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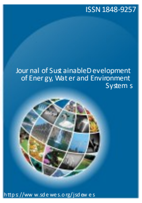

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Original Research Article

Groundwater Extraction Systems Using the Rope Pump and the Manual Volumetric Pump: A Case Study in Chachapoyas, Amazonas, Peru

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ABSTRACT

This study evaluated two low-cost technologies for groundwater extraction in the high Andean community of Chachapoyas, Peru: the rope pump and the manual volumetric pump. The rope pump, constructed with local materials and operated by pedaling, showed a progressive increase in flow rate from 48.79 L/min (1 m) to 69.56 L/min (5 m), associated with greater immersion and stability of the water column. In contrast, the manual volumetric pump exhibited a decrease in flow rate as the discharge height increased, from 21.97 L/min (2 m) to 11.68 L/min (10 m), reflecting the hydraulic limitations inherent in positive displacement systems. Both technologies are viable for domestic and agricultural water supply in rural communities with limited energy resources. The results highlight the need to adapt their design and maintenance to local hydrogeological conditions to ensure their operational sustainability.

KEYWORDS

Andean regions, Rural water supply, Low-cost technologies, water, pumps

INTRODUCTION

Access to reliable water supply remains a major challenge in rural and remote areas, particularly in regions facing water stress and limited infrastructure development. Musie and Gonfa [1] highlighted the persistent difficulties in ensuring water availability in vulnerable regions. Lu et al. [2] demonstrated that water resources are unevenly distributed and require localized assessment. Zhou et al. [3] emphasized that water security is highly sensitive to environmental and socio-economic changes. Sintayehu et al. [4] showed that drought conditions further exacerbate water scarcity in rural areas.

Although groundwater extraction technologies such as motorized and photovoltaic pumping systems have expanded water access [5], their implementation often requires significant capital investment [6], technical maintenance capacity, and energy reliability [7]. These constraints are especially relevant in geographically complex and high-altitude environments [8], where climatic variability and limited technical support may compromise

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system sustainability [9]. In such contexts, low-complexity mechanical pumping systems represent a potentially more resilient and locally manageable alternative [10].

Groundwater represents a strategic resource for strengthening rural water security [11], particularly in contexts where surface water availability is seasonal or unreliable and where energy-dependent pumping systems may face operational and economic constraints [12]. In many low-income regions, hand-operated pumping technologies have been widely implemented due to their relative affordability, ease of installation, and independence from external energy sources [13]. These systems have therefore become central components of decentralized rural water supply schemes [14].

Despite their widespread adoption, long-term functionality and service reliability remain significant concerns [15]. It has been reported that a substantial proportion of installed hand pumps may be non-operational at any given time due to inadequate maintenance structures, limited availability of spare parts, insufficient technical capacity, and inappropriate technology selection relative to local environmental and socio-technical conditions [16]. Sustainable operation and maintenance (O&M) frameworks emphasize that technological choices must align with the financial, managerial, and technical capabilities of user communities to ensure long-term viability [17]. Furthermore, not all standardized hand pump models perform equally under varying hydrogeological and environmental conditions. User preference for simpler mechanical systems has been observed in cases where technological complexity exceeds local maintenance capacity [18]. These considerations highlight that technical performance cannot be evaluated solely in terms of nominal pumping capacity but must also account for environmental constraints that may directly influence hydraulic feasibility and operational sustainability.

In this context, as an alternative to traditional pumping methods, the rope pump and the manual volumetric pump technologies are viable and easily adaptable in rural communities [19]. Both pumping systems can be built using recyclable materials, and they offer favorable ergonomics for operation and maintenance tasks, making them technically sustainable for adaptation in any area. Consequently, if properly adapted and integrated into the rural water framework, these technologies can become solutions capable of meeting the growing water demands of households. Rope pump and piston systems harness the basic principle of kinetic energy, transforming it into mechanical energy through the use of a rope and the piston movement inside the cylinder. These simple devices ensure a constant water supply, promoting community participation and local autonomy without relying on external energy sources [20].

With respect to the rope pump, studies such as those by Bazaanah and Dakurah [19], considered four factors: robustness, flow rate, availability of spare parts, and access to expertise, to determine the sustainability and efficiency of the system compared to standardized internal combustion motor pumps in Ghana. They concluded that rope pumps are a feasible and sustainable technology that can meet the water needs of communities. This system can supply water at different depths, as confirmed by Kadlowec *et al.* [21] who evaluated water extraction up to 35 meters, while Bazaanah and Dakurah [19] reported that the pumping height varies up to 26 meters for natural wells and up to 45 meters for artificial wells. Meanwhile, Mohammed [22] demonstrated that rope pumps require less energy (to produce, install, and operate) and materials for their operation, relying solely on human energy, compared to other technologies such as solar pumps and motorized pumps.

On the other hand, the manual volumetric pump is a mechanical device designed to extract water through the upward and downward movement of a piston inside a cylinder. This system operates through a piston mechanism that moves within the cylinder, generating volumetric changes that facilitate fluid intake and discharge. It uses check valves that open and close the flow, allowing water to be drawn from a well through a pipe and then pumped to the surface. It is ideal for shallow to medium-depth wells and stands out for its simplicity, low cost, and ease of maintenance. The manual volumetric pump, operated manually, suctions and pumps a constant volume of liquid in each cycle (suction and pumping). The operation of manual pumps is based on two principles: acceleration and displacement. Since it is a piston and cylinder type pump, it relies on the incompressibility of water inside a cylinder to lift it to the required heights. Foster *et al.* [15] conducted a review of manual pumps across Africa, where they found a total of 600,000 manual pumps in operation but recommended strengthening the sector's capacity to ensure greater sustainability in water supply. For example, in parts of Africa where manual pumps such as Fridev, India Mark II, Nira AF-85, and Vergnet have been standardized for water supply, rural coverage has stagnated in recent years due to factors such as climate variability, poor service provision [23], pollution, and lack of infrastructure maintenance [24].

The maximum theoretical suction head of manually operated pumps is fundamentally constrained by atmospheric pressure. Under standard sea-level conditions, the practical suction limit approaches 10.3 m of water column; however, this value decreases as atmospheric pressure declines with increasing altitude. For example, reductions of approximately 1.5 m in theoretical suction height at 1500 m above sea level and about 3 m at 3000 m have been reported [25]. These reductions directly affect the pressure differential available to lift water, potentially limiting pump operability and discharge capacity. Although manually operated pumps have been widely evaluated at low and mid elevations, quantitative experimental evidence on their suction performance and delivered flow under reduced atmospheric pressure in high-altitude settings remains limited.

We hypothesize that reduced atmospheric pressure at high altitude constrains suction generation, leading to measurable changes in delivered flow rate and operational thresholds compared with performance reported at lower elevations. Accordingly, this study experimentally evaluates the hydraulic performance of a rope pump and a manual volumetric pump under high-altitude conditions, using a high-Andean test site as a case study to inform technology selection and adaptation for rural water supply.

MATERIALS AND METHODS

This section presents the methodological framework employed to experimentally evaluate the hydraulic performance of the rope pump and the manual volumetric pump. The experimental design was structured to control operational variables, ensure measurement repeatability, and allow statistical validation of the results. Detailed descriptions of system configuration, testing conditions, and analytical procedures are provided to support methodological transparency and reproducibility.

Experimental Setup and Experimental Design

An artesian well with a storage volume of 5 m³ and reinforced concrete walls was used as the water source. The well has an open base in contact with the aquifer, allowing direct recharge, with a static water level of 1 m. A controlled experimental design was implemented to evaluate the hydraulic performance of two manually operated pumping systems under varying suction and discharge conditions. The independent variable for both systems was suction depth (1–5 m). For the manual volumetric pump, discharge height (0–10 m) was included as an additional independent variable. The dependent variable was delivered flow rate (L/min), calculated from measured discharge volumes over controlled time intervals. Operational speed was maintained constant (40 ± 1 rpm for the rope pump and 30 ± 1 cycles/min for the manual volumetric pump) to reduce variability. Each experimental condition was replicated ten times and operated by a single technician to minimize operator-induced variation.

Rope Pump Configuration

The rope pump was constructed according to MacCarthy *et al.* [26], consisted of an upper driving wheel (bicycle rim with gear), a chain transmission system coupled to a stationary bicycle, a ¼-inch braided nylon rope, neoprene pistons spaced at 30 cm intervals, a 1-inch PVC discharge pipe, and a lower guide box incorporating a ceramic bearing for stability. The rotating pulley guided the rope–piston assembly inside the 1-inch pipe to convey water to the discharge point (Figure 1) [27].

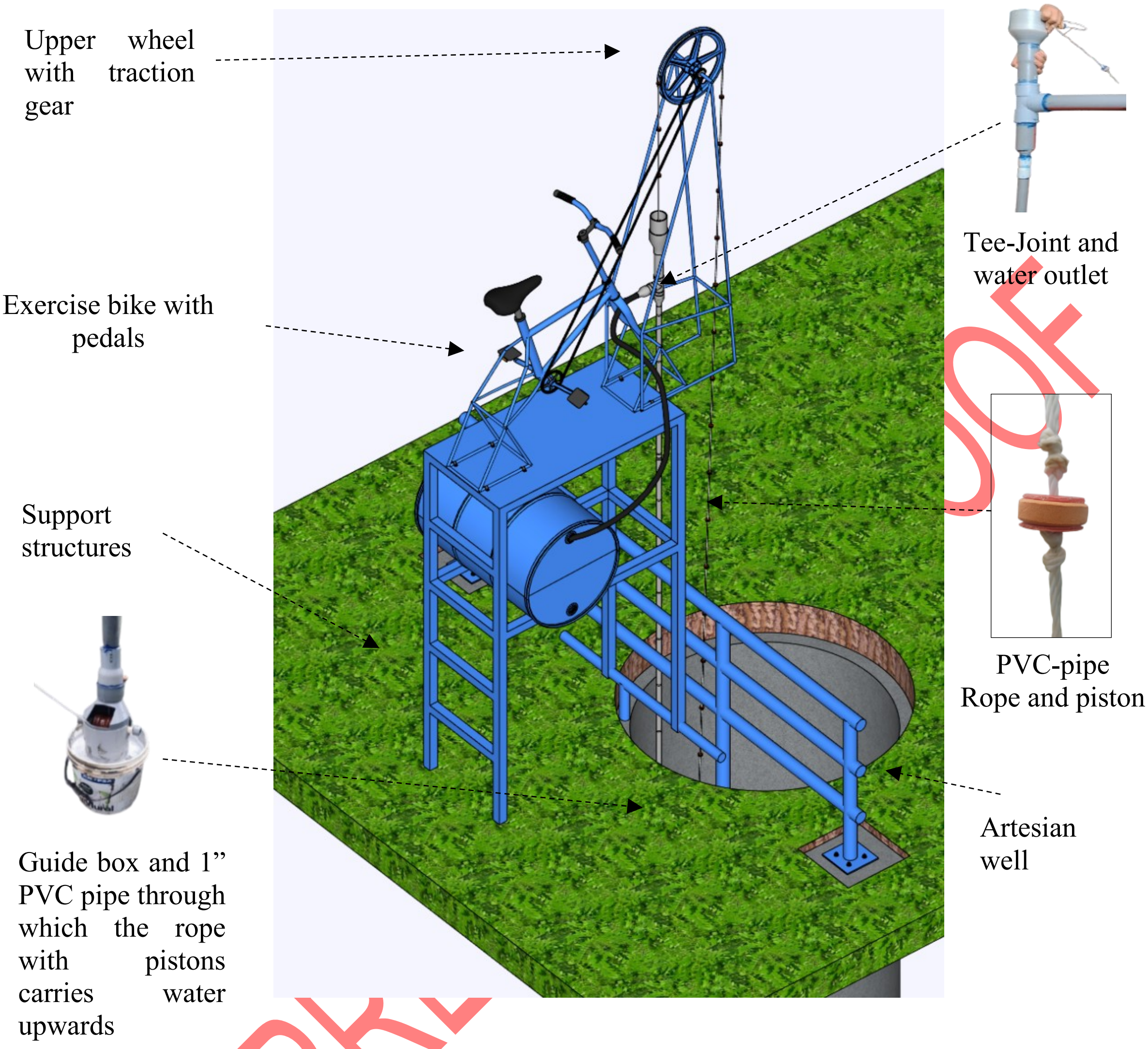


Figure 1. Rope pump system installed over an artesian well

The rope was fabricated from 3.2 mm (1/8") white nylon strands twisted to achieve an overall diameter of approximately 6.35 mm (1/4"). Neoprene pistons with a diameter of 24 mm were attached at regular intervals. A radial clearance of approximately 1 mm between the piston and the internal pipe wall was maintained to reduce friction while minimizing leakage losses [27]. Polyethylene terephthalate (PET) inserts derived from bottle caps were incorporated at the piston ends to enhance mechanical resistance and durability.

A 2-inch electrical spool insulator was used as an axial guide at the base of the well (Figure 2). This component directed the rope and pistons into a 4-to-1-inch reducer connected to the vertical discharge pipe. The assembly was fixed to a concrete block to maintain rope alignment and operational tension.

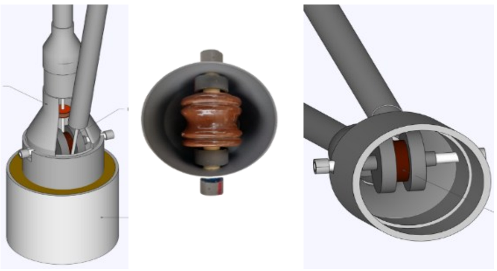


Figure 2. Guide-box

Manual Volumetric Pump Configuration

The manual volumetric pump (Figure 3) was constructed according to the configuration described by Lu [28]. The system consisted of a metal tripod (0.6 × 1.6 m) supporting a 3-inch diameter and 40 cm long PVC cylinder. A neoprene piston (Ø 3", 5 cm height) was connected to a ½" × 40 cm iron rod and operated by a 1.5 m galvanized steel lever.

Two check valves were installed: one at the bottom of the cylinder (suction valve) and another in the discharge line. A 3" to 1" PVC reducer connected the cylinder to a 1-inch galvanized iron T-fitting, where the vertical branch was connected to the suction line and the horizontal branch to the discharge pipe. An analog pressure gauge (0–80 psi) was installed in the discharge line to monitor pumping pressure during operation.

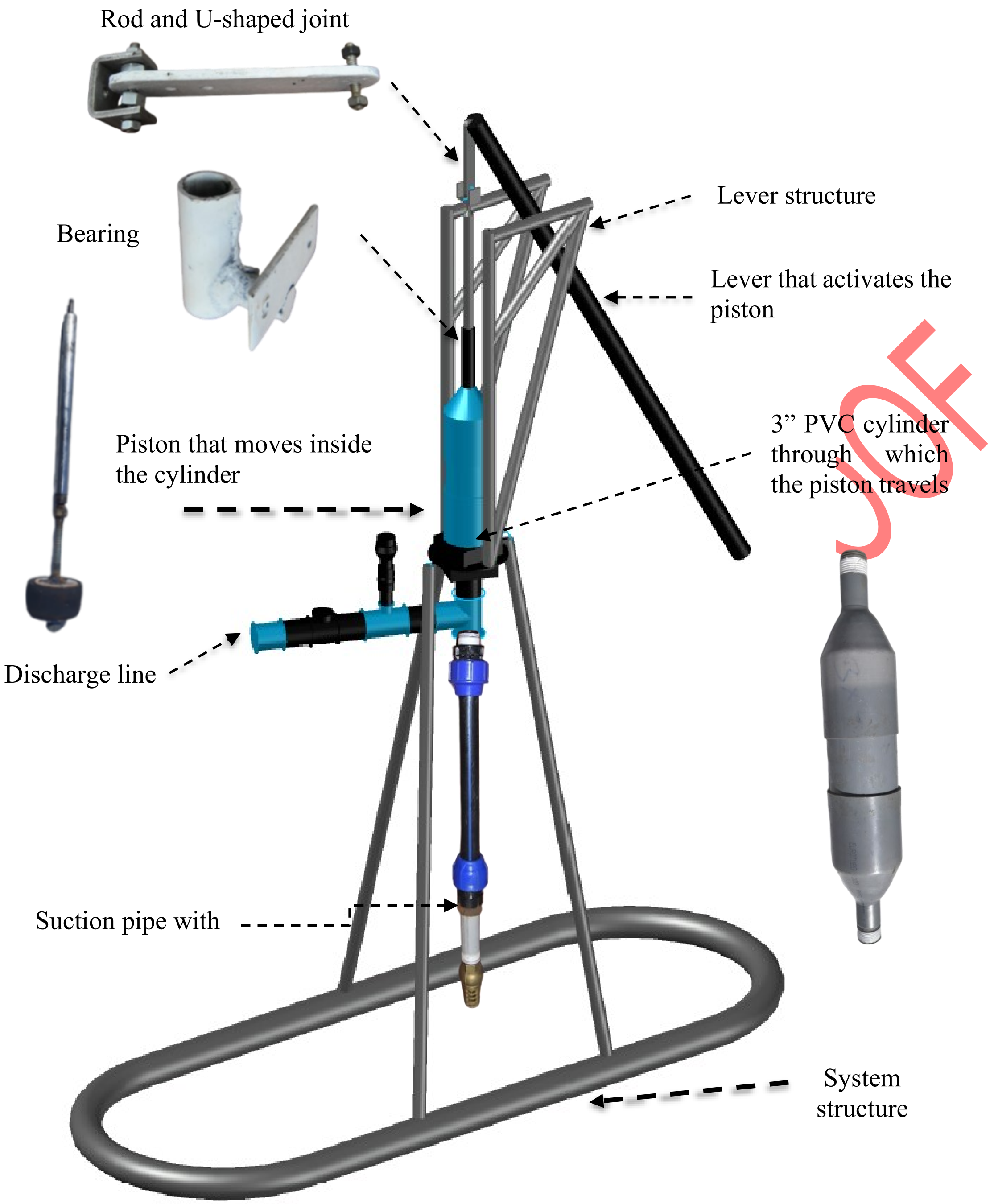


Figure 3. Manual volumetric pump configuration for groundwater extraction

Experimental Procedure

The experimental procedure was conducted separately for each pumping system under controlled operational conditions, as described below.

Rope Pump Testing. The flow rate of the rope pump was evaluated at suction depths ranging from 1 to 5 m [27]. For each suction depth, the discharged volume during one minute of operation was measured using a graduated container, as shown in Figure 4(a–c). Ten repetitions were performed for each measuremen. The constant pedalling speed was approximately 40 ± 1 rpm, controlled by a digital tachometer (accuracy 0.01 rpm).

Flow rate (Q) was calculated according to eq. (1):

$$Q = \frac{V}{t} \tag{1}$$

where V is the measured volume (L) and t is time (min). The same expression was applied for both pumping systems.

(a) (b) (c)

Figure 4. Water extraction at different depths: (a) 1 m; (b) 3 m; (c) 5 m

Manual Volumetric Pump Testing. The manual volumetric pump was evaluated under varying suction depths (1–5 m) and discharge heights (0–10 m), as shown in Figure 5. Discharge height increments of 2 m were tested for each suction condition [29]. Flow rate was determined by measuring the time required to fill a 4 L container. Pumping frequency was maintained at 30 ± 1 cycles per minute using a digital metronome, as shown in Figure 5a. Ten repetitions were performed for each combination of suction depth and discharge height, as illustrated in Figure 5b. The evaluated parameters were consistent with those reported by Shah *et al.* [25].

(a) (b)

Figure 5. Manual volumetric pump flow data collection: (a) water pumping; (b) measurement of pumped flow.

Data Analysis

The analysis was performed at a significance level of $\alpha = 0.05$. Normality test: For the rope pump data, the Anderson-Darling test was applied. This test was selected for its high sensitivity to the tails of the distribution, which is crucial for detecting deviations in data with significant variability. Once normality was confirmed, Tukey's test was used to perform multiple comparisons between the extracted flow rates using Minitab 17 software. This test was chosen because it controls for Type I error when performing multiple comparisons, allowing for the evaluation of the system's technical performance.

For the data obtained from the manual volumetric pump, normality was assessed using the Shapiro-Wilk test due to the larger sample size. Since normality was not met, the Kruskal-Wallis test was applied to compare the differences between the data groups, followed by Dunn's test to identify which groups differed from each other. All analyses were performed using R software version 4.3.0. In addition, a box plot analysis was performed to visualize the flow distributions. The analysis of results and the statistical tests performed were based on the assumptions mentioned, ensuring the reliability of the results. Error bars in the figures represent ±1 standard deviation, providing a visual reference of experimental variability. Regarding the curves shown in the figures, they were included only as graphical support and were not used for statistical inference.

STUDY AREA

The study was conducted at the National University Toribio Rodríguez de Mendoza de Amazonas, located in Chachapoyas, Peru (6°14'3.20"S; 77°51'18.16"W), at an altitude of 2330 m above sea level (Figure 6).

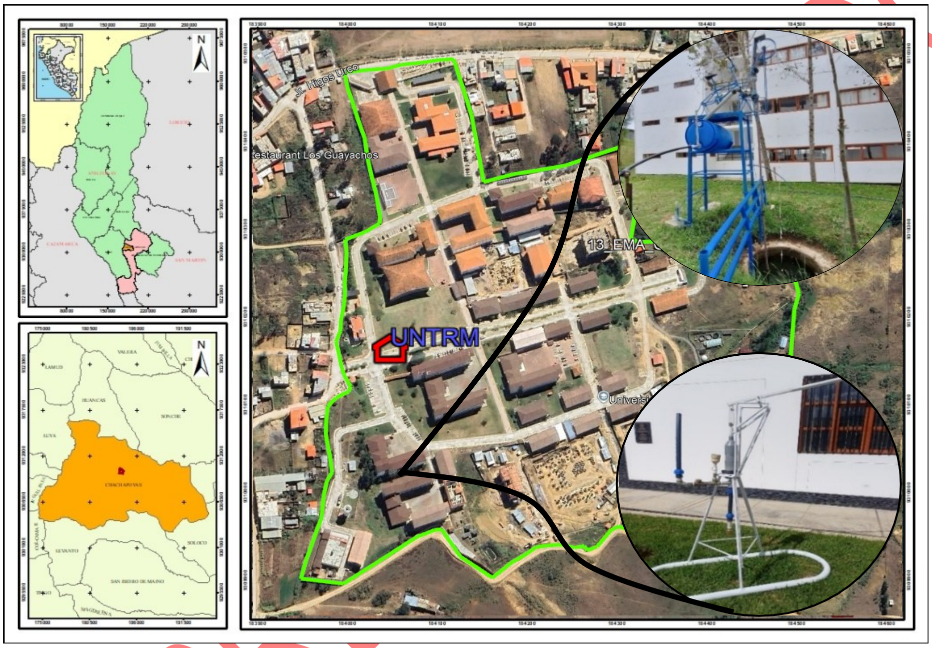


Figure 6. Location of the water pumping systems installation

Chachapoyas is situated in a transition zone between the Andean highlands and the Amazon basin. The region presents average temperatures ranging from 9°C to 25°C and an annual rainfall of approximately 800 mm [30]. Soils are generally shallow and well-drained, with loamy-clay to clay textures [31]. The site is representative of high Andean environments where shallow groundwater constitutes an important water source, particularly under increasing climatic variability [32] and human impacts [33].

RESULTS

The experimental results are presented below in order to evaluate the hydraulic performance of the rope pump and the manual volumetric pump under high-altitude Andean conditions. The analysis focuses on the relationship between flow rate and the governing operational parameters, namely suction depth for the rope pump and discharge height for the manual volumetric pump.

Flow Rate of the Rope Pump

The performance was evaluated by analysing the volume of water extracted per unit time versus the suction depth. A constant increase in the flow rate was observed as the depth increased, starting at 48.79 L/min at 1 meter and reaching 69.56 L/min at 5 meters. Although there is slight variability in the measurements, as indicated by the error bars, this variability is not significant enough to alter the general trend. Additionally, a strong positive correlation between suction depth and output flow rate was observed, as shown in Figure 7.

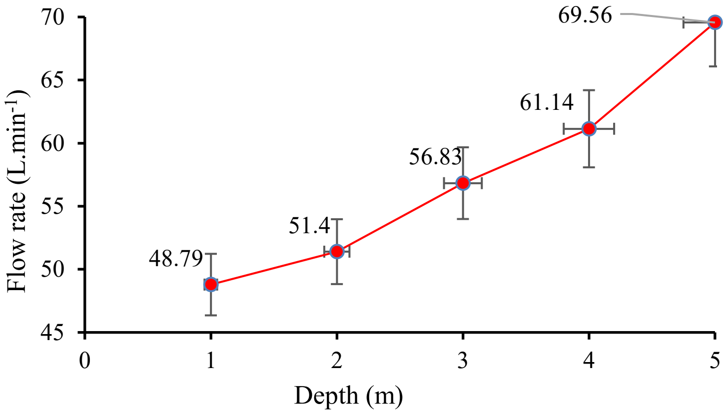


Figure 7. Flow rate of the rope pump as a function of suction depth

To determine whether there were differences in flow rate values across different raised heights, the Anderson-Darling normality test was performed with a significance level of 0.05 (Figure 8). The result yielded a p-value of 0.268. Given the behavior of the data, the Tukey test was applied to examine the distribution and grouping of the flow rate data based on the raised heights. This can be seen in Table 1.

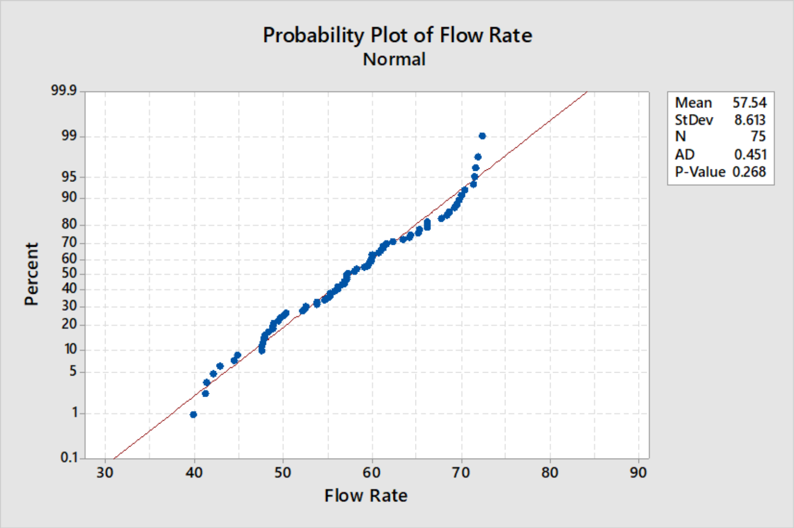


Figure 8. Anderson Darling normality test

Table 1. Grouping of flow samples

Suction Depth	N	Mean	Grouping
5	15	69.56	A
4	15	61.14	B
3	15	56.83	B
2	15	51.40	C
1	15	48.79	C

Means that do not share a letter are significantly different
Note: N = 15 represents the number of experimental replicates per suction depth

The Tukey multiple comparisons test identified significant differences between the means of flow rates at different suction depths. Group 5 exhibited the highest mean (69.56 L/min) and was significantly different from all other groups (letter A). Groups 4 (61.14 L/min) and 3 (56.83 L/min) did not differ significantly from each other (letter B) but were distinct from shallower groups. Groups 2 (51.40 L/min) and 1 (48.79 L/min) exhibited the lowest means and were not significantly different from each other (letter C). In conclusion, there is an observed increase in the extracted flow rate with suction depth, with depth 5 achieving the highest significant flow rate.

Flow Rate of the Piston Pump

The extracted flow rate for the manually operated volumetric pump was determined, as shown in Figure 9, which illustrates the relationship between flow rate and discharge height. A descending trend was observed: as discharge height increases, the flow rate consistently decreases. The initial flow rate, recorded at a discharge height of 2 meters, was 21.97 L/min, while the lowest value, at 10 meters, was 11.68 L/min. A decreasing trend characteristic of hydraulic systems was observed, where increased height results in greater gravitational resistance and energy losses, reducing the effective water flow at the outlet.

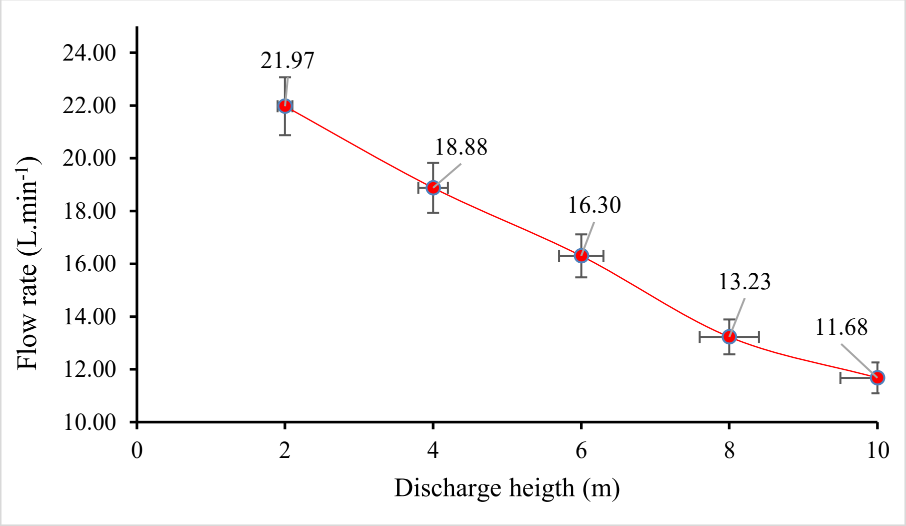


Figure 9. Flow rate of the piston pump as a function of discharge height. The line is provided solely as a visual aid and was not used for statistical inference

To determine if significant differences existed among the evaluated values, a normality test was conducted (Figure 10), yielding a P-Value of 0.017, indicating significant differences in the collected values. This result was further confirmed using the Kruskal-Wallis test, which found a p-value of 0.002. Once normality was assessed, and the distribution was found to be non-normal, the Kruskal-Wallis test was applied to the flow rate-suction depth variables, as presented in Table 2.

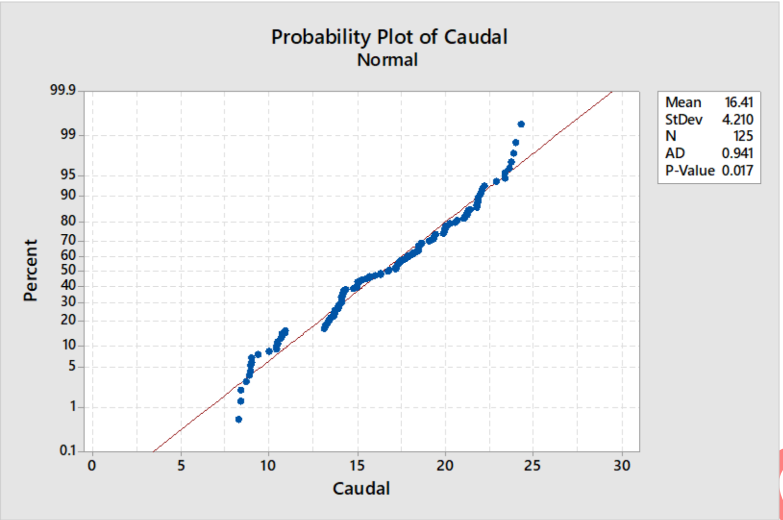


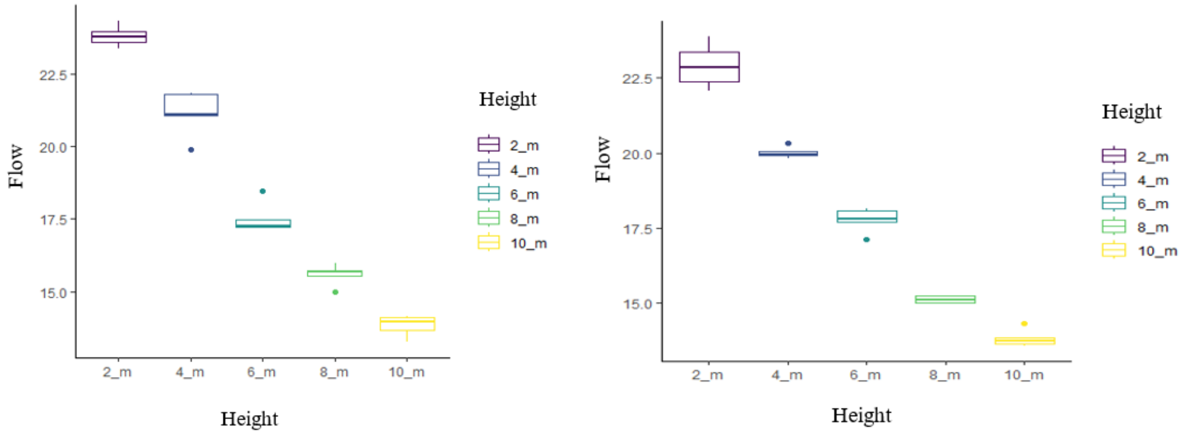
Figure 10. Normality test results for the piston pump data

Table 2. Grouping of flow samples

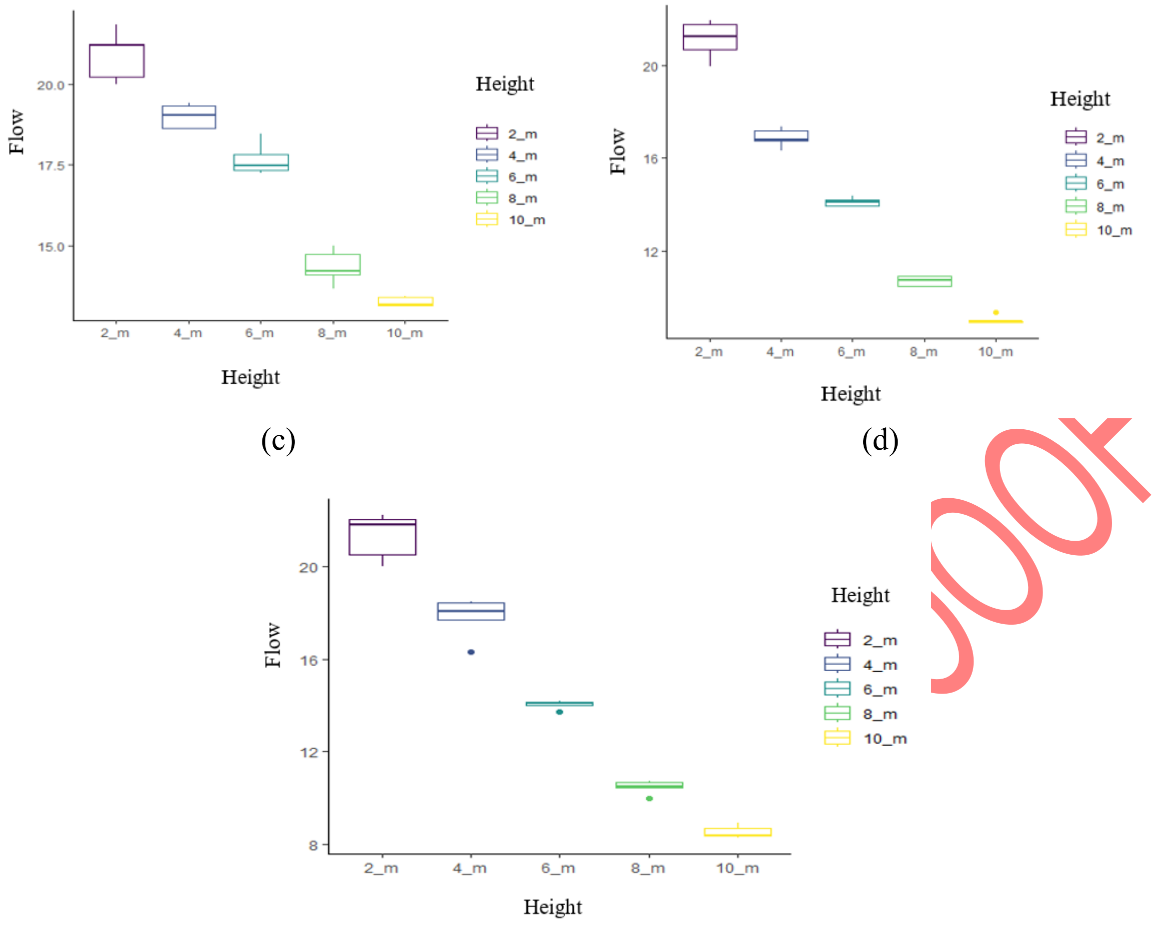
Suction Depth	N	Median	Ave Rank	Z
1	25	17.24	77.9	2.29
2	25	18.15	75.1	1.87
3	25	17.49	67	0.62
4	25	14.09	47	2.47
5	25	14.09	48	2.31
Overall	125		63	

H = 16.44 DF = 4 P = 0.002
H = 16.44 DF = 4 P = 0.002 (adjusted for ties)

The distribution of flow rate values for the manually operated volumetric pump is presented in Figure 11a–e. The box plots illustrate the relationship between flow rate and discharge height for suction depths ranging from 1 to 5 m. The results indicate that flow rate decreases as discharge height increases. Conversely, lower discharge heights are associated with higher extracted flow rates.



(a) (b)



(c) (d)

(e)

Figure 11. Box plots of the manual volumetric pump as a function of discharge height and extracted flow rate: (a) 1 m; (b) 2 m; (c) 3 m; (d) 4 m; (e) 5 m

DISCUSSION

This section discusses the performance of the evaluated pumping systems under the specific operational conditions of the study area, focusing on hydraulic behavior, efficiency, and applicability in rural Andean environments.

Performance Evaluation

In Figure 7, the pump's performance was analyzed based on the flow rate extracted concerning suction depth. Results ranged from 48.79 L/min at a depth of 1 meter to 69.56 L/min at 5 meters, demonstrating a consistent increase with depth. The revolutions per minute (rpm) varied between 25 and 55, as measured with a tachometer. This response can be attributed to the design and capacity of the system to maintain uniform pressure at greater depths, ensuring consistent performance. Davidson *et al.* [27] determined the performance of the rope pump, achieving flow rates between 20 L/min and 55.77 L/min. Their analysis extended to depths of 10 meters, with rpm values ranging from 27 to 59. They simulated a well using a 255 L container and lifted water up to the third floor of a building.

At 2330 m above sea level, atmospheric pressure is significantly lower than at sea level, reducing the theoretical suction limit of hand-operated pumps. According to Shah *et al.* [25] suction height decreases by approximately 1.5 m at 1500 m and up to 3 m at 3000 m altitude. Therefore, evaluating pump behaviour under Andean conditions is not only a matter of geographical context but also a hydraulic necessity. Reduced atmospheric pressure affects negative pressure generation, cavitation potential, and volumetric efficiency, which directly influence pump applicability in these regions.

When comparing the rope pump with previous studies, slight differences in flow rates have been reported, influenced by factors such as piston diameter and spacing, rope type, operational conditions (manual or pedal-driven), discharge pipe diameter, and wheel RPM. For instance, research by Kadlowec *et al.* [21] used polypropylene rope and PVC plumbing pipes and fittings (1.27 cm and 2.54 cm in diameter), with piston spacing variations of 1 to 2 pistons per meter. The pump was installed 15 meters high on the fourth floor of a building, while the simulated well was a 55-gallon barrel located on the ground floor. RPM varied from 40 to 80, achieving flow rates of 6 L/min with half-inch piping and 1 piston per meter and 16 L/min with 1-inch piping and 2 pistons per meter. They concluded that piston spacing influences output flow rate, with greater quantities achieved at 2 pistons per meter of rope. Furthermore, larger pipe diameters increased the volume of water extracted but required more pumping power due to higher water displacement volumes. These findings align with this study, where a 1-inch discharge pipe and 3 pistons per meter were used. Regarding the velocity at which the rope enters the pipe, flow rates decreased, consistent with Kadlowec et al.'s findings. This phenomenon is explained by some water spilling out of the discharge pipe and over the pump head, reducing efficiency.

Kadlowec *et al.* [21] reported flow rates between 30 and 55 L/min depending on piston spacing and pipe diameter. Their study demonstrated that system configuration, pumping depth and operational speed significantly influences pump performance. Although the absolute values reported in those contexts differ from the 69.56 L/min observed at 5 m in this study, such variability can be explained by differences in piston spacing, pipe diameter, immersion depth, and operator-induced rotational speed [34]. Importantly, most of these studies were performed at lower elevations, where atmospheric pressure does not impose the same suction constraints observed in Andean environments. Therefore, the present results extend the available performance data by demonstrating that rope pump efficiency can remain stable—and even improve within shallow operating ranges—under mid-altitude atmospheric conditions when adequate submergence minimizes air entrainment and stabilizes the water column.

When comparing the results with previous studies, the increase in flow rate with suction depth, although counterintuitive, has been documented before. For instance, a study by Kadlowec *et al.* [21] reported that a rope pump operating at a depth of up to 10 meters achieved a maximum flow rate of 55.77 L/min, a value close to the flow rate observed in this study. However, the flow continues to increase, reaching 69.56 L/min at 5 meters, suggesting an improvement in efficiency with increased depth. This phenomenon has also been observed in research by MacDonald *et al.* [14] which indicated that the efficiency of rope pumps increases as the submergence of the suction line improves. According to these studies, increasing the suction depth can reduce air entrainment in the suction pipe, thereby enhancing the stability of the water column and reducing turbulence. This, in turn, increases the system's hydraulic efficiency.

Design Implications

Although a higher static head generally requires more energy to lift the water, in our tests the rope pump showed a moderate increase in flow rate with increasing suction depth. The observed increase in the flow rate of the rope pump with suction depth, while seemingly contradicting the conventional theory of piston-suction pumps, where flow rate typically decreases with suction height [25], is consistent with the behavior documented in positive displacement pumping systems. Unlike traditional suction pumps, which depend on atmospheric pressure and are therefore limited by cavitation at higher suction heights, the rope pump functions as a mechanical conveyor where pistons physically push the water column upwards. This conveying mechanism implies that performance depends more on the stability of the water column than on suction limitations [26]. The increased flow rate between 1 and 5 meters of depth is likely due to greater continuity of the water column and reduced air intake with greater immersion, as shorter water columns have been shown to reduce pump functionality in manual systems [29]. Greater immersion minimizes vortex formation and air entrainment [35], allowing for greater volumetric efficiency, a phenomenon also observed in studies of rope pumps [36].

In the absence of specific studies on manually operated volumetric pumps, analyses were conducted using other manual pump systems like the Modified India Mark II, Afridev, and Vergnet pumps, which share similar operating principles.

Research highlights that the efficiency of manual pumps depends on internal geometry, lever length, piston angle, and operational and maintenance conditions [37]. Recent analyses demonstrated that modifications to piston configurations could reduce leakage and improve flow stability, emphasizing the importance of system design and adjustment to maximize performance [21]. Figure 9 illustrates that the flow rate of a manually operated volumetric pump decreases with increasing discharge height. This finding aligns with the inverse relationship between pressure and flow rate in hydraulic systems. At a 2-meter height, the initial flow rate was 21.97 L/min, decreasing progressively to 11.68 L/min at a 10-meter height. This pattern is consistent with the limitations imposed by the pressure required to overcome the water column. As discharge height increases, the energy needed to move the fluid rises, resulting in a reduced effective flow. This is characteristic of positive displacement pumps. Previous studies indicate that the hydraulic efficiency of such pumps can be affected by system resistance and fluid viscosity, especially at greater heights, where friction and cavitation losses become more pronounced [38].

Further observed reductions in flow rate may also be due to operational factors, such as internal component wear and system adjustment precision. Optimizing piston design, reducing friction, and employing high-durability materials can mitigate these losses and enhance overall performance. Preventive maintenance also plays a crucial role in ensuring the pump operates at maximum capacity under demanding conditions. Although these pumps offer high performance and reliability across various industries, their performance is closely tied to system design and operating conditions. Future studies could focus on improving efficiency and minimizing losses related to mechanical wear, friction, and flow variations.

For manually operated volumetric pumps, reported flow rates in African rural systems typically range between 12 and 28 L/min at discharge heads around 10 m [17]. The lower flow values observed in this study at increased discharge heights are consistent with the expected hydraulic behavior of positive displacement systems, where greater static head directly increases resistance and reduces effective output. These findings suggest that altitude-related suction limitations do not override the fundamental hydraulic constraints of piston-type systems but may interact with them depending on well geometry and operational conditions [39].

Comparing the India Mark II and III manual pumps with the manual volumetric pump, with respect to manufacturing, the first two have disadvantages because being made of iron material they tend to rust shortly after use, and changing it to stainless steel material increases its initial cost, which is why they have to be subject to financing from international organizations such as UNICEF as is the case in many regions of India that although the technology is well accepted [40], the problem still exists. On the other hand, the manual volumetric pump does not present these problems because most of its components are made of PVC pipes. Although Oki *et al.* [41] mention that the India Mark II, III, and Afridev manual pumps are widely used in Africa, approximately 30% tend to deteriorate rapidly in moving parts or bearings, and in some cases, the percentage is even higher (36%) [15].

The consistent operation of handpumps for water extraction is influenced by key factors, especially in rural regions of Africa where many people rely on these systems. While an estimated 60,000 new pumps are installed each year, supplying water to 670 million people [42], the performance and sustainability of these systems depend on several determinants [43]. Technical factors, such as construction quality and ongoing maintenance, play a significant role in the longevity of the pumps. Additionally, hydrogeological conditions, including fluctuations in the water table and the risk of well collapse, are critical in determining pump efficiency. Financial considerations, such as the availability of funds for repairs and maintenance, further impact the operational lifespan of these systems. Social factors, including the community's capacity for effective management, are equally vital for ensuring that the wells remain functional over time [44].

A study in Emina-Boadi-Kumasi (Ghana) by Mantey *et al.* [45] found that wells with manual pumps were the preferred water source for domestic consumption (53%) compared to public sources (18%), piped water (6%), and dug wells (5%). Additionally, individuals consumed an average of 20 L/day of water to meet their needs, with higher amounts for children and women. In comparison, the manually operated volumetric pump extracted 21.97 L in 1 minute at a 2-meter discharge height, demonstrating the capacity to supply sufficient water for human consumption. When projected to an hour, the pump could extract approximately 1,300 liters, sufficient not only for human consumption but also for small-scale agricultural and livestock activities.

Implications for water supply in high-altitude Andean communities

This study aimed to evaluate the applicability of low-cost pumping technologies for groundwater extraction in an Andean environment. The measured flow rates of the rope pump and the manual volumetric pump define the practical operating ranges of each technology under the hydroclimatic conditions of Chachapoyas. These results indicate that both systems can effectively meet typical water demands for domestic use and small-scale irrigation needs when water levels are maintained within the evaluated ranges, which is common in high-altitude Andean springs and shallow wells [33]. The results address this by demonstrating that, in high Andean communities, rope pumps are particularly suitable for shallow artesian wells, where they can provide high flow rates with simple mechanical components, while manual volumetric pumps offer a robust alternative for situations where it is necessary to raise the discharge point and the manometric head requirements are greater.

Comparability and external validity in different areas

The results presented here are specific to the rope and piston pump prototypes tested, which were constructed with particular dimensions and locally available materials. Flow rates in manually operated pumps are strongly influenced by pump geometry (e.g., piston diameter, valve design, rope tension) and by user-induced variability (e.g., strokes per minute, revolutions per minute, applied force). These factors make direct comparison with other studies difficult, as differences in design and operator effort may lead to significant variations in performance. For this reason, the findings should be interpreted as representative of the tested designs under the reported conditions, rather than universally generalizable. Reporting of configuration metadata, as recommended by RWSN field evaluations, is crucial to enable future cross-study comparability and to guide standards for appropriate technology in rural water supply. It should be noted that these findings underline the importance of adapting pumping technologies to local conditions and establishing evaluative guidelines for their successful implementation in rural contexts elsewhere.

CONCLUSION

This study experimentally demonstrated that both the rope pump and the positive displacement piston hand pump are technically viable and low-cost alternatives for groundwater extraction in high Andean conditions (2330 m a.s.l.), providing novel quantitative evidence for environments with similar conditions. The rope pump showed a statistically significant increase in flow rate with greater suction depth (up to 69.56 L/min at 5 m), attributed to improved water column stability and reduced air entrainment, confirming its suitability for shallow artesian wells requiring high discharge with minimal mechanical complexity. In contrast, the positive displacement piston hand pump showed a significant decrease in flow rate with greater discharge height (from 21.97 L/min at 2 m to 11.68 L/min at 10 m), consistent with the hydraulic limitations of positive displacement systems with higher static head. In general, both technologies can meet domestic and small-scale agricultural water demands in high-altitude rural communities, although their performance depends on the geometric configuration, operating conditions, and maintenance, highlighting the importance of context-specific design and implementation for sustainable rural water supply.

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NOMENCLATURE

Q	flow rate	[L/min]
V	volume	[L]
t	time	[min]

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