve and the delivery valve, as shown in Fig. 4. In addition, it includes an air chamber, an air valve, and a drive pipe connected to the water source. These components work together in a cyclic manner, where the opening and closing of the valves occur intermittently. The pump's operation is based on the water hammer phenomenon, which involves sudden pressure changes due to the rapid closure of the waste valve.

Fig. 4: *Parts of a working hydraulic ram pump: (1) drive pipe, (3) waste valve, (4) air chamber and (6) delivery pipe*

The sequence begins when water flows through the drive pipe from a certain elevation, gaining velocity due to gravity. As the water enters the pump body, it exits through the waste valve initially, which is open. When the velocity and momentum of the water increase, the waste valve suddenly closes, causing a water hammer effect that produces a high-pressure surge. This high pressure forces the delivery valve to open, allowing a portion of the water to enter the air chamber. The air chamber compresses the trapped air, storing energy that helps maintain a steady discharge even when the water hammer effect subsides. Once pressure equalizes, the delivery valve closes, and the air valve allows the compressed air to push water through the delivery pipe to the desired elevation.

2.2.2 System Modelling

An initial conceptual model of the hydraulic ram pump was developed from the literature to define its main components (supply reservoir, drive pipe, waste valve, pressure vessel, delivery pipe, check valve) and their interactions. The model maps mass and energy flow: supply head converts to flow in the drive pipe; abrupt valve closure creates a pressure spike that charges the pressure vessel and forces water into the delivery pipe. Key input (supply head, drive flow, pipe length, valve timing, vessel pre-charge) and output (delivery head, average pumped flow, cycle frequency) parameters were identified, along with the flow of energy, materials, or signals through the system. At this stage, critical design and operation variables were also established. The model acted as a blueprint that ensures a well-structured and technically feasible design.

2.2.3 Engineering Design and Detailing

After finalizing the conceptual model, the design was developed in CAD to produce accurate technical drawings (Fig. 5) with component dimensions, tolerances, and assembly sequences. Materials were selected based on strength, durability, cost, and local availability. Practical factors such as load distribution, safety, structural stability and maintainability were incorporated to ensure the design is robust, easy to assemble and practical to build.

2.2.4 Material Selection and Procurement

After completing the design, all necessary components were identified and selected. Each component was chosen based on its compatibility with the design specifications, its reliability, and overall performance characteristics. A procurement plan was prepared to ensure that quality materials and components were available on time. This step also considered cost-effectiveness and supply reliability to avoid delays during assembly and testing; the components procured for the prototype are shown in Fig. 6.

A detailed record of all materials purchased and utilized in constructing the hydraulic ram pump was maintained to ensure accurate cost estimation. The bill of purchases lists all components and accessories acquired for the project, while the cost report summarizes the actual quantities and costs of materials used during construction. This breakdown provides a clear understanding of the economic feasibility and material efficiency of the hydraulic ram pump system.

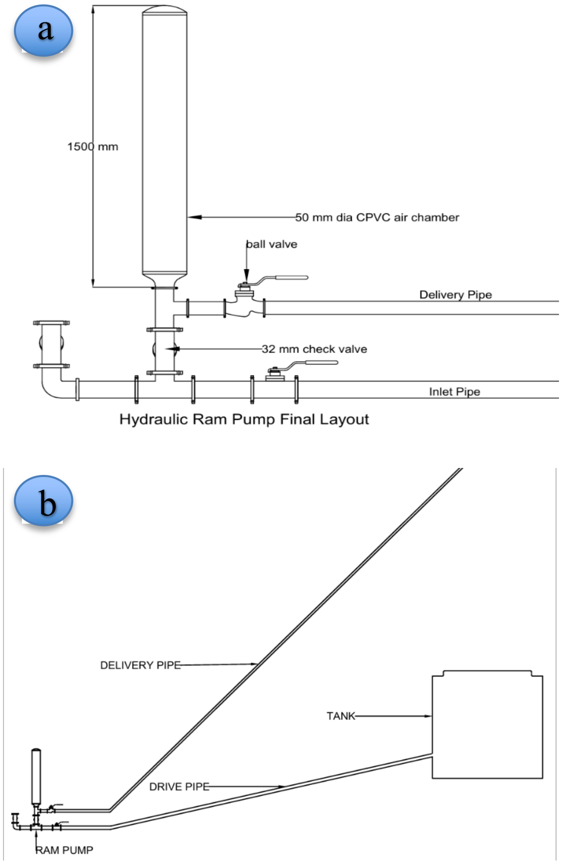


***Fig. 5**: AutoCAD drawings of the prototype: (a) hydraulic ram pump layout showing component dimensions and assembly sequence; (b) schematic representation of the ram pump set-up, including the supply tank, drive pipe and delivery line*

***Fig. 6:** Locally procured parts used to build the prototype: (a) individual components of the hydraulic ram pump before assembly; (b) the same components after assembly into the pump body*

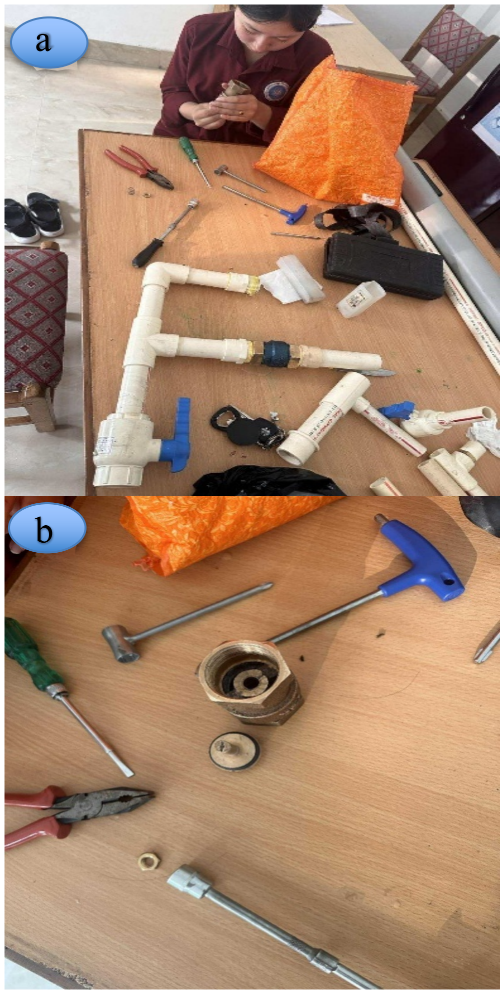


***Fig. 7:** Assembly of the pump: (a) fitting the parts in accordance with the technical drawings; (b) modifying the 32 mm brass check valve by removing its spring to serve as the waste valve*

2.3 Fabrication and Assembly

With all components in hand, fabrication and assembly of the system were carried out. Fabrication followed the technical drawings to maintain precision and meet the required tolerances. The assembly process was systematic, starting with sub-assemblies and then integrating them into the full system (Fig. 7). Proper alignment, fitting, and secure connections were ensured at every stage. Electrical and control elements were integrated where required. Quality checks were performed continuously to make sure the assembled structure met the intended design standards.

2.4 Development of the working model

After assembly, the complete system was configured into a working model. All connections and linkages were verified, and initial operational checks were carried out to confirm proper functionality. Any minor issues that appeared during this stage were resolved through adjustments and fine-tuning (Fig. 8). This working model became the foundation for all subsequent testing and performance evaluations.

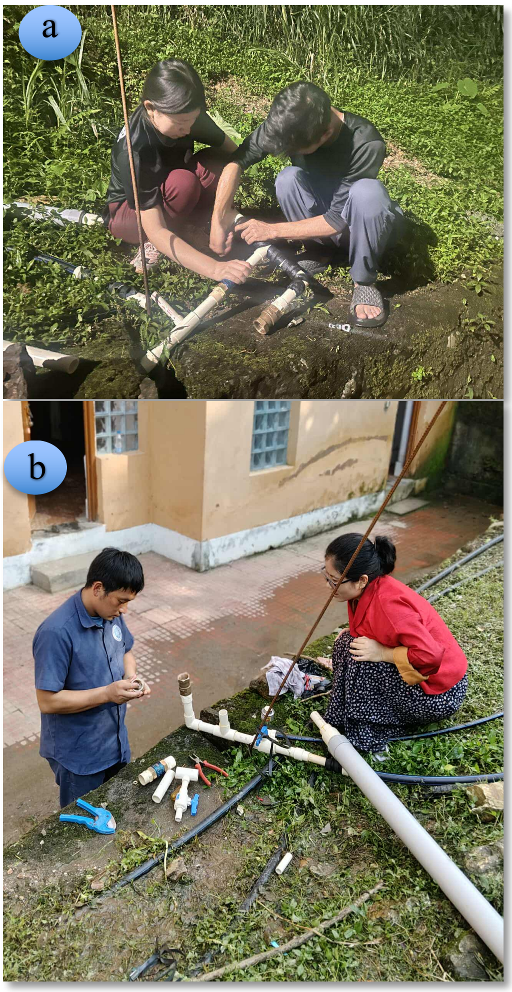


Fig. 8: *Development of the working model: (a) fixing the pump fittings and checking alignment; (b) sealing potential leakage points at the pipe joints*

2.5 Pump Installation and Calibration

The working model was then installed at the prepared site (Fig. 9). Instruments were carefully calibrated to guarantee accurate and reliable data collection. Structural alignment was checked to avoid any measurement errors during operation. Baseline readings were recorded after calibration to establish reference points for testing. The installation phase was critical in ensuring that the system performed consistently during experiments.

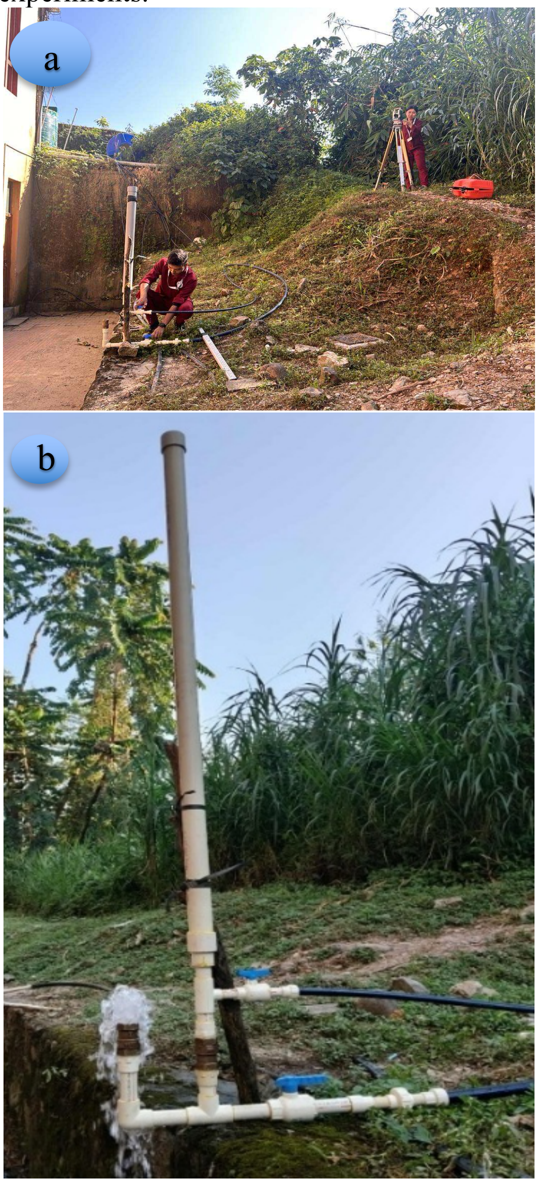


Fig. 9: *Field testing: (a) installation of the hydraulic ram pump at the prepared site; (b) the pump in operation, delivering water to the elevated outlet*

2.5.1 System Optimization (When Not Working)

Based on the analysis, areas with room for improvement were identified. Adjustments were made to components or operational settings to enhance system performance without compromising stability or safety. The improved configuration was then re-tested to verify the effectiveness of the changes.

2.6 Data Collection and Data Analysis

Data gathered during the experiment were carefully compiled and processed for further calculations to be carried out.

2.6.1 Definition of variables

For this experiment, the independent variables were the supply head and the delivery head, both parameters were set and controlled directly during the experimental trials. The dependent variables were the discharge, the hydraulic input and output power and the resulting efficiency of the pump which were functions of the two independent variables.

Table 1: *Discharge measured for 9 m delivery head*

Sl. No	Supply Head (m)	Time (sec)	Discharge (m³/h)
1	[illegible]	[illegible]	0.000
2	[illegible]	[illegible]	0.000
3	3.8	260	0.208
4	4.0	245	0.220
5	4.2	236	0.229
6	4.3	225	0.240

Q = 0.1197x - 0.1935
R^2 = 0.9019

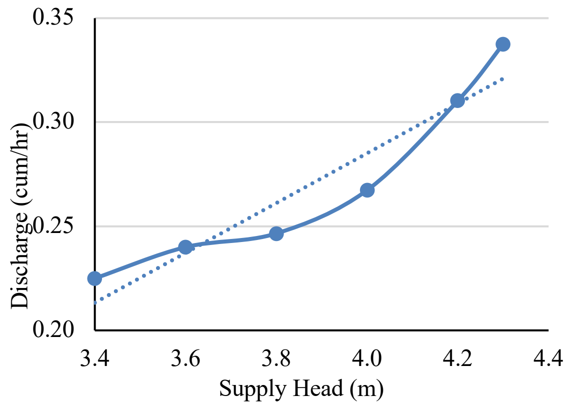


Fig. 10: *Pump performance curve for a 9 m delivery head: measured discharge against supply head over the range 3.4 m to 4.3 m (data from Table 1)*

At constant delivery head of 9 m and varying supply head, a positive correlation between supply head and discharge rate can be observed. From Fig. 10, it can be observed that when supply head increases from 3.4 m to 4.3 m, the discharge rises steadily from about 0.225 m³/h to 0.338 m³/h. This trend indicates that higher supply head provides more hydraulic energy, reducing discharge time and increasing flow rate. The relationship appears linear, showing that an increase in head yields increased discharges.

Table 2: *Discharge measured at 10 m delivery head*

Sl. No	Supply Head (m)	Delivery Head (m)	Volume (L)	Time (sec)	Discharge (L/sec)	Discharge (m³/h)
1	3.4	9.0	15.0	240	0.063	0.225
2	3.6	9.0	15.0	225	0.067	0.240
3	3.8	9.0	15.0	219	0.068	0.247
4	4.0	9.0	15.0	202	0.074	0.267
5	4.2	9.0	15.0	174	0.086	0.310
6	4.3	9.0	15.0	160	0.094	0.338

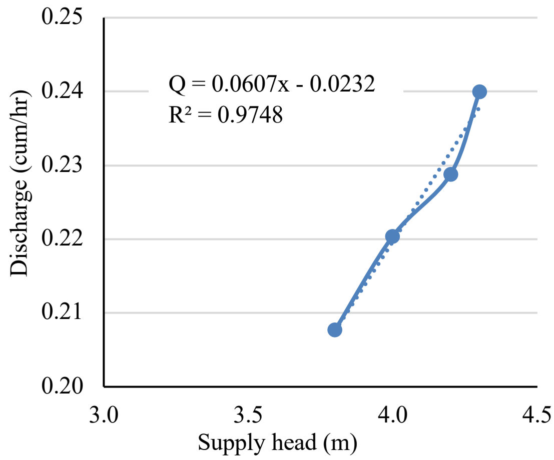


Fig. 11: *Pump performance curve for a 10 m delivery head: measured discharge against supply head over the range 3.8 m to 4.3 m (data from Table 2)*

Fig. 11 shows the relationship between supply head and discharge rate for varying supply head and constant delivery head of 10 m. As the supply head increases from 3.8 m to 4.3 m at a constant delivery head of 10 m, the discharge rate also increases from 0.208 m³/h to 0.240 m³/h. The positive relation between supply head and discharge indicates the pump delivers a higher discharge with increased supply head, which further improves efficiency.

Fig. 12 shows the variation of discharge when the supply heads of the two delivery heads are kept at 9 m and 10 m respectively. As the head of supply is increased from 3.4 m to 4.3 m, the discharge also rises for both cases. For a 9 m delivery head, discharge increases steadily from 0.225 m³/h to 0.338 m³/h, while for a 10 m head there is no lift achieved below the supply head of 3.8 m.

***Table 3:** Consolidated pump performance comparison across supply head, delivery head, discharge and efficiency for both 9 m and 10 m delivery head configurations*

Sl. No	Supply head (m)	Delivery head (m)	Discharge (m^3/h)	Efficiency (%)	Hydraulic output power (watt)
1	3.4	9	0.225	6.667	3.679
2	3.6	9	0.240	7.111	3.924
3	3.8	9	0.247	7.306	4.032
4	4.0	9	0.267	7.921	4.371
5	4.2	9	0.310	9.195	5.074
6	4.3	9	0.338	10.000	5.518
7	3.4	10	0.000	0.000	0.000
8	3.6	10	0.000	0.000	0.000
9	3.8	10	0.208	7.180	3.962
10	4.0	10	0.220	7.619	4.204
11	4.2	10	0.229	7.910	4.365
12	4.3	10	0.240	8.296	4.578

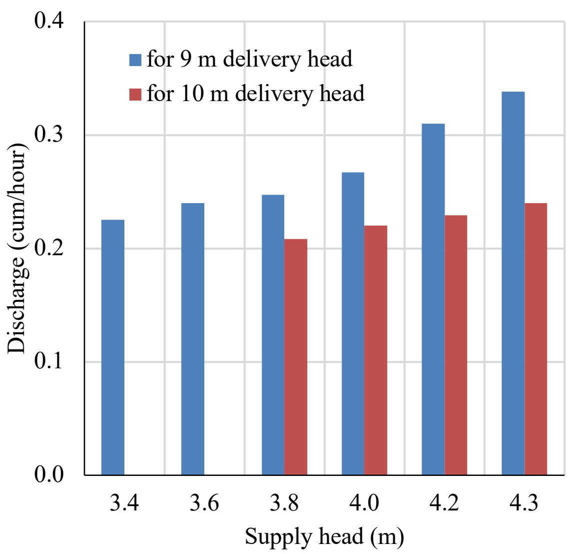


***Fig. 12:** Pump performance comparison for the 9 m and 10 m delivery heads: discharge against supply head for both configurations (data from Tables 1 and 2)*

The methodology concluded with a comprehensive review of the entire development and testing process. The final outcomes were evaluated against the initial objectives set during the early stages of the work. Key findings, performance achievements, and the practical relevance of the developed system were summarized. Limitations were also acknowledged, and recommendations were made for future improvements, potential applications, and further research.

***Table 4:** Hydraulic input power*

Sl. No	Time (sec)	Discharge (m^3/h)	Hydraulic Power (watt)
1	16.000	3.375	55.181

***Table 5:** Hydraulic output power of 9 m delivery flow*

Sl. No	Supply Head (m)	Time (sec)	Discharge (m^3/h)	Hydraulic Power (watt)
1	3.400	240.000	0.225	3.679
2	3.600	225.000	0.240	3.924
3	3.800	219.000	0.247	4.032
4	4.000	202.000	0.267	4.371
5	4.200	174.000	0.310	5.074
6	4.300	160.000	0.338	5.518

***Table 6:** Hydraulic power output of 10 m delivery flow*

Sl. No	Supply Head (m)	Time (sec)	Discharge (m^3/h)	Hydraulic Power (watt)
1	3.800	260	0.208	3.962

2	4.000	245	0.220	4.204
3	4.200	236	0.229	4.365
4	4.300	225	0.240	4.578

3. RESULTS AND DISCUSSION

The prototype of a hydraulic ram pump was assembled at a total cost of Nu. 6,253.05 (Nu. six thousand two hundred fifty-three and five chhertum only). Major expenditures were incurred on the vertical check valves and pipes, while other fittings contributed minimally to the overall cost. Since the hydraulic ram pump will not incur additional cost after the initial one, it shall be considered cost-efficient.

3.1 Results from the Experiment

Measurements of discharge at two delivery heads, one at 9 m and the other at 10 m, were recorded for varying supply heads and the results are as follows. The hydraulic input power supplied by the drive flow was measured as 55.181 W (Table 4), and this value was used as the reference for all efficiency calculations reported below:

Fitting trendlines to the data in Tables 5 and 6, for the 9 m delivery head, a linear relationship between supply head and discharge of $Q = 0.1197x - 0.1935$ ($R^2 = 0.90$) was observed. For the 10 m delivery head, discharge follows $Q = 0.0607x - 0.0232$ ($R^2 = 0.97$), where x is supply head in metres, Q is discharge in m^3/h. The consistently high R^2 values indicate that supply head is a strong single predictor of discharge, efficiency and output power within the tested range.

The experimental results clearly showed that as the supply head increased, both the discharge rate and efficiency increased. From Tables 5 and 6, it can be observed that when the supply head was raised from 3.4 m to 4.3 m, there was a noticeable increase in discharge for both 9 m and 10 m delivery heads. For the 9 m delivery head, discharge rises from 0.225 m^3/h to 0.338 m^3/h, showing a linear correlation. While for the 10 m delivery head, discharge increases more gradually, from 0.208 m^3/h at 3.8 m to 0.240 m^3/h at 4.3 m though there was no discharge for supply head below 3.8 m.

The efficiency, consolidated alongside discharge and hydraulic output power for both delivery heads in Table 3, follows the same trend: at 9 m head, efficiency increases from 6.67% to 10%, whereas at 10 m head it increases from 7.18% to 8.30% for the same supply head of 3.8 m to 4.3 m.

This finding aligns well with hydraulic principles: a higher supply head provides more potential energy, resulting in stronger pressure surges due to the water hammer effect and better overall pumping performance.

Some minor issues were encountered during the process of assembling the parts and while carrying out the experiment. Issues such as small leakages at pipe joints and slight variations in performance depending on the water source flow, rupture of the air chamber were encountered. However, these challenges can be resolved through skills and knowledge in choosing better quality materials and following various techniques to seal leakages. Despite these small limitations, the pump developed functioned automatically and efficiently, without the requirement for manual intervention.

4. CONCLUSION

The study established that the performance and efficiency of a hydraulic ram pump are affected by many parameters like supply and delivery head, the design of the air chamber and the modification of the valve configuration and number of valves. The experiment showed that a slight increase in the supply head led to considerable increase in discharge rate and overall efficiency of the pump. Although increasing the delivery head reduced discharge rate, the pump was still capable of lifting water up to 10 metres with a supply head as low as 3.8 metres considering the small-scale pump used for the experiment. At the lower delivery head of 9 m, a maximum efficiency of 10% was achieved at a supply head of 4.3 m. The air chamber proved to be a vital component, helping to stabilize pressure fluctuations and ensure a smooth and continuous flow. The pump's ability to operate automatically without any external power source highlights its potential as an environmentally friendly and sustainable technology.

In future research, it will be of significance to explore more on valve size, numbers and pipe diameters used, design and material of air chamber since it significantly determines the efficiency and flow of water from pump to delivery point.

In summary, this research project successfully demonstrated that hydraulic ram pumps are both a practically suitable and sustainable alternative to the conventional pumps to Bhutan's mountainous terrain and higher water resource availability, which aligns well with Bhutan's goals of environmental preservation and renewable energy use while delivering reliable water solutions.

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