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Orginal Article

Economic Evaluation of Hydraulic Ram Pumps Using Life-Cycle Cost Analysis

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Abstract

Background: *A hydraulic ram pump is a sustainable technology that can be a good alternative to pumps powered by electricity or diesel fuel. However, various ram pumps are commercially available in the market, ranging from small-scale to large-scale.*

Methods: *This study employed a Life-Cycle Cost Analysis for six selected ram pumps in its economic evaluation at one-, five-, and ten-year periods, respectively. It also used a sensitivity analysis to determine the confidence level for interest rates in recurring and residual values across all evaluation periods.*

Results: *The evaluation shows that small-scale ram pumps may appeal to consumers during the one year due to their low market price and initial project cost. Further evaluations also reveal that small-scale ram pumps surpass the cost investment of large-scale ram pumps in the five and ten-year evaluations because of higher expenses related to maintenance, material replacements, and services. The sensitivity analysis also confirmed that the data calculations have a high confidence level in all evaluation periods.*

Conclusion: *Thus, the study concluded that the uncertainty level is low, and the economic evaluation can serve as a good basis for consumers when purchasing hydraulic ram pumps, considering the sustainable investment cost over an extended period of operation.*

Keywords

economic, evaluation, hydraulic ram pump, interest rate, large-scale ram pumps, Life-Cycle Cost Analysis, product cost, sensitivity analysis, small-scale ram pumps, water pump capacity

INTRODUCTION

Providing an alternative water-pumping technology to residents living in highland areas who lack the financial means to buy electric or diesel-powered pumps can significantly enhance their living conditions. This initiative not only offers socio-economic advantages but also contributes to environmental conservation. Furthermore, it supports the sustainability goal set forth by the United Nations, which promotes using renewable energy sources over traditional ones that produce carbon emissions to avoid contributing to global pollution (17 Global Goals, 2020). To encapsulate this goal, a hydraulic ram pump serves as an alternative to the more sophisticated water pumps that can be used by residents living in mountainous areas with rivers or streams near their homes as a water source supply.

The hydraulic ram pump is a water pumping technology that utilizes the potential energy of water to push an amount of water from the source to a higher elevation without using electricity or diesel fuel (Hussin et al., 2017). This technology typically consists of three main parts as a water pumping system (Asvapoositkul et al., 2019). The first part is an elevated drive pipe connected to the water source. The second part is a ram body that contains moving parts (i.e., delivery valve and waste valve) and a pressure chamber. Lastly, the third part is a delivery pipe for distributing water outflow. The working principle of this pump is that it produces a water hammer effect, which creates shock waves from its moving parts and manages to utilize the energy received from the elevated source to pump water in a periodic operating cycle (Fatahi-Alkouhi & Lashkar-Ara, 2019). Researchers and innovators have recently created hydraulic ram pumps that can be easily installed and situated anywhere. They have provided various ram pump sizes employing different materials, which also offer a range of market prices that are available commercially.

Traditionally, ram pumps are usually large and made from durable materials. This is particularly true for the first ram pump model invented by John Whitehurst (Manohar et al., 2019), the improved version by Joseph de Mongolfier (Taye, 2017), and those developed by various companies such as Rife Hydraulic Engine (n.d.) and Green & Carter Ltd. (n.d.), were big and made of cast iron materials. Some notable hydraulic ram pumps commercially marketed recently are those from the Alternative Indigenous Development Foundation Inc. (2023) and Gilman Ram Pump (n.d.) in the Philippines. They were designed for household use and agricultural irrigation supply in most rural areas. Although they offered customized sizes, most of their products were large-scale and made from galvanized iron materials, ranging from 100 mm to 125 mm in drive pipe intake diameter. Their design typically accommodated a maximum water supply discharge of up to 40 L/s, with an estimated delivery discharge outflow of around 2 L/s.

Moreover, a recent development of hydraulic ram pumps involved composite materials. These materials are much stronger compared to the traditional ones. Unlike galvanized iron, they have excellent qualities that help avoid corrosion (Alikhani et al., 2020). The moving metal parts are removed, and built-in valves are introduced to resist a strong water hammer effect, thus minimizing maintenance. These modifications were employed by Water Powered Technologies (n.d.) in the United Kingdom and Glockemann Water Pump (n.d.) in Australia. They modified the traditional hydraulic ram pump design, changed the pressure chamber size to minimize bulkiness, and integrated another mechanical device as moving parts. The design still accommodated a larger drive pipe diameter, even though the chamber had evolved to a smaller type than the traditional one. Their designs could pump water up to 1 L/s to a higher delivery elevation. This decrease in discharge outflow resulted from the changes in pressure chamber size, as larger sizes helped propagate pressure shock waves, which enabled compressed air to pump water effectively (Oliveira Junior et al., 2021). However, since these ram pumps are manufactured for large-scale purposes, they can be expensive rather than affordable for consumers.

Researchers have developed such pumps that can be assembled quickly, driven by the innovation of finding alternatives that make ram pumps more affordable and can be built using readily available materials. The hydraulic ram pump by Land to House (n.d.), a company in the United States, was made of PVC, galvanized iron, and brass pipe fittings, which allowed for easy construction by consumers. It used the water hammer principle from a large discharge inflow at a higher elevation to generate a surge of water as a delivery discharge outflow (Kesharwani et al., 2021). Since it only utilized simple and readily available materials, the company commercialized a limited number of small-scale hydraulic ram pump products. The conventional moving parts, critical components of the ram that helped push water in a periodic cycle, were replaced with smaller, commercially available pipe fittings. The company produced a typical size of a 25 mm diameter ram that could pump water with an ideal maximum delivery discharge outflow of around 0.015 L/s. Developing a small-scale hydraulic ram pump inspired other researchers to conduct further studies on its performance. Some of these researchers (Bosa et al., 2019; Celerinos & Sanchez-Companion, 2022; Sarma et al., 2016) utilized different pipe fittings and recycled materials, enabling anyone to easily construct the ram pump for household water supply or small-scale irrigation farming.

However, the absence of a comprehensive cost evaluation among different hydraulic ram pumps, considering various expenditures throughout their operation period, has resulted in a notable gap in the existing literature. Hence, only the study by Hatipoğlu et al. (2018) provided a cost estimate of the hydraulic ram pump as a feasibility study. However, it failed to stipulate a systematic approach to cost analysis for a thorough economic evaluation. Therefore, one needs to conduct a cost analysis to determine which hydraulic ram pumps suit consumers as long-term investments in in their market costs. This analysis also helped evaluate the financial sustainability of consumers, taking into account when they purchased this water pump product.

This study evaluated the expenses associated with various ram pumps of differing sizes and materials based on their market prices and long-term investment costs. Hence, it utilized the hydraulic ram pump by Celerinos & Sanchez-Companion (2022), which was applied in small-scale irrigation farming to determine the served water pump capacity and evaluation alongside five selected ram pumps available on the market. These ram pumps were categorized into small-scale and large-scale, seeking to ascertain their initial product costs and hypothetically calculate their maintenance costs, service and labor costs, and material replacement costs throughout their operating period, employing systematic evaluation using the Life-Cycle Cost Analysis (LCCA). Lastly, this study provided an economic evaluation for future investments, which was subsequently evaluated for one year and forecasted their outcomes in five- and ten-year periods.

METHODS

This study is structured into two primary phases: 1) acquiring data from the developed hydraulic ram pump and from ram pumps available in the market, and 2) analyzing the data presented in the following sections. The subsequent sections provide a brief discussion of the developed hydraulic ram pump, along with the selected hydraulic ram pumps. Additionally, the evaluation criteria and the Life-Cycle Cost Analysis are outlined in the following sections. Furthermore, a sensitivity analysis is included to validate the data calculations.

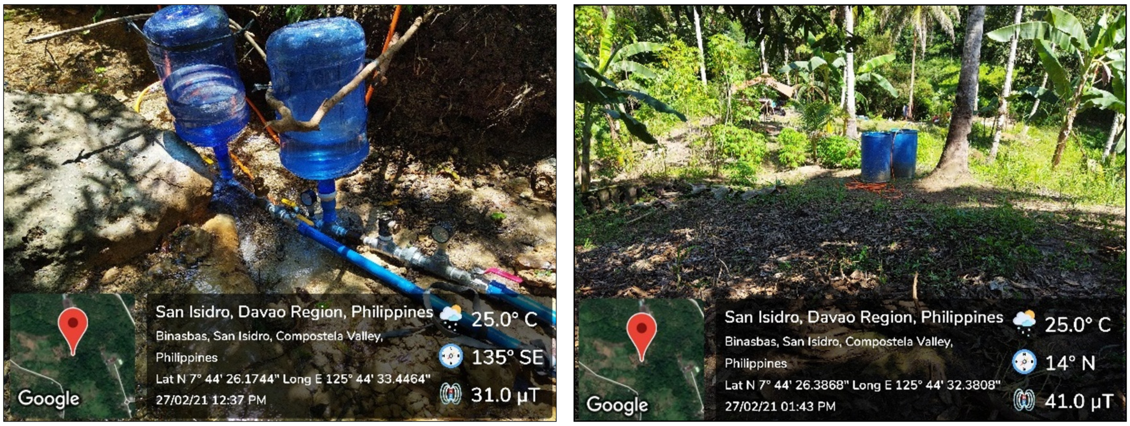
Criteria for Selecting Hydraulic Ram Pumps

The selection of hydraulic ram pumps in this study is essential for the economic evaluation. The author carefully decided, considering the limitations of the available information for each selected ram pump. The evaluation is based on two criteria: 1) cost and 2) capacity. For the cost, the hydraulic ram pumps were categorized based on sizes and materials, allowing calculations of various expenditures. They were classified as small-scale and large-scale, considering factors such as accessibility and durability. In the selection, traditional ram pumps made from galvanized iron were evaluated alongside the modified rams using composite materials and innovative ones built with readily available pipe-fitting materials. For the capacity, the volume of water generated during the cyclic operation of the hydraulic ram pump was based on the specifications provided by the manufacturer for the ideal served water volume. Due to the author's constraints, this study conducted an actual performance evaluation exclusively for the developed hydraulic ram pump by Celerinos & Sanchez-Companion (2022). It did not include the actual water pumping system performance assessment of other selected ram pumps.

Selected Hydraulic Ram Pumps

Developed Hydraulic Ram Pump

The hydraulic ram pump developed by Celerinos & Sanchez-Companion (2022), as shown in Figure 1a, has been selected for an economic evaluation with other ram pumps available on the market. This selection was made because this water pump utilized recycled materials common in any household, with most piping and fittings readily available. The developed ram pump was based on the ram design by Land to House (n.d.), wherein the ram inlet had a diameter of 25 mm, and the ram outlet had a diameter of 12.5 mm. The modification to the design was that the pressure chamber was changed to a 20-L disposable polycarbonate bottle instead of a 3-inch PVC tube because the larger chamber could absorb compressed air to avoid damage to the ram body from the propagation of pressure shock waves (Oliveira Junior et al., 2021). The developed hydraulic ram pump was categorized as small-scale, can pump 700 liters of water daily, and is used as a water pumping system for small agricultural farming in Brgy. Binasbas, San Isidro, Davao de Oro, Philippines, as shown in Figure 1b. The study by Inthachot et al. (2015) was adopted for the actual setup of the water pumping system using a stream as the water source supply.



(a) (b)

Figure 1. *Developed hydraulic ram pump: a) situated in a stream source, and b) topographic view of the actual water distribution for agricultural farming*

Small-scale Hydraulic Ram Pump

In the aforementioned, the developed hydraulic ram pump in this study was based on the ram pump design by Land to House (n.d.), specifically the model with a 25 mm inlet diameter and a 12.5 mm outlet, as shown in Figure 2. This model was also selected as a small-scale ram pump for an economic evaluation. It was constructed using various sizes of PVC pipe fittings and brass valves. This design is also appropriate for the small-scale ram pump category, as all materials used are easy to assemble and readily available on the market.

Figure 2. *Selected small-scale hydraulic ram pump by Land to House (n.d.)*

Large-scale Hydraulic Ram Pump

Moreover, this study selected four commercially available ram pumps in the large-scale category, as shown in Figure 3. A galvanized iron was the usual material used for large-scale rams by AIDFI (2023) and Gilman Ram Pump (n.d.), as presented in Figures 3a and 3b, respectively. Both ram pumps had a 100 mm inlet drive pipe diameter and a 50 mm delivery pipe diameter. In contrast, the modified hydraulic ram pump designs by Water Powered Technologies (n.d.) and Glockemann Water Pump (n.d.) utilized composite materials and were also selected as large-scale rams. Although they eliminated the pressure chamber in their design and introduced another mechanical device in the ram body, they still used a 100 mm inlet drive pipe diameter and a 50 mm delivery pipe diameter, as shown in Figures 3c and 3d. Other details of these hydraulic ram pumps are available on their respective websites.

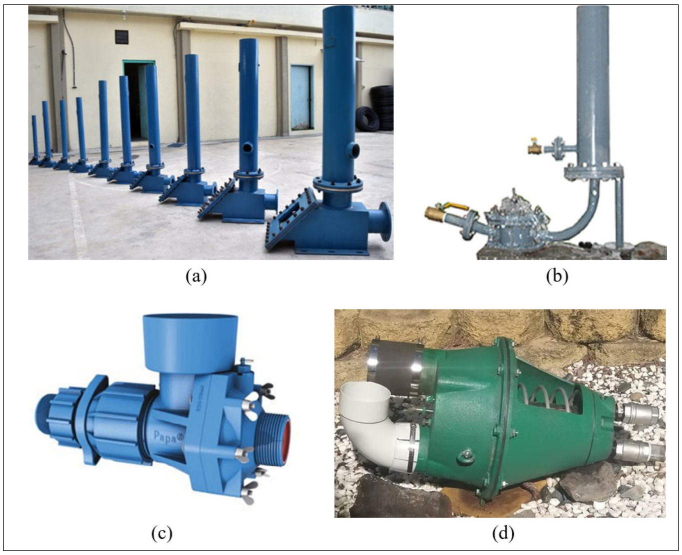


Figure 3. *Selected large-scale hydraulic ram pumps by: a) AIDFI (2023), b) Gilman Ram Pump (n.d.), c) Water Powered Technologies (n.d.), and d) Glockemann Water Pump (n.d.)*

Evaluation of Hydraulic Ram Pumps

The step-by-step process for the economic evaluation of all hydraulic ram pumps is presented in Figure 4. The market price of the developed hydraulic ram pump was calculated and evaluated together with five other selected hydraulic ram pumps from both small-scale and large-scale categories. Subsequently, each ram pump's water pump capacity was determined over one day. After determining the costs and pump capacities, the present value of all recurring costs—such as maintenance during operation, replacement of broken components, and service fees—were computed for one year and forecasted for five and ten years. Sensitivity analysis was then conducted to determine the level of uncertainty in the calculations. Potential options were discussed to guide consumers in making future selections of hydraulic ram pumps.

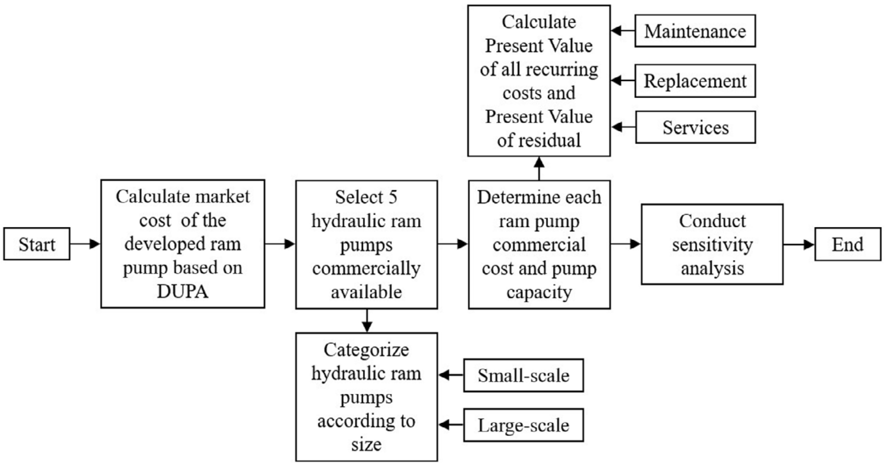


Figure 4. *Systematic flow process for evaluating hydraulic ram pumps*

Cost Estimates of the Developed Ram Pump

To carry out the procedure depicted in Figure 4, the cost estimate of the developed ram pump for its market value was then followed. The calculation for cost estimates of this hydraulic ram pump was based on the updated Detailed Unit Price Analysis (DUPA) imposed by the Department of Public Works and Highways (DPWH) in the Philippines (Department of Public Works and Highways, 2015). The product cost included both direct and indirect costs, where the direct cost was derived from materials and labor, and the indirect cost encompassed consumables and profit, based on the actual additional cost and a 20% profit margin as the standard cost in the Philippines. Table 1 shows the detailed cost computation of the developed hydraulic ram pump.

Table 1. *Detailed cost of the newly developed hydraulic ram pump*

No. of pcs (A)	Unit	Description	Material Cost (B)	Labor Cost (C) $C=5.5\%B$	Con. Cost (D) $D=2\%B$	Unit Cost (E) $E=B+C+D$	Amount (F) $F=E \times A$
1	pc	Stainless Gate valve 25mm	499.75	27.49	10.00	537.23	537.23
4	pcs	Stainless Threaded coupling 25mmx50mm	179.75	9.89	3.60	193.23	772.93
1	pc	GI Union 25mm	173.75	9.56	3.48	186.78	186.78
5	pcs	GI Tee S/S 25mm	399.75	21.99	8.00	429.73	2,148.66
1	pc	Brass swing check valve 25mm	659.00	36.25	13.18	708.43	708.43
1	pc	Stainless Threaded coupling 25mmx25mm	149.75	8.24	3.00	160.98	160.98
1	pc	Brass spring check valve 25mm	500.00	27.50	10.00	537.50	537.50
1	pc	PVC Coupling 25mm	14.00	0.77	0.28	15.05	15.05
1	pc	Disposable polycarbonate bottle 20 Liters	150.00	8.25	3.00	161.25	161.25
1	pc	GI Bushing reducer 25mmx12.5mm	79.75	4.39	1.60	85.73	85.73
1	pc	Stainless Threaded coupling 25mmx12.5mm	52.75	2.90	1.06	56.71	56.71
1	pc	Brass Gate valve 12.5mm	270.00	14.85	5.40	290.25	290.25
1	pc	Teflon tape ¾	21.00	1.16	0.42	22.58	22.58
1	can	Solvent	96.75	5.32	1.94	104.01	104.01
1	pc	Sandpaper	18.00	0.99	0.36	19.35	19.35
TOTAL AMOUNT (G) $G=\Sigma F$							5,807.41
PROFIT 20% (H) $H=20\%G$							1,161.48
AMOUNT OF RAM PUMP PRODUCT $(G+H)$							**₱ 6,968.90**

Commercial Prices of Hydraulic Ram Pumps

As previously mentioned, the technical specifications of the chosen commercial ram pumps, including their prices, are available on their official websites. This pricing information plays a vital role in this study, serving as the foundational data for the evaluation. Additionally, the study compiled the estimated water pump capacity of each selected hydraulic ram pump over one day. Table 2 outlines the commercial costs of hydraulic ram pumps alongside their pump capacities for further evaluation.

Furthermore, this study did not evaluate pump efficiencies, considering the limitations of hydraulic ram pumps, which typically have an output discharge efficiency ranging from 10% to 20%. Since this efficiency range is typical amongst all ram pumps, their capacities also fall within this standardized range, as specified in their technical specifications. Henceforth, this outcome resulted in a balanced approach to analyzing pump capacity, providing a fair basis for an evaluation based on other parameters.

Table 2. *Cost and pump capacity of all selected hydraulic ram pumps*

Item No.	Product Name	Type	Location	*Market Price (Php)	Pump Capacity (liters/day)
1	AIDFI Ram Pump	large-scale	Philippines	40,000.00	5,000
2	Gilman Ram Pump	large-scale	Philippines	44,955.00	5,100
3	Water Powered Technologies Ram Pump	large-scale	UK	86,000.00	3,400
4	Glockemann Ram Pump	large-scale	Australia	25,000.00	3,500
5	Land to House Ram Pump	small-scale	USA	8,750.00	1,211
6	Developed Ram Pump	small-scale	Philippines	6,968.90	700

**Note that the author has only converted the commercial prices to Philippine pesos and adhered strictly to the amounts provided, refraining from making any additional cost adjustments.*

Economic Cost Evaluation

According to Fuller (2010), the Life-Cycle Cost Analysis (LCCA) is the best methodological assessment approach for evaluating product costs. This study examined the product cost based on its expenditures throughout its operational lifespan. The analysis was computed using Equation 1, which assumed an interest rate in the recurring of the present value at 30% for small ram pumps and 60% for larger ram pumps due to their robustness factor. Additionally, the interest rate in the residual of the present value was consistently set at 10% for all ram pumps considered in the study. This equation is expressed as:

$$LCC = C + PV_{recurring} - PV_{residual\ \ value} \qquad (1)$$

where LCC is the Life-Cycle Cost, *C* is the year zero construction cost (hard and soft costs), $\mathrm{PV}_{recurring}$ is the present value of all recurring costs (utilities, maintenance, replacements, services, etc.), and $\mathrm{PV}_{residual\ value}$ is the present value of the residual cost at the end of the study life.

In the presented equation, the first constant variable is the initial cost of a product at year zero. In this study, the market value of each selected ram pump was determined, as exhibited in Table 2, while the developed ram pump was calculated, as shown in Table 1. The market value was the basis for the initial construction cost, which was calculated using the DUPA, as all selected ram pump products came with material specifications provided by the manufacturers. However, this cost may not be the primary basis for economic analysis, as it could fluctuate over time. The LCC equation indicated that the initial cost could be adjusted if more detailed information about the materials used in the ram pumps and their water pumping system becomes available.

Following the initial cost, the second variable in the above equation was hypothetically calculated for each hydraulic ram pump. This variable represented three recurring costs on its present value: 1) maintenance, 2) service and labor, and 3) material replacement. The recurring costs were calculated for one year and forecasted for five and ten years. First, the maintenance cost of the hydraulic ram pump is generally classified as a type of non-fuel pump due to its distinctive operation, which requires no diesel or electricity to function. These costs are primarily limited to inspection for both developed and selected ram pumps. Also, this cost is critical to the analysis, as ram pumps frequently require personnel to inspect periodically for any foreign objects that might have intruded into the ram pump body, potentially causing fluctuating performance and becoming ineffective.

Second, service and labor costs are necessary to keep the ram pump operational. These expenses cover the wages of personnel operating the ram pump, which serves as the primary source of water supply to ensure continuous functionality. They are part of the recurring costs and are estimated by the minimum wage standards outlined in the Philippines. Third, the material replacement costs incurred in this study arise when certain materials of the ram pump are missing or need repair to restore functionality. This study's small-scale and large-scale hydraulic ram pumps had precise specifications for their constructed materials, implying that material replacement could be calculated in their varying category. It is important to note that the material compositions of each ram pump have already been identified, as these serve as the basis for calculating the three aforementioned recurring costs. Consequently, the manufacturers provide these material compositions, and the costs of material replacements always fluctuate based on market prices.

Furthermore, the last variable in Equation 1 is the residual cost of the hydraulic ram pump on its present value. This cost has also been forecasted for each ram pump product's cost using LCC (Tiwari et al., 2016). Similar to the second variable of the LCC equation, varying time-period approaches were still considered. The equation is expressed as:

$$PV = \frac{F_y}{(1+Dics)^y} \qquad (2)$$

where PV is the present value of the residual cost, Fy is the future value of the ram pump considering the number of projected year (y), and the discount rate is denoted as $Dics$.

In addition, to elaborate on understanding the forecasted cost of ram pump products in the economic evaluation, Figure 5 demonstrates the schematic illustration of the product's future value, considering the appreciation or depreciation of some costs in the yearly period analysis using the LCC equation.

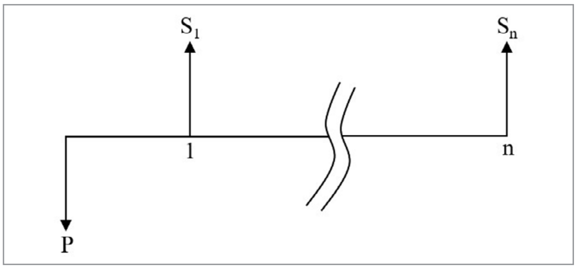


Figure 5. *Future value factor*

In the figure above, P represents the initial cost of a ram pump product at time zero (n=0) with an interest rate i per year. This study's the initial cost is simply the construction cost at year zero. Also, the notation S_1 is the cost at year one, and the future cost is denoted as S_n in the nth year. The nth year in this study projects the costs across five and ten-year analysis periods.

The LCCA results of all selected hydraulic ram pumps were then compared to their respective water pump capacities, indicating potential future investment costs for consumers. This computation followed a simple arithmetic calculation from the LCC equation divided by the served or delivered water output from the hydraulic ram pump in one day. This calculation was applied to all selected hydraulic ram pumps.

Sensitivity Analysis

Lastly, in the study conducted by Val & Stewart (2003) and Zakeri & Syri (2015), they found that the assumed interest rates significantly impact the LCCA computation. Specifically, this study assumed an interest rate of 30% for small-scale and 60% for large-scale hydraulic ram pumps in the recurring of the present value. In comparison, the interest rate was set at 10% for all selected hydraulic ram pumps in the residual of the present value. It is important to note that any changes in these interest percentages can significantly affect the analysis results. To assess the associated uncertainties, it is crucial to perform a sensitivity analysis to understand how these interest percentages can affect the results over time. For this analysis, 95% fractiles were employed to evaluate the model error presented in Equation 1. This study formulated a null hypothesis, which stated that there was no significant difference in the calculation of the LCC, while the alternative hypothesis stated a significant difference in the LCC results. The statistical deviations of LCC results for this analysis were determined using IBM SPSS statistics software version 22.0 (2013) at the University Information Technology Office of Ateneo de Davao University, Davao City, Philippines.

RESULTS AND DISCUSSION

One-, Five-, and Ten-year Evaluation

The economic evaluation of hydraulic ram pump products using LCCA provides a foundational assessment of whether consumers are likely or unlikely to invest significantly in these products, considering the economic factors that may influence their long-term viability. Since this type of water pump operates continuously using only water, recurring costs are anticipated in its economic evaluation. Table 3 presents the recurring costs for maintenance during operation, replacement of broken components, and service fees for all selected hydraulic ram pumps over one year.

Table 3. *One-year evaluation for recurring costs*

Item No.	Ram Pump	Type	Maintenance (Php)	Service and labor (Php)	Replacement (Php)	Total Recurring Costs (Php)
1	AIDFI	Large-scale	2,018.13	3,256.53	2,522.67	7,797.34
2	Gilman	Large-scale	2,770.42	4,533.41	2,770.42	10,074.25
3	Water Powered Technologies	Large-scale	1,929.07	2,279.81	1,929.07	6,137.94
4	Glockemann Water Pump	Large-scale	3,545.34	5,801.46	3,545.34	12,892.13
5	Land to House	Small-scale	8,641.51	6,721.17	3,840.67	19,203.35
6	Developed Ram Pump	Small-scale	8,711.13	6,018.60	3,484.45	18,214.18

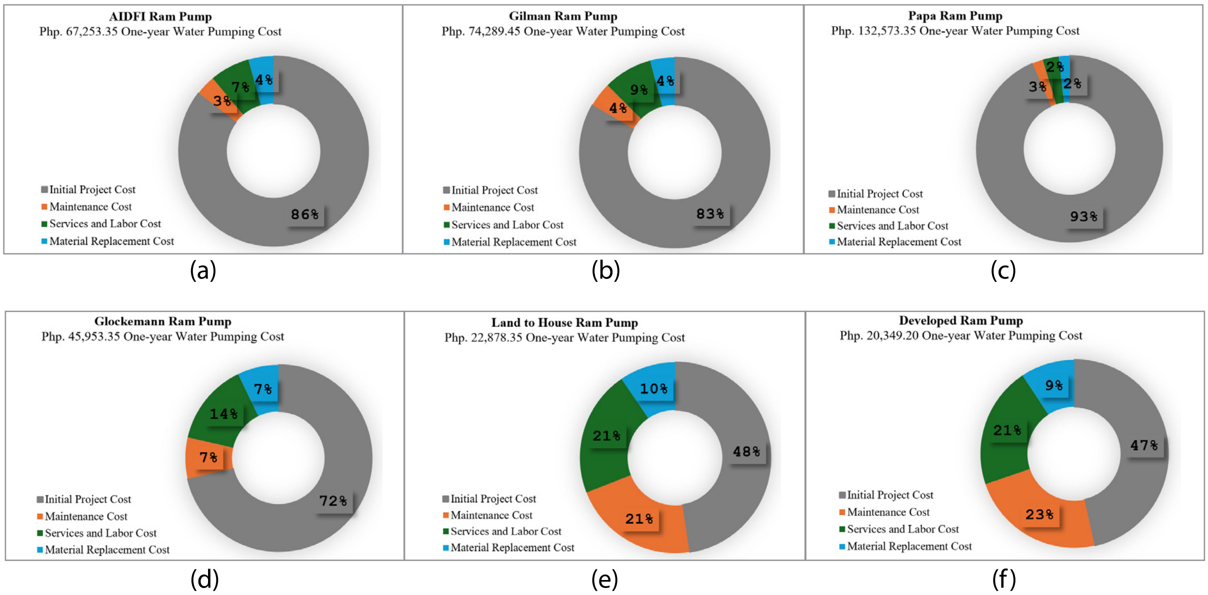


Figure 6. *One-year evaluation period by: a) AIDFI, b) Gilman, c) Water Powered Technologies, d) Glockemann Water Pump, e) Land to House, and f) Developed Hydraulic Ram Pump*

In the table shown, selected large-scale ram pumps were typically designed for low maintenance, indicating that the moving parts (i.e., delivery valve and waste valve) might have been defective during operation. However, those components were made from durable metal and composite materials, which meant that maintenance primarily involved addressing only misplaced small parts, tightening some loose springs, and changing the rubber gasket since it was prone to breakage. On the other hand, its major components (i.e., pressure chamber and ram casing) remained intact. It is important to recognize that damaged components incur associated labor and service costs, including periodic maintenance. As a result, large-scale ram pumps demonstrated low recurring costs ranging from Php 6,000 to Php 12,000 over a one-year evaluation period.

Moreover, small-scale ram pumps incurred higher recurring costs of approximately Php 19,000 over the same evaluation period, as presented in the accompanying table. This is primarily because their main components (e.g., waste valve, delivery valve, and pressure chamber) are not robust enough to withstand the continuous surge pressure caused by the water hammer effect. This analysis is also visually demonstrated in Figure 6, which provides a cyclic percentage illustration detailing the recurring costs and the initial project cost of each selected hydraulic ram pump at year zero.

In the analysis of a one-year period, it became clearer that larger and more robust ram pumps exhibited higher initial costs, ranging from 72% up to a maximum of 93% of LCC results, as shown in Figures 6a, 6b, 6c, and 6d. This cost percentage arose because large-scale ram pumps required significant water volume for their intake supply. Hence, constructing extensive water pumping systems had to be considered for these ram pumps to produce high water pressure and work continuously and effectively.

The result provided lower initial costs for small-scale hydraulic ram pumps, as illustrated in Figures 6e and 6f. These smaller and innovative ram pumps were often considered an alternative to larger hydraulic ram pumping systems (Celerinos & Sanchez-Companion, 2022). They only required adequate water pumping systems, and their sustaining costs contributed to a more inferior percentage, reaching a maximum of 48% of the LCC over one year. However, it is important to note that drawing definitive conclusions based on one year does not provide a comprehensive economic assessment for the selected hydraulic ram pumps. Therefore, the LCCA was extended to include projections over five and ten years. The results of this extended analysis are presented in Table 4, which summarizes the forecasted costs for one-, five-, and ten-year periods, respectively.

Table 4. *Summary of Life-Cycle Cost Computations*

Item No.	Ram Pump	Type	Year	Initial Project Cost (Php)	Present Value (Php)		Life Cyle Cost (Php)
					Recurring Costs	Residual Value	
1	AIDFI	Large-scale	1	50,453.35	7,797.34	27,520.01	30,730.68
			5		32,513.84	18,796.54	64,170.66
			10		52,702.38	11,671.17	91,484.57
2	Gilman	Large-scale	1	55,408.35	10,074.25	30,222.74	35,259.86
			5		42,008.25	20,642.54	76,774.07
			10		68,092.07	12,817.39	110,683.03
3	Water Powered Technologies	Large-scale	1	96,453.35	6,137.94	52,610.92	49,980.37
			5		25,594.39	35,933.97	86,113.77
			10		41,486.49	22,312.17	115,627.68
4	Glockemann Water Pump	Large-scale	1	35,453.35	12,892.13	19,338.19	29,007.29
			5		53,758.44	13,208.25	76,003.55
			10		87,138.20	8,201.28	114,390.28
5	Land to House	Small-scale	1	19,203.35	19,203.35	5,237.28	33,169.43
			5		80,075.40	3,577.13	95,701.62
			10		129,795.93	2,221.12	146,778.16
6	Developed Ram Pump	Small-scale	1	17,422.26	18,214.18	4,751.52	30,884.91
			5		75,950.67	3,245.36	90,127.57
			10		123,110.06	2,015.11	138,517.20

In the five and ten-year evaluation periods, as shown in the table, results revealed that large-scale ram pumps had much less present recurring value, which obtained less than a hundred thousand pesos, due to their material rigidity. However, the first year of evaluation, large-scale ram pumps had a higher computed

LCC, particularly for their market prices. This showed that the selected larger rams incurred much higher costs per usage during their recurring stage. Another reason for this finding is that large-scale ram pumps, using rigid materials, provided much better cost efficiency for long-lasting performance. This resulted in a high residual value, as projected in the five and ten-year forecasts.

Delving deeper into Table 4, small-scale ram pumps, when considered an alternative water pump, had a higher computed LCC, which obtained more than a hundred thousand pesos since it is understandable that the present recurring value provided a higher amount for their long operating period. This included higher maintenance costs, service costs, and material replacement costs. In addition, small-scale ram pumps only achieved a low residual value because their materials are not rigid enough to be repurposed after disposal. This finding can be interpreted that smaller rams can be costly over a longer operation regarding their performance. Another interpretation of the results is that since they only used recycled and readily available materials, they consequently had minimal forecasted amounts when analyzed for a shorter period but incurred a larger amount when forecasted for long-term performance, as demonstrated in Figure 7. Therefore, smaller ram pumps appreciated their cost during the recurring stage.

It can also be observed in the figure below that small-scale ram pumps had low LCC results in the first year of evaluation and eventually surpassed the LCC results of large-scale ram pumps before the start of the fifth-year evaluation period. Hence, a significant increase in the trend between the fifth year and the tenth year became apparent in this evaluation. As mentioned, this increase in cost resulted from significant expenses associated with maintenance, the repair budget and service fees, respectively. Additionally, when employing LCC, interest rates can be best used based on actual derivations of all expenses incurred during construction up to their service operation as a water pumping system. It is also suggested to perform LCCA comparing the performance of hydraulic ram pumps, electrically powered water pumps, and pumps powered by gasoline or diesel fuel.

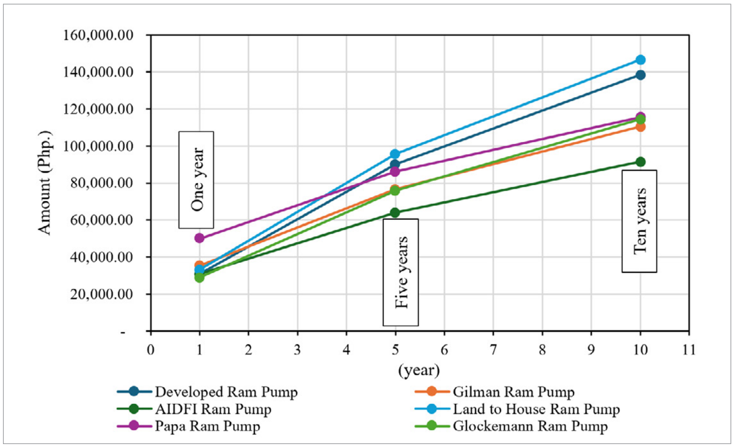


Figure 7. *Life-Cycle Cost trend of one-, five-, and ten-year evaluation periods*

Evaluation including Water Pump Capacity

The economic evaluation could not have been completed without assessing all selected hydraulic ram pumps according to their water pump capacity. In Table 5, the assessed LCC versus served water outputs for small-scale rams showed higher results, particularly for the developed ram pump, which served 700 liters daily. In the ten-year evaluation, the small-scale ram pumps achieved more than one hundred pesos per serving liter of water daily. Likewise, the large-scale rams estimated lower LCC versus served water outputs, which achieved less than thirty-five pesos per served liter of water daily in the ten-year evaluation, since their pump capacity can provide an ideal maximum output that was almost three to five times greater than that of the developed ram pump. However, as noted in the evaluation criteria, the capacities of other ram pumps were not tested in real-world applications to determine their actual water pump capacity; instead, these data were compiled from their respective websites.

Table 5. *Life-Cycle Cost versus Pump Capacity*

Item No.	Ram Pump	Type	Year	Life Cyle Cost (Php)	Pump Capacity (lit/day)	LCC per Pump Water
1	AIDFI	Large-scale	1	30,730.68	5,000	6.15
			5	64,170.66		12.82
			10	91,484.57		18.30
2	Gilman	Large-scale	1	35,259.86	5,100	6.91
			5	76,774.07		15.05
			10	110,683.03		21.70
3	Water Powered Technologies	Large-scale	1	49,980.37	3,400	14.70
			5	86,113.77		25.33
			10	115,627.68		34.01
4	Glockemann Water Pump	Large-scale	1	29,007.29	3,500	8.29
			5	76,003.55		21.72
			10	114,390.28		32.68
5	Land to House	Small-scale	1	33,169.43	1,211	27.39
			5	95,701.62		79.03
			10	146,778.16		121.20
6	Developed Ram Pump	Small-scale	1	30,884.91	700	44.12
			5	90,127.57		128.75
			10	138,517.20		197.88

In the abovementioned context, although smaller ram pumps can be costly in their long-term operation due to constant maintenance and material replacements, these pumps could serve as an alternative since their materials are conventional and can be built within an hour. If there were any inconveniences during operation, immediate repairs were feasible because the materials were easily arranged, affordable, and readily available at any hardware store (Celerinos & Sanchez-Companion, 2022). Additionally, considering their served water outputs for all selected hydraulic ram pumps, all LCC results can be comparable to those of sophisticated water pumps using electricity or fuels as a power source. Hence, hydraulic ram pumps operated continuously using only water, indicating that recurring costs were more significant considerations for these pumps than expenses for fuels or electricity, especially given the recently rising costs of these commodities in the market, which also contributed to global carbon emissions (Borres et al., 2014). Furthermore, it is recommended that future research would explore a comprehensive analysis of products across various scales of hydraulic ram pumps using LCCA, which would provide deeper insights into long-term economic performance. This assessment will focus on their actual implementation for water distribution to determine the socio-economic impacts on communities.

Validation of Life-Cycle Cost Calculations

The results of the LCCA for all selected hydraulic ram pumps depend on the assumed interest rates. A sensitivity analysis of all interest rates was conducted at varied percentages. The analysis employed a statistical deviation of 95% fractiles. Table 6 shows that all calculated p-values were greater than the set value of 0.05. Therefore, the formulated alternative hypothesis was ejected in favor of the null hypothesis.

This result inferred that even when varying the percentage rates of recurring costs on the present value and residual costs on the present value for small-scale and large-scale hydraulic ram pumps at 30% and 10%, respectively, there were no significant differences in the results of the calculated LCC. Hence, the uncertainty level of each calculated LCC for one-, five-, and ten-year evaluation periods was low, as presented in the table below. This finding also aligned with the range of interest percentages reported by Val & Stewart (2003) and Zakeri & Syri (2015). Thus, the numerical deviations in Equation 1 for all selected hydraulic ram pumps were negligible in the economic evaluation.

Table 6. *Deviation of LCC from the varied interest rates*

Item No.	Ram pumps	Type	Years of evaluation (p-value)			Remarks
			1 year	5 years	10 years	
1	AIDFI	Large-scale	0.99272	0.85439	0.92679	$p > \alpha$ accept null hypothesis
2	Gilman	Large-scale	0.95023	0.96488	0.93094	$p > \alpha$ accept null hypothesis
3	Water Powered Technologies	Large-scale	0.76176	0.4162	0.30542	$p > \alpha$ accept null hypothesis
4	Glockemann Water Pump	Large-scale	0.68887	0.62017	0.51184	$p > \alpha$ accept null hypothesis
5	Land to House	Small-scale	0.68003	0.38360	0.32103	$p > \alpha$ accept null hypothesis
6	Developed Ram Pump	Small-scale	0.47743	0.37547	0.31621	$p > \alpha$ accept null hypothesis

CONCLUSION

The innovation of hydraulic ram pumps as an alternative water pump to more sophisticated pumps powered by electricity or diesel fuel provided a significant step in achieving sustainable water supply solutions, particularly by using materials widely available in any hardware store. This study highlighted the evaluation of small-scale and large-scale hydraulic ram pumps, focusing on their economic viability throughout their performance. It was found that smaller ram pumps can be constructed easily using affordable materials. They initially offered a low cost and notably stood out as an investment for consumers in a one-year economic evaluation period because their low maintenance costs were appealing, as well as leveraging materials that involved pipe fittings and recycled components for the end users.

However, when the economic evaluation period was extended to a longer duration, a pivotal revelation was also found. In the five and ten-year evaluation periods, the small-scale ram pumps surpassed the present cost investment of the large-scale ram pumps. Thus, operational and maintenance expenses gradually increased, even though bigger and more robust hydraulic ram pumps were sold at higher prices. This underscored the importance of considering a broader horizon for the economic evaluation of a product to assess its sustainability as an investment. The study further showed that the frequent maintenance and material replacements for small-scale ram pumps offset the lower demand for large-scale ram pumps.

The study concluded that despite the manufacturer's varied market prices, consumers could opt for lower-cost products over more expensive ones, specifically when selecting hydraulic ram pumps that can sustain performance over a prolonged period. Hence, small-scale ram pumps are a good alternative for smaller water distribution systems, especially for geographically isolated and disadvantaged residents. Moreover, large-scale ram pumps are also suitable investments for larger water distribution purposes, particularly irrigation systems, as they offer long-lasting performance.

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Ethical Approval

Not applicable.

Competing interest
The authors declare no conflicts of interest.

Data Availability
Data will be made available by the corresponding author on request.

Declaration of Artificial Intelligence Use
The author did not utilize any artificial intelligence (AI) tools and methodologies in the preparation and development of the paper.

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