

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 ($F_{2,42} = 362.58$, $p < 0.001$, $\eta^2 = 0.945$). 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.

ARTICLE HISTORY

Received June 15, 2026
Received in revised form
July 15, 2026
Accepted August 20, 2026
Available online August 24,
2026.

KEYWORDS

hydraulic ram pump; supply
head; volumetric discharge;
hydraulic power; repeatability

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