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Head–Flow Response and Short-Term Repeatability of a Low-Cost PVC Hydraulic Ram Pump

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ABSTRACT

Hydraulic ram pumps use the energy of flowing water to lift a portion of that water without external power, yet their reported performance depends strongly on how head conditions and flow boundaries are defined. This study examined the head–flow response and short-term repeatability of a low-cost hydraulic ram pump constructed from nominal 2-inch PVC components and fitted with a nominal 3-inch, 0.60-m air chamber. Three operating configurations combined supply and delivery heads of 1.50/4 m, 1.70/5 m, and 1.90/6 m. Each configuration was evaluated through fifteen volumetric tests using a fixed collection volume of 100 L. Discharge was calculated for every replicate from collection volume and filling time, then assessed using descriptive statistics, 95% confidence intervals, one-way analysis of variance, Tukey comparisons, and a Kruskal–Wallis test. Mean measured discharge increased from 10.53 ± 0.23 L s−1 in the first configuration to 11.59 ± 0.18 and 13.92 ± 0.54 L s−1 in the second and third configurations, respectively. Differences among configurations were pronounced ($F_{2,42}$ = 362.58, $p < 0.001$, η^2 = 0.945). Estimated input-side hydraulic power rose from 154.7 to 259.0 W, whereas the intermediate configuration produced the lowest coefficient of variation (1.53%). The highest-head configuration favored throughput and available hydraulic power, while the intermediate state provided the most consistent short-duration measurements. Hydraulic efficiency could not be determined because drive, waste, and delivered flows were not measured separately.

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1. Introduction

Access to water is shaped by both source availability and the elevation difference between the source and the point of use. Springs, streams, and irrigation channels in rural or mountainous terrain are often located below storage tanks, homes, livestock facilities, or cultivated fields. Electric and fuel-driven pumps can overcome this elevation difference, but their use becomes difficult where power is unreliable, fuel transport is costly, or maintenance support is limited. A hydraulic ram pump offers a simple alternative by converting part of the gravitational energy of a continuous source flow into periodic pressure pulses that lift a smaller volume of water. This operating principle supports remote water supply, irrigation, and low-head energy recovery when sufficient flow and natural fall are available [1-3]

The hydraulic ram cycle is inherently transient. Water accelerates along the drive pipe while the waste valve is open; rapid valve closure then decelerates the water column and produces a pressure rise. That pulse opens the delivery valve, directs part of the flow into the air chamber and delivery line, and subsides as energy is transferred. The delivery valve subsequently closes, the waste valve reopens, and the cycle begins again. Air trapped in the chamber cushions the pulse and sustains delivery between valve events. Valve-closing time, repeated valve motion, and possible backflow make this behavior more complex than a single static water-hammer force [4,5].

Pump performance reflects the combined effects of hydraulic head, flow rate, pipe geometry, valve dynamics, and air-chamber compliance. Supply head determines the gravitational energy available to accelerate water in the drive pipe, whereas delivery head represents the elevation demand imposed on useful flow. Waste-valve mass, stroke, seat geometry, and opening area influence cycle timing and local losses. Previous studies have shown that redesigning the waste valve can reduce losses and improve lifting performance [6], while low-cost PVC construction remains attractive for small irrigation systems in hilly terrain [7]. Component arrangement also affects pressure behavior and the range of heads over which cycling remains regular [8].

An increase in supply head does not guarantee simultaneous improvement in every performance measure. Tests of combined conventional and ram-pump systems have identified restricted operating ranges and decreasing delivered flow as discharge head rises [9]. Other experiments found that additional supply head increased flow and pressure-surge amplitude, although the setting with the highest efficiency or lowest waste fraction occurred elsewhere [10]. Testing-rig studies likewise reported different factor combinations for maximum volumetric efficiency, outlet discharge, and pressure [11]. Throughput, efficiency, pressure regularity, structural loading, and cost therefore need to be evaluated as distinct outcomes.

Recent optimization work has formalized these competing objectives by examining delivery flow, efficiency, critical drive head, and cost within a single decision framework [12]. Proposed changes to valve reopening, including magnetic repulsion, also show that reliable

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operation at low head depends on the balance of hydraulic and mechanical forces [13]. Field assessments of ram-pump technology similarly consider flow, head, maintainability, and operational reliability together [14]. Meaningful comparison across studies additionally requires an explicit flow boundary, because drive flow, waste flow, and delivered flow represent different parts of the hydraulic balance.

This study evaluates a low-cost PVC hydraulic ram pump at three coupled supply-head/delivery-head states: 1.50/4 m, 1.70/5 m, and 1.90/6 m. Fifteen repeated 100-L filling tests were available for each state, allowing both mean response and short-term variation to be examined. The analysis had four objectives: to compare measured discharge among the configurations, quantify within-configuration repeatability, estimate theoretical velocity and head-related energy indicators, and identify which state best serves throughput, input-side power, or repeatability. Supply and delivery heads were treated as a coupled configuration because both changed together. The working expectation was that higher-head states would yield greater measured discharge and available hydraulic power, but that the state with the largest flow would not necessarily produce the smallest relative variation.

2. Methods

2.1 Experimental design and apparatus

The field experiment used a hydraulic ram pump assembled mainly from nominal 2-inch PVC pipe and fittings. The system consisted of a source connection, drive pipe, waste valve, delivery valve, air chamber, and delivery line. The air chamber was constructed from nominal 3-inch PVC with a recorded height of 0.60 m, and water served as the working fluid. Geometric heads, a fixed 100-L collection volume, and filling times were recorded for replicate analysis. Synchronized pressure, valve-displacement, and separate drive, waste, and delivered-flow measurements were not available, so transient force and hydraulic efficiency were excluded from the quantitative evaluation.

Three operating configurations were tested. C1 paired a 1.50-m supply head with a 4.0-m delivery head, C2 paired 1.70 m with 5.0 m, and C3 paired 1.90 m with 6.0 m. Their delivery-to-supply head ratios were 2.67, 2.94, and 3.16, respectively. Pump body, chamber dimensions, PVC material, valve arrangement, working fluid, and collection volume remained unchanged. Because supply and delivery heads increased simultaneously, the experiment compared complete operating states rather than independent main effects of either head. The schematic arrangement of the experimental hydraulic ram system is shown in Figure 1, illustrating the source reservoir, drive pipe, ram pump, air chamber, delivery pipe, storage reservoir, and the definitions of supply head (Hs) and delivery head (Hd).

Table 1 summarizes the three coupled supply-head/delivery-head configurations and the apparatus characteristics maintained constant throughout the experiments, allowing differences in measured response to be interpreted primarily in relation to the tested operating states.

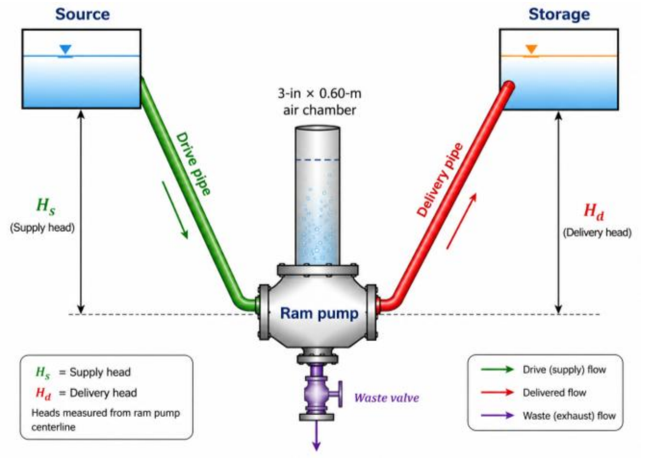

Figure 1. Schematic arrangement of the tested hydraulic ram system. Hs is the supply head and Hd is the delivery head; dimensions are not to scale

Table 1. Experimental configurations and fixed apparatus characteristics

Configuration	Supply head (m)	Delivery head (m)	Hd/Hs	Fixed apparatus
C1	1.50	4.0	2.67	2-in PVC pump body; 3-in × 0.60-m air chamber
C2	1.70	5.0	2.94	Same pump, chamber, valves, fluid, and collection volume
C3	1.90	6.0	3.16	Same pump, chamber, valves, fluid, and collection volume

2.2 Volumetric measurements

Discharge was measured volumetrically by recording the time required to collect 100 L at each operating state. Fifteen measurements were completed for each configuration, giving 45 observations in total. Filling times ranged from 9.23 to 9.75 s for C1, 8.32 to 8.82 s for C2, and 6.67 to 7.75 s for C3. Repeated measurements were made with the same apparatus and collection procedure to characterize short-duration variation under each head pair.

Discharge for replicate i was calculated as Qi = V/ti, where V was the fixed collection volume of 100 L and ti was filling time in seconds. The mean for each configuration was obtained from the fifteen replicate discharge values rather than by dividing volume by the mean time. This approach retains the reciprocal relation between time and flow at the observation level and prevents elapsed time from being interpreted as a discharge measurement.

The measurement record identifies the volumetric collection procedure but does not specify whether the collection point represented the drive stream, waste-valve stream, delivered stream, or a combined path. The response is therefore reported conservatively as measured volumetric discharge rather than useful delivery discharge. No efficiency or water-balance calculation was attempted. Such calculations would require simultaneous measurements of water entering the pump, leaving through the waste valve, and reaching the elevated outlet. Because the collection boundary was not explicitly documented, the measured discharge should be interpreted as a general volumetric flow response rather than as useful delivery discharge, and no inference regarding hydraulic efficiency should be made from these measurements alone.

2.3 Hydraulic calculations

The velocity associated with each supply head was estimated from $v_{th} = (2gH_s)^{1/2}$, using $g = 9.81$ m s^{-2}. This ideal relation converts gravitational head to velocity head and was used only to compare the three supply-head settings. It does not account for entrance effects, drive-pipe friction, fitting and valve losses, unsteady motion, fluid compressibility, or pipe-wall deformation. The calculated values therefore represent theoretical head scaling rather than instantaneous velocity measured inside the drive pipe.

Gravitational potential-energy density was calculated as $e_p = \rho gH_s$ with water density $\rho = 998.2$ kg m^{-3}. Its unit is J m^{-3}, which is numerically equivalent to Pa. The quantity expresses energy per unit volume and should not be interpreted as the total potential energy of an unspecified mass of water. Substitution of v_{th} into $0.5\rho v^2$ yields the same value as ρgH_s by definition, so the corresponding kinetic-energy density is not an independent observation.

Available hydraulic power for the measured stream was estimated from $P_{av} = \rho gQH_s$, with Q converted to m^3 s^{-1}. The indicator combines supply head and observed volumetric rate to show how gravitational power changed among configurations. It describes the input side of the measured stream, not useful output power. Computing efficiency would additionally require an identified delivered discharge and its associated delivery head or pressure.

Water-hammer pressure and impact force were not estimated because the required transient variables were not measured. A defensible calculation would need actual pipe diameter and wall thickness, an appropriate wave speed, pre-closure velocity, valve-closure time, and preferably high-frequency pressure records. Experimental and numerical studies of hydraulic shock show that pressure and flow must be resolved in time and related to the valve event [15,16]. Omitting a force estimate avoids assigning precision to a dynamic quantity that the experiment did not observe.

2.4 Statistical analysis

Arithmetic mean, standard deviation, standard error, 95% confidence interval, minimum, maximum, and coefficient of variation were calculated for the fifteen discharge observations in each configuration. The coefficient of variation, defined as 100 × SD/mean, served as a relative measure of short-term repeatability. Confidence intervals used the t distribution because each group contained fifteen observations and population variances were unknown.

A one-way analysis of variance tested whether mean measured discharge differed among C1, C2, and C3. Effect size was expressed as eta squared, $\eta^2 = SS_{between}/SS_{total}$. Tukey's honestly significant difference procedure evaluated pairwise contrasts while controlling the family-wise error rate. A Kruskal–Wallis test provided a rank-based sensitivity check. Statistical decisions used $\alpha = 0.05$, while interpretation also considered effect size, uncertainty, and hydraulic meaning.

Each group consisted of repeated measurements from one pump at one operating state. The fifteen observations therefore represent measurement replication, not independent pumps or study sites. Inferential results describe separation among the three states during this test campaign and should not be extrapolated as a universal response for other pump geometries, materials, or installations.

2.5 Quality assurance

Quality checks began by calculating every discharge value directly from its recorded 100-L filling time. Litres were converted to cubic metres only for power calculations, and all head values were expressed in metres. Configuration means were checked against the replicate data, and the velocity, energy-density, and power values were independently recomputed from their defining equations.

Measured and derived quantities were kept separate throughout the analysis. Filling time remained a time variable, the air chamber was treated as a fixed component, and no transient force was reported without wave-speed, closure-time, or pressure data. Comparisons of operating states were consequently limited to measured discharge, estimated input-side hydraulic power, and the coefficient of variation.

3. Results and Discussion

3.1 Measured discharge and uncertainty

Filling time declined as the operating state changed from C1 to C3. Mean values were 9.499 s for C1, 8.633 s for C2, and 7.193 s for C3. Because collection volume remained fixed, this decrease corresponds to increasing discharge. Mean measured discharge was 10.532 L s^{-1} for C1, 11.586 L s^{-1} for C2, and 13.923 L s^{-1} for C3. C2 exceeded C1 by 10.0%, while C3 exceeded C1 by 32.2%, an absolute difference of 3.391 L s^{-1}.

Variation within each configuration was small relative to the differences among configuration means, although its magnitude was not uniform. Standard deviations were 0.232, 0.177, and 0.537 L s^{-1} for C1, C2, and C3, producing coefficients of variation of 2.21%, 1.53%, and 3.86%. C2 had the tightest relative clustering; C3 combined the largest mean discharge with the largest dispersion. The corresponding 95% confidence intervals were 10.403–10.660, 11.488–11.683, and 13.625–14.220 L s^{-1}. Figures 2 and 3 demonstrate the clear separation among the three configurations, with Figure 2 showing the distribution and within-configuration variability of individual measurements and Figure 3 showing differences in mean discharge and their 95% confidence intervals.

The one-way analysis of variance detected a strong difference among operating states ($F_{2,42} = 362.58$, $p < 0.001$). Eta squared was 0.945, meaning that 94.5% of the variation observed during this campaign occurred between the three configuration groups. Every Tukey contrast was significant: C2 exceeded C1 by 1.054 L s^{-1}, C3 exceeded C1 by 3.391 L s^{-1}, and C3 exceeded C2 by 2.337 L s^{-1}. The Kruskal–Wallis test reached the same conclusion ($H = 39.18$, $p < 0.001$), indicating that the result was not dependent on the parametric test alone.

The large effect size describes this apparatus and test sequence rather than performance across the broader population of hydraulic ram pumps. Between-state differences were much larger than the scatter produced by repeated measurements, which naturally yields a high η2. Other pipe dimensions, valve settings, source conditions, and maintenance states could alter both mean flow and variability. The present evidence is therefore strongest for distinguishing C1, C2, and C3 under the recorded conditions.

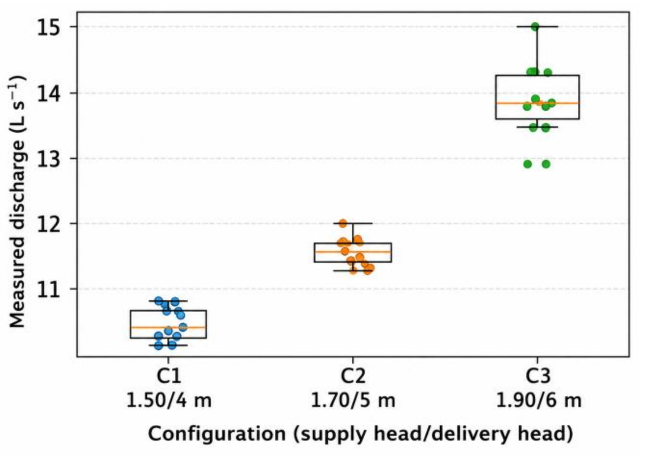

Figure 2. Distribution of replicate measured discharge for C1, C2, and C3. Boxes show interquartile ranges, centre lines show medians, and points represent individual measurements

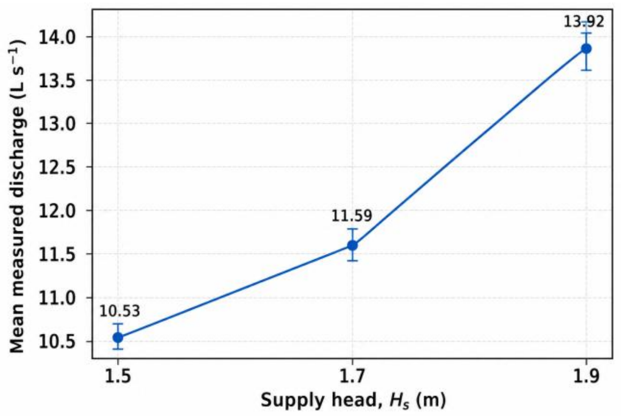

Figure 3. Mean measured discharge for the three supply-head settings. Error bars show 95% confidence intervals (n = 15); the associated delivery heads were 4, 5, and 6 m

3.2 Hydraulic scaling and preferred operating state

Theoretical velocity increased from 5.425 m s−1 at a supply head of 1.50 m to 5.775 m s−1 at 1.70 m and 6.106 m s−1 at 1.90 m. C3 was 12.5% higher than C1. Because velocity scales with the square root of head, the increase was smaller than the change in gravitational energy density. Energy density rose from 14.689 to 16.647 and 18.605 kJ m−3, a 26.7% increase between C1 and C3. Both metrics describe ideal head-related scaling and not energy transferred through the full unsteady cycle.

Combining measured discharge with supply head gave estimated available hydraulic powers of 154.7 W for C1, 192.9 W for C2, and 259.0 W for C3. The C3 estimate was 67.5% above C1 because power depends on the product of head and flow. Relative to the C1 baseline in Figure 4, energy density reached approximately 127%, discharge 132%, and available power 167% in C3. These distinct rates of increase show the value of reporting power alongside head and flow, provided it remains identified as an input-side estimate.

Table 2 summarizes the principal statistical and hydraulic indicators for the three operating configurations, highlighting the increase in discharge, theoretical velocity, energy density, and available hydraulic power from C1 to C3, together with the comparatively low variability of C2.

Table 2. Statistical and hydraulic summary of the tested configurations

Config.	Measured discharge (L s−1)	CV (%)	vth (m s−1)	Energy density (kJ m−3)	Available power (W)
C1	10.53 ± 0.23 CI: 10.40–10.66	2.21	5.42	14.69	154.7
C2	11.59 ± 0.18 CI: 11.49–11.68	1.53	5.78	16.65	192.9
C3	13.92 ± 0.54 CI: 13.63–14.22	3.86	6.11	18.61	259.0

Note. Discharge values are mean ± standard deviation (n = 15). Energy density equals ρgHs, and available power equals ρgQHs. The power values are input-side estimates and do not represent useful output power or hydraulic efficiency.

Performance ranking depended on the selected criterion. C3 produced the largest measured discharge, theoretical velocity, energy density, and available hydraulic power while operating at a 6-m delivery head. It is therefore the preferred tested state when maximum measured throughput or input-side power is the priority. C2 had the lowest coefficient of variation and is preferable when short-term repeatability matters most. C1 required only 1.50 m of natural fall, which may be decisive at sites where a larger supply head is unavailable.

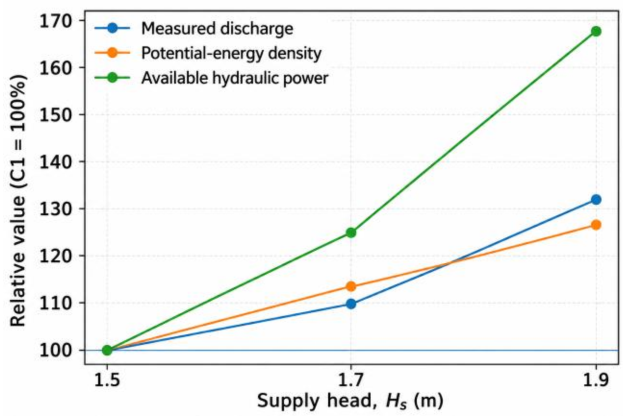

Figure 4. Relative change in measured discharge, potential-energy density, and available hydraulic power. Values are normalized to C1 (100%)

Available source flow was reported at approximately 31.7 L s−1, more than twice the highest mean discharge recorded during the collection tests. Source depletion was therefore unlikely to have constrained the short measurements at C3. This comparison does not close the pump water balance, however, because the proportions entering the drive pipe, leaving through the waste valve, and reaching the elevated outlet were not recorded separately. Abundant source flow can coexist with a comparatively small delivered fraction.

3.3 Interpretation of the head–flow response

The upward head–flow response is hydraulically plausible within the tested states. Additional supply head increases the potential energy available to accelerate the drive-pipe water column, and the ideal velocity relation predicts greater pre-closure velocity as Hs rises. Comparable waste-valve timing could then produce a larger momentum change and support a higher average flow in the monitored stream. Experiments on other hydraulic ram configurations have also shown that inlet height and valve loading affect discharge, pressure, or efficiency [17-20].

Supply head did not vary independently of delivery head. Hd increased from 4 to 6 m as Hs increased from 1.50 to 1.90 m, and the ratio Hd/Hs rose from 2.67 to 3.16. Additional supply head tends to strengthen the driving cycle, whereas additional delivery head increases the energy required to lift useful water. The monotonic increase in measured discharge cannot therefore be assigned to supply head alone. It also cannot be assumed to represent a proportional increase in useful delivery.

This coupled-head design helps explain why the present pattern may differ from studies focused on delivered water. Asvapoositkul et al. [9] observed a restricted operating range and declining useful lift as discharge head became more demanding. Kriaa [10] showed that supply-head increases can raise flow and surge amplitude while maximum efficiency occurs at a different setting. Greater circulation, stronger pressure oscillation, and higher delivery efficiency are therefore not interchangeable outcomes. Their relationship depends on the flow boundary and the performance measure selected.

Correct interpretation also depends on preserving the distinction between filling time and discharge. A shorter interval for collecting a fixed volume represents a larger flow, not a smaller capacity. The same care applies to head-derived energy terms: ρgHs is an energy density, and the kinetic-energy density obtained from the ideal head–velocity relation is algebraically identical to it. Treating measured discharge, theoretical energy density, and estimated hydraulic power as separate quantities prevents a mathematical transformation from being presented as an independent observation.

3.4 Throughput–stability trade-off

C3 combined the largest mean discharge with the largest coefficient of variation. Its CV of 3.86% was more than twice the 1.53% obtained for C2, although the 32.2% gain in mean discharge over C1 remained much larger than its within-state variation. C3 should therefore not be described as operationally unstable on the basis of these tests. The result instead identifies a trade-off between maximum throughput and short-term measurement repeatability. Applications that require uniform delivery may value this distinction differently from applications that prioritize total volume.

Both pump dynamics and measurement error could contribute to the wider spread at C3. Waste-valve closure changes local velocity and pressure, while delivery-valve motion may include repeated opening or backflow when chamber and lift conditions are mismatched [4,5]. Component arrangement can also influence pressure regularity [8]. The manual timing interval lasted only about seven to ten seconds; a 0.1-s reaction error would equal roughly 1.0–1.4% of that duration and could account for part of the observed scatter.

A criterion-dependent ranking agrees with recent optimization studies. Sumaria et al. [11] found that the settings maximizing volumetric efficiency, outlet discharge, and pressure were not identical. Nizhum et al. (2026) likewise treated delivery flow, efficiency, critical drive head, and cost as competing objectives. The present experiment addresses fewer variables, but its decision problem is similar: C3 is favored by throughput and estimated input-side power, whereas C2 is favored by repeatability. Selection should follow the intended service requirement rather than a single composite label of performance.

3.5 Energy interpretation and design implications

The energy results need to be interpreted according to their dimensions. The term ρgHs is gravitational potential energy per unit volume and is numerically equal to hydrostatic pressure at the same head. It is not total energy unless a water volume is specified. Likewise, inserting vth = (2gHs)1/2 into 0.5ρvth2 returns exactly ρgHs. Agreement between those two expressions follows from their definitions and does not constitute validation by independent measurements.

The expression ρgQHs adds an observed volumetric rate and thus provides a more informative measure of gravitational power associated with the monitored stream. Its increase from 154.7 W in C1 to 259.0 W in C3 indicates substantially greater input-side power at the higher-head state. Useful output power would instead require delivered discharge and delivery head, while efficiency would compare that output with a clearly defined input. The absence of separate flow measurements prevents either quantity from being estimated reliably.

Air-chamber dimensions also require careful interpretation. Treating the nominal 3-inch diameter as 0.0762 m and the recorded height as 0.60 m gives a simple cylindrical volume of about 2.74 L. Actual capacity will differ because nominal pipe size is not the internal diameter and fittings occupy part of the chamber. More importantly, dynamic performance depends on trapped-air volume during operation rather than the empty geometric volume. Water occupancy and gradual air dissolution can change that volume during extended service.

Friction in the drive pipe, local losses, turbulence through the waste valve, leakage, valve impact, pipe-wall deformation, and acoustic energy all reduce real performance. Models that resolve valve motion and pressure-wave behavior demonstrate how these losses and possible backflow can be diagnosed [5]. Waste-valve opening, mass, diffuser geometry, and flow-passage design also influence head loss and lifting capacity [6]. Magnetic repulsion has been explored as another means of modifying valve reopening under low-head conditions [13]. These mechanisms suggest that further improvement of the PVC prototype should be guided by measured valve and pressure dynamics rather than geometric head alone.

Replication of the experiment would benefit from a complete geometric and operational specification. Essential details include actual internal pipe diameters, drive-pipe length and slope, delivery-pipe length, valve mass, stroke, seat diameter, cycle frequency, gauge location and sampling rate, and the trapped-air fraction during operation. These variables govern inertia, friction loss, wave propagation, valve timing, and chamber compliance. Reporting them would allow the observed configuration response to be tested at other sites and scales.

3.6 Sustainability, limitations, and future work

Hydraulic ram pumps remain attractive for off-grid water supply because they can run continuously without purchased electricity or fuel when a dependable flow and natural fall are present. This operating independence can strengthen water access where conventional pumping is limited by energy supply or maintenance logistics. Ram-pump principles have also been proposed for recovering pressure energy in distribution systems, with storage used to buffer intermittent delivery [3]. Conventional ram pumps can perform effectively at low drive heads, although unit size may become restrictive as design flow increases [1]. The tested PVC pump is therefore best regarded as a site-specific low-head option.

Operation without external energy does not remove the need for responsible water management. Part of the source flow is discharged through the waste valve and should be returned safely to the channel or reused where practical. Installation must also maintain downstream flow and prevent erosion around the waste outlet. The discharge values measured here should not be used directly to size domestic or irrigation supply because the useful delivered fraction was not isolated. Design decisions require verified delivery over daily and seasonal time scales.

Four limitations define the scope of the findings. First, supply and delivery heads changed together, so their individual effects cannot be separated. Second, the volumetric collection boundary was not explicitly documented, preventing the measured discharge from being assigned confidently to the drive, waste, or delivered stream; consequently, the reported discharge should not be interpreted as useful delivery flow or used to calculate hydraulic efficiency. Third, key apparatus specifications, including actual pipe diameters, drive-pipe length, valve mass and stroke, and operating air volume, were incomplete. Fourth, the short manual collection periods characterize immediate repeatability but not long-term reliability, component fatigue, air loss, clogging, or seasonal variation.

Further work should proceed in stages. Initial tests should repeat C1–C3 using automated timing, separate flow meters for drive, waste, and delivery streams, and direct measurement of valve frequency. A factorial or response-surface experiment could then vary supply head, delivery head, valve mass, valve stroke, drive-pipe length, and air-chamber volume independently. Synchronized high-frequency pressure records would allow transient behavior to be linked to valve motion. Longer trials should assess delivered daily volume, Rankine or D'Aubuisson efficiency, waste fraction, pressure regularity, component stress, maintenance demand, and life-cycle cost. Such measurements would support the multi-objective optimization advocated in recent hydraulic ram research [12,14].

4. Conclusion

Volumetric tests showed a consistent increase in measured discharge across the three coupled head configurations. Mean values were 10.53 ± 0.23 L s−1 at 1.50/4 m, 11.59 ± 0.18 L s−1 at 1.70/5 m, and 13.92 ± 0.54 L s−1 at 1.90/6 m. The difference among configurations was large ($F_{2,42}$ = 362.58, $p < 0.001$, η^2 = 0.945), and both Tukey comparisons and the Kruskal–Wallis test supported the same ordering. Calculating discharge for each replicate from fixed volume and filling time provided a dimensionally consistent measure of the observed head–flow response.

Head-related indicators followed the same progression. Theoretical velocity increased from 5.42 to 6.11 m s−1, potential-energy density from 14.69 to 18.61 kJ m−3, and estimated input-side hydraulic power from 154.7 to 259.0 W. C3 was the strongest state for measured throughput and available hydraulic power, whereas C2 had the lowest coefficient of variation and the best short-term repeatability. No single configuration was superior for every objective.

The experiment does not establish hydraulic efficiency or water-hammer force. Supply and delivery heads were varied simultaneously, the monitored stream was not resolved into drive, waste, and delivered components, and no high-frequency pressure record was available. Future optimization requires independent head variation, explicit flow boundaries, automated timing, complete pipe and valve geometry, valve-cycle measurements, and longer-duration testing. Subject to these limitations, the results provide a transparent basis for comparing low-cost PVC hydraulic ram configurations and demonstrate why throughput, repeatability, efficiency, and field sustainability must be assessed separately.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used OpenAI's ChatGPT to support language editing, structural organization, and improvements in clarity and readability. The tool was not used to generate, fabricate, or alter the experimental data, statistical results, figures, or scientific conclusions. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Amir Zainuddin, Marufah, Fauzan Hamdi, Nurilham Prasetia, and Putri Arvianti Ramadani: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Validation, Visualization, Writing – original draft, and Writing – review & editing. Amir Zainuddin: Supervision, Project administration, and Corresponding author.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

[1] Kesharwani S, Tripura K, Singh P. Classical hydraulic ram pump performance in comparison with modern hydro-turbine pumps for low drive heads. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. 2021;235(6):1463-86.

[2] Rahman M, Rabha DK, Nath T. The performance analysis of hydraulic ram pump: Influence of specific parameters and validation with COMSOL Multiphysics. International Journal of Experimental Research and Review. 2023;32:216-34.

[3] Zeidan M, Ostfeld A. Hydraulic ram pump integration into water distribution systems for energy recovery application. Water. 2022;14(1):21.

[4] Evangelista S, Tortora G, Viccione G. Experimental and numerical CFD modelling of the hydrodynamic effects induced by a ram pump waste valve. Sustainability. 2023;15(17):13104.

[5] Li J, Yang K, Guo X, Huang W, Shi C, Guo Y, et al. Mathematical model of hydraulic ram pump system. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. 2022;236(6):1097-108.

[6] Li J, Yang K, Guo X, Huang W, Wang T, Guo Y, Fu H. Structural design and parameter optimization on a waste valve for hydraulic ram pumps. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy. 2021;235(4):747-65.

[7] Firmana D, Staddal I, Mustofa M. Rancang bangun pompa hidram sebagai solusi sistem pengairan di daerah perbukitan. Jurnal Teknologi Pertanian Gorontalo. 2022;7(2):80-4.

[8] Maatki C. Enhancing the efficiency and stability of hydraulic ram pump design. Physics of Fluids. 2025;37(2).

[9] Asvapoositkul W, Nimitpaitoon T, Rattanasuwan S, Manakitsirisuthi P. The use of hydraulic ram pump for increasing pump head—Technical feasibility. Engineering Reports. 2021;3(5):e12314.

[10] Kriaa K. Effects of supply head variations on the performance of hydraulic ram pumps. Ain Shams Engineering Journal. 2025;16(5):103352.

[11] Sumaria MGC, Guarte RC, Lua J, Timbal ME. Development of a testing rig for the ram pump. Pertanika Journal of Science & Technology. 2025;33(S1):137-55.

[12] Nizhum NM, Choudhury FH, Shabib Al Forkan MM, Shaid Sujon MA, Ehsan MM. Experimentation of hydraulic ram pump and multi-objective optimization of design parameters using ANN-RSM enhanced ensemble machine learning model. Flow Measurement and Instrumentation. 2026;109:103257.

[13] Chen MJ, Ho FH, Lin CY. Application of magnetic repulsion in hydraulic ram pump: A case study on drainage valve. Next Sustainability. 2025;6:100199.

[14] Yussupov Z, Yakovlev A, Sarkynov Y, Zulpykharov B, Nietalieva A. Results of the study of the hydraulic ram technology of water lifting from watercourses. International Journal of Engineering Science. 2022;177:103713.

[15] Abebe A, Tadesse Y, Beyene A. Conversion of thermally amplified hydraulic shock for power generation: Modeling and experimental analyses. Journal of Energy Resources Technology. 2023;145(2).

[16] Mebrat AA, Tadesse Y, Beyene A. Design, simulation, and experimental validation of thermally infused hydraulic ram pump. Journal of Energy Resources Technology. 2022;144(2).

[17] Kurniawan YB, Triyono S, Amien ER, Tusi A. Uji pengaruh beban klep buang serta ketinggian input dan output terhadap efisiensi pompa hidram. Jurnal Agricultural Biosystem Engineering. 2023;2(2):216-21.

[18] Kusuma ASJ, Ridwan R, Amien ER, Asmara S. Uji kinerja pompa hidram dengan 1 klep buang dan 1 klep hisap diameter 1 inci. Jurnal Agricultural Biosystem Engineering. 2022;1(1):102-7.

[19] Putra IE, Wardianto D, Pratama A. Variasi ketinggian sumber air terhadap tekanan dan debit air pompa hidram. Jurnal Teknologi dan Vokasi. 2024;2(2):77-83.

[20] Nurfauzan M, Zulkarnain I, Ridwan R, Suharyatun S. Uji kinerja pompa hidram. Jurnal Agricultural Biosystem Engineering. 2022;1(4):591-7.

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