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Design and Field Testing of a Battery-Assisted, Mechanically Buffered Floating Water Pumping Prototype for Smallholder Irrigation in Benin

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Abstract This study presents the design and preliminary field testing of a battery-assisted, mechanically buffered floating water pumping prototype developed for smallholder irrigation in contexts with limited access to energy and infrastructure. The system is conceived as a proof of concept that combines mechanical energy buffering, via compression springs and a flywheel, with intermittent electromagnetic assistance supplied by a battery, rather than as a fully autonomous energy system. The prototype was designed, assembled, and tested under real field conditions in the commune of N'Dali, northern Benin. At this exploratory stage, the evaluation focused exclusively on functional behavior and hydraulic performance, while energetic efficiency was intentionally excluded from the scope of the analysis. Field experiments based on volumetric measurements yielded a mean discharge of 0.21 L s-1 under a total dynamic head of approximately 0.87 m. The prototype exhibited stable flotation, reliable mechanical operation, and required minimal human intervention during test cycles. Although energy consumption, efficiency, and long-term durability were not quantified, the results demonstrate the technical feasibility of a low-energy, mechanically assisted floating pumping system adapted to smallholder irrigation. The prototype therefore constitutes a robust experimental platform for subsequent instrumentation, energy performance assessment, and design optimization.

Keywords: *Experimental Prototype, Floating Pump, Rural Irrigation, Hydraulic Performance, Proof of Concept*

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1. Introduction

Access to reliable irrigation water remains a critical challenge for agricultural production in rural sub-Saharan Africa [1], where farming systems are predominantly rain-fed and highly vulnerable to climatic variability [2,3]. In Benin, less than 1% of cultivated land is equipped with irrigation infrastructure, despite substantial irrigable potential [4,5]. In northern Benin, extended dry seasons, irregular rainfall patterns, and limited access to modern energy sources constrain both agricultural productivity and rural livelihoods [4].

During dry periods, most smallholder farmers rely on manual irrigation methods, such as watering cans, which are labor-intensive and restrict cultivated plot sizes [6,7]. Motorized pumps provide higher discharge rates but are often financially and logistically inaccessible due to high purchase costs, fuel dependency, maintenance requirements, and environmental impacts [8,9]. Solar-powered pumps offer a sustainable alternative, yet their adoption is limited by high upfront costs and technical complexity [10,11].

Recent studies highlight the potential of low-energy, mechanically assisted pumping systems as intermediate solutions suitable for rural contexts [12,13,14]. However, many proposed designs remain insufficiently tested in real-field conditions or poorly adapted to local socio-technical constraints [13]. There is therefore a need for experimental exploration of alternative pumping concepts prioritizing simplicity, mobility, and functional robustness over immediate energy efficiency.

The present study addresses this gap by proposing and experimentally evaluating an autonomous floating pumping prototype for rural irrigation. The specific objectives are to: i) describe the design and operational principles of the experimental prototype, ii) assess its preliminary hydraulic performance under field conditions, and ii) identify technical limitations and avenues for future research, particularly regarding energetic efficiency and long-term durability, which remain outside the scope of this initial study.

2. Materials and Methods

In this study, the term “battery-assisted” refers to an intermittent and supportive energy input used to sustain rotational motion when mechanical energy stored in springs and the flywheel is insufficient. The prototype is therefore not intended to operate as an energetically autonomous system, but rather as a mechanically buffered pumping device with limited external electrical assistance. Claims related to energetic autonomy are deliberately excluded at this stage.

2.1. Study Area

The experimental evaluation was conducted in Wore-Gourou village, arrondissement of Gbégourou, commune of N’Dali, Borgou Department, northern Benin. The region experiences a Sudano-Guinean climate with a rainy season from May to September and a dry season from October to April, with annual precipitation ranging from approximately 900 to 1,200 mm. The test site consists of a surface water reservoir associated with a developing irrigation scheme (Figure 1). The site was selected as a practical experimental platform rather than a representative hydrological observatory, and no long-term hydrological monitoring was performed.

Figure 1. Surface Water Reservoir Used as the Experimental Test Site

2.2. General Architecture of the Prototype

The system consists of an experimental floating pumping prototype designed for surface water bodies such as reservoirs and small dams. The floating platform is constructed from thick recycled plastic reinforced with a metallic frame to ensure buoyancy, mechanical rigidity, and impact resistance. All exposed metallic components are treated with anti-corrosion coatings.

The mechanical core comprises compression springs mounted on a common shaft and coupled to a flywheel, which smooths rotational motion and stores kinetic energy temporarily. The shaft drives a polymer-based mechanical pump, conveying water through a 25 mm internal diameter PVC discharge pipe.

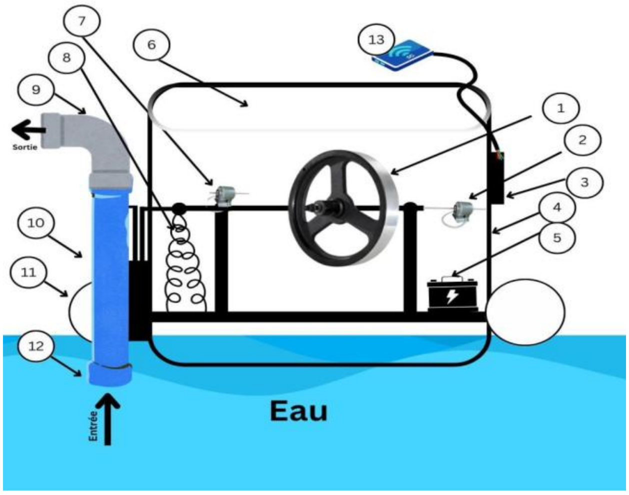
An experimental electromagnetic assistance module includes two coils: one for initial activation and intermittent rotational support, powered by an 18 V lithium battery, and a second coil coupled to the rotating shaft functioning as a generator. At this stage, the electromechanical system is not instrumented for energy flow measurements, and no claim of energetic self-sufficiency is made.

A wired remote control system enables starting and stopping the prototype from the shore, minimizing direct operator contact with water. Figure 2 illustrates the prototype architecture.

2.3. Operating Principle (Qualitative Description)

The prototype operates through mechanically assisted rotation driving the pumping element. Initial mechanical energy is stored in compressed springs, which release to rotate the shaft and flywheel. Mechanical losses progressively reduce rotational speed; when it falls below a threshold, an electromagnetic impulse provides temporary assistance to sustain short-duration pumping cycles.

At this stage, the system is not intended for continuous operation without external energy input but demonstrates the feasibility of combining mechanical energy storage and electromagnetic assistance to achieve limited-duration continuous pumping.



1.Flywheel | 2. Starter coil | 3. Control box | 4. Chassis | 5. 18V Lithium battery | 6. Top cover | 7. Generator coil | 8. Compression springs | 9. 25 mm discharge pipe | 10. Pump | 11. Polystyrene floats | 12. Filter | 13. Control unit

Figure 2. Architectural Illustration of the Experimental Prototype

2.4. Hydraulic Framework

The hydraulic performance of the battery-assisted floating water pumping prototype was assessed using classical fluid mechanics principles under field operating conditions. Particular attention was given to the determination of the mean discharge, as this parameter directly governs the irrigation capacity of the system for smallholder applications in Benin.

The mean discharge Qm ($m^3 s^{-1}$) was determined experimentally using a volumetric method. This approach consists of collecting the water delivered by the pump over a predefined observation period and measuring both the total volume discharged and the corresponding elapsed time. For unsteady flow conditions, which may arise from fluctuations in pump rotational speed, battery voltage, or head variations during field operation, the instantaneous discharge Q(t) varies with time, while the cross-sectional area of the delivery pipe is assumed constant. The mean discharge over an observation period T is therefore defined as the temporal average of the instantaneous discharge and is expressed as:

$$Q((t) = \frac{1}{T}\int_0^T Q(t)\,dt = \frac{1}{T}\int_0^T S \times U(t)\,dt \qquad (1)$$

where Q(t) is the instantaneous discharge ($m^3.s^{-1}$), T (s) is the observation period, $U(t)$ is the instantaneous velocity of the water through this cross-section (m/s), directly dependent on the rotational speed of the device, S is the cross-sectional area of the pipe (m^2). The cross-sectional area of the pipe is given by Equation (2):

$$S = \frac{\pi D^2}{4} \qquad (2)$$

Where D represents the diameter of the pipe (m).

In this study, the pipe diameter (D) and velocity (U) are 20 mm and 0.5 m/s, respectively, with an analysis period (T) of 1 hour.

The total dynamic head (TDH) of the battery-assisted floating pumping system was evaluated in order to characterize the hydraulic load against which the pump operates under field conditions. The TDH was estimated as the sum of the static suction head, the delivery (or discharge) head, and the hydraulic head losses occurring along the conveyance system, as expressed by:

$$TDH = H_s + H_d + \Delta H_p \qquad (3)$$

where H_s (m) is static suction head, H_d (m) is delivery head, and H_p (m) represents total head losses to pipe friction and hydraulic fittings.

The static suction head H_s was defined as the vertical distance between the free water surface at the intake and the pump reference level. In the case of the floating configuration, this parameter remained minimal and nearly constant during operation, as the pump followed water level fluctuations. The delivery head H_d corresponded to the vertical elevation difference between the pump outlet and the discharge point at the irrigation system inlet. This height was measured directly in the field using a measuring tape. In this study, $H_s = 0$ (submerged pump) and $H_d = 0.7m$.

Head losses ΔH_p were estimated analytically, as pressure losses and flow velocities were not measured directly during field tests. Friction losses along the pipes were calculated using the Darcy-Weisbach equation [15], based on the measured pipe length and internal diameter, the estimated mean discharge, and standard values of the friction factor corresponding to the pipe material and flow regime. Additional minor losses associated with bends, valves, and connectors were included using equivalent loss coefficients. This indirect estimation approach is consistent with the practical constraints of field experimentation and provides a reasonable approximation of the hydraulic losses encountered by the pumping system. Head losses ΔH_p were expressed by the following equation:

$$\Delta H_p = f \times \frac{L}{D} \times \frac{U^2}{2g} + \sum k \times \frac{U^2}{2g} \qquad (4)$$

Where f denotes the Darcy-Weisbach friction factor, and k the local loss coefficient for each hydraulic obstruction (such as bends, valves, or sudden expansions), both dimensionless. The friction factor was assumed based on standard values for smooth PVC pipes under low Reynolds number flow conditions ($f \approx 0.02 - 0.03$). Minor loss coefficients for bends and fittings were taken from classical hydraulic literature. These assumptions are consistent with exploratory field tests performed under limited instrumentation conditions. For this study, the Darcy-Weisbach friction factor is $f = 0.02$, and the total local loss coefficient is $\sum k = 1,05$, corresponding to one bend and one valve.

The pressure generated by the pumping system during each operating cycle was estimated using Bernoulli's principle, under the assumption of incompressible flow and steady-state conditions over the observation period. The pressure head developed by the pump was assumed to be equivalent to the total dynamic head previously determined. Accordingly, the corresponding pressure P (Pa) was approximated as:

$$P = \rho g TDH \qquad (5)$$

Where ρ is the density of water (kg m^{-3}), and g acceleration due to gravity (m s^{-2}).

In the context of field testing of a battery-assisted floating pumping prototype, direct pressure measurements were not performed. The pressure values obtained from this relation therefore represent an analytical estimation derived from the hydraulic head rather than an experimentally validated measurement. These calculations were primarily intended to provide a first-order assessment of the hydraulic loading and to support the interpretation of system performance, rather than to serve as predictive or design-certified pressure models.

The pump-generated power is subsequently used to evaluate the minimum hydraulic power necessary for fluid transfer, which is defined by the following equation:

$$P_h = \rho g Q(t) TDH \qquad (6)$$

Where P_h is the hydraulic power (W), g is the acceleration due to gravity (m s^{-2}), $Q(t)$ is the volumetric flow rate ($m^3 s^{-1}$), and TDH = total dynamic head (m).

2.5. Buoyancy and Stability of the Floating Platform

The buoyancy and stability of the floating prototype were considered prerequisite conditions for the proper hydraulic functioning of the system, as they directly influence the relative position of the pump, the constancy of the suction head, and the reliability of discharge measurements under field conditions. The platform was therefore designed using a simplified analytical approach, consistent with rural field experimentation constraints and the absence of advanced instrumentation.

The flotation condition was established based on the static equilibrium between the total weight of the system and the buoyant force, expressed by Archimedes' principle as:

$$\rho g V_{im} \geq g M_{total} \tag{7}$$

where ρ is the density of water (kg m^{-3}), V_{im} is the immersed volume of the floating elements (m^3), and M_{total} is the total mass of the prototype (kg), including all mechanical and electromechanical components. For a total system mass of 20.36 kg, the minimum required immersed volume was estimated at 0.02036 m^3.

To account for uncertainties associated with operating conditions, such as load variations, dynamic excitations induced by wind and surface waves, and material aging, a buoyancy reserve was incorporated through the use of a safety coefficient Ksaf = 1.1. The total volume of the floating elements was therefore defined as:

$$V_{total} = K_{saf} V_{im} \tag{8}$$

resulting in a minimum floating volume of 0.0224 m^3, which ensures that the system remains afloat and that the waterline remains stable during operation.

From a constructive standpoint, this buoyancy reserve was implemented through the installation of expanded polystyrene floats, symmetrically positioned along the longitudinal axis on both sides of the base of the device. Due to its low density and good water resistance, expanded polystyrene is well suited for experimental floating systems. These floats provide additional passive buoyancy and enhanced protection against external disturbances, complementing the analytical design considerations described above.

Both static and dynamic stability of the platform were further ensured by a controlled mass distribution and a lowered center of gravity. The heaviest components, such as the flywheel, structural frame, and transmission elements, were positioned in the lower part of the structure to limit trim variations that could affect the suction head and, consequently, the effective hydraulic load acting on the system. This configuration satisfies the metacentric stability criterion, expressed as:

$$GM = BM - BG > 0 \tag{9}$$

where GM is the metacentric height, BM is the distance between the center G of buoyancy and the metacenter M, and BG is the distance between the center of buoyancy and the center of gravity. A positive value of GM ensures static stability of the floating device under moderate external excitations.

Finally, the tethered control system connecting the prototype to the riverbank contributes to overall stabilization by limiting excessive lateral displacements. This external constraint improves the repeatability of hydraulic conditions during experimental trials and enhances the reliability of the discharge and hydraulic head measurements reported in this study.

2.6. Prototype Testing and Volumetric Flow Evaluation

Field tests employed a volumetric method using a 25 L container, timing the filling with a stopwatch. The prototype (Figure 3) was submerged to approximately 0.97 m, and three consecutive trials were conducted under similar conditions.

For the purpose of determining the average flow rate, the total volume of water V (m^3) discharged by the pumping system from the initial time (t=0s) to a given time t (s) was measured using a calibrated container, and the corresponding elapsed time t (s) was recorded with a stopwatch. The mean discharge was then computed as:

$$Qm = \frac{V}{t} \tag{10}$$

This expression represents a discrete approximation of the temporal integration of the instantaneous discharge. It assumes that the measured volume adequately captures the flow rate fluctuations occurring during the measurement interval. The volumetric method is particularly suitable for field testing in smallholder irrigation contexts, as it is robust, low-cost, and well adapted to the evaluation of prototype pumping systems operating under quasi-steady conditions.

The limited number of repetitions reflects the exploratory nature of the study.

Figure 3. Experimental Prototype

3. Results

3.1. Hydraulic Performance of the Floating Pumping Prototype

Table 1 presents the hydraulic performance measured during field testing of the floating pumping prototype. The instantaneous discharge reached 0.25 L s^{-1}, while the total dynamic head (TDH) was 0.87 m, corresponding to an operating pressure of 0.09 bar. Based on these values, the hydraulic power was estimated at 2.13 W.

Three consecutive volumetric measurements were performed under comparable operating conditions. The recorded filling times were 2 min 02 s, 1 min 56 s, and 2 min 00 s, resulting in a mean discharge of 0.21 L s^{-1} with a standard deviation of ±0.006 L s^{-1}, indicating low variability between trials.

Table 1. Hydraulic Parameters of the Prototype

Parameter	Estmation
Instantaneous flow rate	0,25 L s^{-1}
Total Dynamic Head (TDH)	0,87 m
Pressure	0,09 bars
Hydraulic Power	2,13 W

The instantaneous discharge value reported in Table 1 corresponds to the nominal filling rate derived from a single container measurement, whereas the mean discharge represents the arithmetic average of the three consecutive trials (n = 3).

Throughout the test duration, the prototype maintained continuous pumping and stable flotation without mechanical failure or operator intervention. No measurements of energy consumption, rotational speed, torque, or system efficiency were conducted during this experimental phase.

3.2. Operational Configuration During Hydraulic Testing

During field experiments, the floating pumping prototype operated under a stable and repeatable material configuration. No structural modification was introduced between test runs, ensuring consistent hydraulic operating conditions.

System activation and control were provided by an 18 V lithium battery, coupled with a wired remote control offering an operational range of approximately 15 m. This configuration enabled start–stop operations from the riverbank and minimized external disturbance during testing.

The mechanical assembly consisted of tempered steel compression springs coupled to a cast-iron flywheel (15 cm diameter). Power transmission was ensured by a 10 mm diameter galvanized steel shaft, which remained mechanically stable throughout the experiments.

Water abstraction was achieved using a polymer-based mechanical pump connected to a 25 mm internal diameter PVC discharge pipe. The pumping line operated without leakage or blockage under the tested hydraulic conditions.

The system was supported by a thick recycled plastic floating hull reinforced with metallic elements. Stable flotation and mechanical integrity were maintained throughout the tests. Secondary components, including electrical wiring and fastening elements, showed no observable degradation during operation.

4. Discussion

The experimental results demonstrate the functional feasibility of the proposed floating pumping prototype under real field conditions. The system achieved a mean discharge of 0.21 L s^{-1} with low variability between trials, while maintaining continuous operation and stable flotation throughout the test duration. These observations indicate that the prototype can sustain steady hydraulic performance despite the absence of sophisticated control or regulation mechanisms.

The measured flow rate remains modest when compared to conventional motorized pumping systems, which typically deliver discharges ranging from 1.4 to 4.2 L s^{-1} in small-scale irrigation contexts [16]. However, the present prototype is not intended to compete with energy-intensive equipment. Instead, its performance level is consistent with alternative low-energy or non-motorized pumping technologies designed for decentralized rural applications. Locally assembled hydraulic ram pumps, for example, have been reported to achieve optimal discharges of approximately 12.9 L min^{-1} (≈ 0.215 L s^{-1}) under comparable smallholder conditions [17], values closely aligned with those observed in this study. Unlike hydraulic ram pumps, however, the proposed system does not rely on natural elevation differences or continuous upstream head, which significantly broadens its applicability in flat rural landscapes such as those prevalent in northern Benin.

The measured total dynamic head of 0.87 m and corresponding low operating pressure (0.09 bar) reflect the limited hydraulic energy available per unit mass of water. These values are characteristic of low-head pumping systems and are consistent with the measured hydraulic power of 2.13 W. Similar performance ranges have been reported for experimental and prototype-scale pumping devices intended for localized irrigation, livestock watering, or domestic water supply [18,19]. The absence of excessive pressure fluctuations during operation further supports the mechanical stability of the system under the tested conditions.

Compared with solar-powered pumping systems, which can deliver significantly higher discharges depending on photovoltaic capacity and solar irradiance, the present prototype offers a contrasting operational paradigm. Solar pumps often require substantial initial investment, careful sizing, and specialized maintenance, which can limit adoption among resource-constrained smallholder farmers [20,21]. In contrast, the floating pumping prototype operates independently of solar availability and exhibits reduced sensitivity to short-term climatic variability, a feature that is particularly relevant in regions experiencing increasing rainfall irregularity and extended dry seasons [22].

A distinctive contribution of this study lies in the integration of mechanical energy storage (compression springs) with intermittent electromagnetic assistance as the core operating principle. Previous research has shown that spring-based energy storage systems, when coupled with electromagnetic generators or actuators, can sustain cyclic mechanical motion while reducing dependence on continuous external power input [23,24]. The present work extends these concepts to a rural irrigation context, demonstrating that such a hybrid mechanical–electromagnetic configuration can support autonomous pumping cycles under field conditions.

The floating architecture further enhances the operational flexibility of the system. Stable flotation was maintained throughout the experiments, and no mechanical or structural instability was observed. This mobility allows deployment across a range of surface water bodies, including reservoirs, small dams, and ponds, thereby accommodating the spatial and seasonal variability of water resources commonly encountered in rural West Africa. Similar advantages have been reported for floating pumping and floating energy systems, particularly in environments characterized by fluctuating water levels [25,26].

Despite these encouraging outcomes, several limitations must be acknowledged. First, the study did not include measurements of energy consumption, rotational speed, torque, or system efficiency, preventing a quantitative assessment of energetic performance. Second, the limited number of experimental repetitions (n = 3) constrains statistical generalization. Third, the long-term durability of key components, particularly springs and electromagnetic coils subjected to repeated loading cycles, was not evaluated. These limitations are consistent with the proof-of-concept nature of the prototype and do not invalidate the functional demonstration reported here.

Future work should focus on instrumenting the system to enable detailed energy balance analysis, including efficiency and loss characterization. In this perspective, renewable and hybrid energy alternatives can be linked to the work of Basem et al. [27], which highlights the potential of hybrid energy configurations for improving the reliability and sustainability of agricultural pumping systems. Design optimization aimed at reducing frictional losses, improving material durability, and enhancing hydraulic efficiency is also required. In addition, the integration of simple adaptive control strategies, potentially including low-cost sensor-based or AI-assisted controllers, could enable dynamic adjustment of pumping cycles in response to real-time irrigation demand, as suggested in recent studies on intelligent irrigation systems [28,29].

Overall, the results confirm that the proposed floating pumping prototype constitutes a technically viable, low-energy solution for decentralized water lifting in rural environments. While its discharge capacity remains limited relative to motorized systems, its simplicity, mobility, and reduced reliance on external energy sources position it as a promising complementary technology for small-scale irrigation and water supply in resource-constrained settings.

5. Conclusion and Perspectives

This study presented the design and preliminary experimental evaluation of an autonomous floating pumping prototype intended for rural irrigation applications. Results confirm the technical feasibility of the concept and its ability to deliver continuous pumping over short operating cycles under real field conditions.

At this stage, the prototype serves as an experimental platform rather than a validated irrigation technology. Immediate future work priorities include: (1) instrumenting the prototype with current, voltage, and rotational speed sensors to quantify energy flows and overall efficiency; (2) conducting accelerated life-cycle testing of springs and electromagnetic components to assess durability; and (3) optimizing the hydraulic design of the impeller and discharge line to reduce frictional losses. These steps are essential before any scale-up or comparative techno-economic assessment.

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Conflict of Interest

The authors declare no financial, personal, or professional conflicts of interest that could have influenced this study.

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