ARE WATER WHEELS A RURAL COST-EFFECTIVE ENERGY TECHNOLOGY?

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Abstract: Water wheels are an economically viable alternative to electrical water pumping in rural areas. This study constructed and analyzed a small-flow water wheel with a low pressure head, built from materials that are easily accessible and inexpensive. The flow rate was measured under different elevation conditions (1–7.5 m) and perimeter blade velocities (0.5–3.0 m s-1). Energy efficiency was estimated, and two equations were proposed to describe the relationship between flow rate, trough velocity, and pressure head. The initial start-up cost of the equipment is approximately 50% of the minimum wage in Brazil. The attractiveness of the initial investment in relation to the pumping capacity is equivalent to that of photovoltaic systems. In places where the river velocity is approximately 1.5 m s-1, the water wheel can irrigate an area of 200 m², while raising water to 22 m of pressure head. The equipment has a low initial cost and low efficiency in terms of energy transformation; however, it is a promising water pumping technology at small elevations with watercourses moving approximately 1.5 m.s-1.

Keywords: Water pumping; Low flow; Low pressure-head.

A RODAS D'ÁGUA É UMA TECNOLOGIA RURAL EFETIVA E DE BAIXO CUSTO?

Resumo: Uma alternativa economicamente viável para o bombeamento de água em propriedades rurais tem sido as rodas d'água. Objetivou-se construir e analisar uma roda d'água de pequenas vazões para elevação a baixas pressões manométricas. Os materiais empregados foram de fácil acesso e baixo custo. A vazão foi medida sob diferentes condições de elevação (1 a 7,5 metros) e velocidades perimetrais das calhas (0,5 a 3,0 m.s-1). A eficiência energética foi estimada e duas equações foram propostas para descrever a relação entre vazão, velocidade da calha e altura de elevação. O custo inicial do equipamento é de cerca de 50% do salário mínimo no Brasil. A atratividade do investimento inicial em relação a capacidade de bombeamento é equivalente a sistemas fotovoltaicos. Para locais onde a velocidade do rio é de cerca de 1,5 m.s-1, a roda d'água pode suprir irrigação para uma área de 200 m², elevando água a 22 metros de altura manométrica. O equipamento mostrou-se de baixo custo inicial, pouco eficiente em termos de transformação energética. Entretanto, é uma tecnologia promissora para o bombeamento de água a pequenas elevações e que dispõe de cursos d'água com cerca de 1,5 m.s-1.

Palavras-chave: Bombeamento de água; Baixas vazões; Baixas pressões manométricas.

INTRODUÇÃO

Finding an appropriate location and constructing cost-effective water pumps in rural areas is a research priority worldwide. Daily human population necessities, livestock requirements, industrial demands, and agricultural irrigation are global primary uses of water globally.

The use of electric pumps to fulfill water requirements has been a common practice in the past. However, high energy costs present a major economic barrier for low-income

rural areas. (ESPERANCINE et al., 2007). Approximately 1.1 billion people worldwide do not have electricity in rural areas (HERINGTON et al., 2017), which results in the use of decentralized energy forms that are less environmentally friendly, such as diesel, gasoline, and natural gas (REIS et al., 2013).

Water wheels are an accessible and simple water pumping technology that became prevalent in the 18th century (CAPECCHI, 2013). However, their adoption was restricted by the lack of significant information on performance scenarios, installation criteria, construction costs, and lack of proper location (HUNG et al., 2018).

There are three main methods for constructing water-wheel based water pump system: an overshot, a breast shot, and an undershot. Of the three, the undershot water wheel, well known as stream wheels, is the oldest and simplest method. Undershot water wheels can be floating or attached to a river, and are utilized to harness the kinetic energy of shallow free surface flows only (HUNG et al., 2018).

The main criterion for placing a water wheel is watercourse speed. Quaranta et al. (2018) reported that this application is promising in fast flowing rivers. Additionally, Quaranta and Rivelli (2015), and Denny (2003), reinforce that they are suitable devices for very low head sites. The objective of this study is to analyze the initial investment and performance of an alternative water wheel in different scenarios of pressure head, river transfer velocity, and water flow supply in order to contribute to cost-effective water pumping in rural areas.

MATERIAL AND METHODS

Construction and designer aspects

A wooden water wheel prototype was developed at the Laboratory of Environmental Engineering, Caiapônia Campus (692 m elevation above sea level), University of Rio Verde. The process of construction was based on cost-saving implementations, which essentially consist of a volumetric pumping system, wooden water wheel, and water lifting system.

The chassis of the system was fabricated from wood to provide support for the pumping system and water wheel itself (TYAGI, 2015), to simplify the test applications. The diameter of the wheel extended to 0.94 m, with 0.24 m width, 0.12 m height, and 15 blades (Figure 1).

Figure 1. An alternative configuration of an undershot water wheel, 0.94 m in diameter with 15 blades.

The circular wooden structure was adapted using an electrical wire spool. The blades were made of galvanized steel and attached (screwed on) to the wood. The chassis-wheel axle connections were abundant, greased to harness maximum kinetic energy transfer.

The wheel axle was 1.055 m long, with 0.50 m from the outer side of the wheel to the first connector (Figure 2A). The second connection point was 0.40 m away from the first. A double engine crankshaft was plugged transversally into the axle of the wheel (Figure 2B).
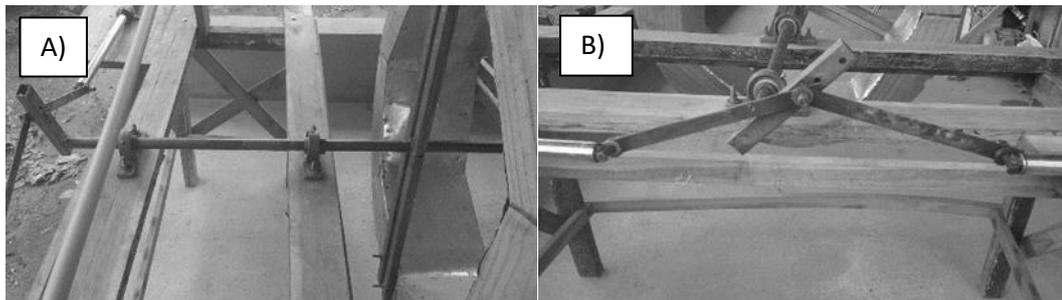

Figure 2. Undershot wheels: (A) support and connections greased; (B) the chassis-wheel axel connections to the pistons.

To achieve the lowest possible cost, two motorcycle vibration dampers were used as the pumping device (Figure 3). Therefore, two modifications were made in the original equipment. First, the removal of the central part of the motorcycle vibration dampers. A vacuum interior was necessary to facilitate the pumping volume ($1.407\ 10\text{-}4\ \text{m}^3$ piston-1). Second, a cut at the bottom of the fixed motorcycle vibration part, which transforms the closed chamber in an open cylinder device. To reduce friction, these components were lubricated by nautical lithium white grease (GRAH et al., 2014). Figure 3 shows the complete pumping system.
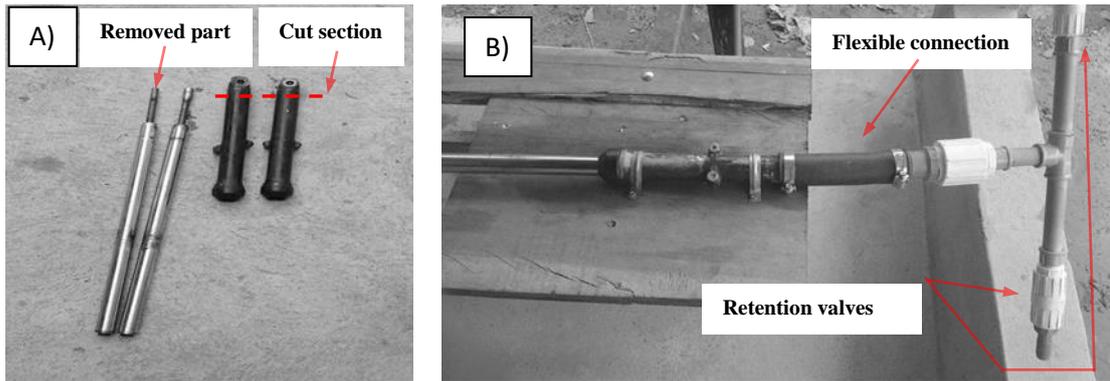
Figure 3. Pumping system: A) adaptably motorcycle vibration damper's; (B) elevation pipe system.

Figure 4 shows the initial water lift system, composed of two retention valves at both water wheel sites. The water entrance valve (bottom, 1") allows suction into the system only. The top valve, on pressure, allows the water to pump into the chamber regularization device (3/4" diameter PVC pipe). The fifth retention valve was installed before the elevation pipe to improve the water pulse. The elevation water pipes (1/2" diameter) were made of flexible tubes, 40-m in length. Because of this span, head loss was ignored, but at other lengths, it could represent an important energy component (ALVES et al., 2014).
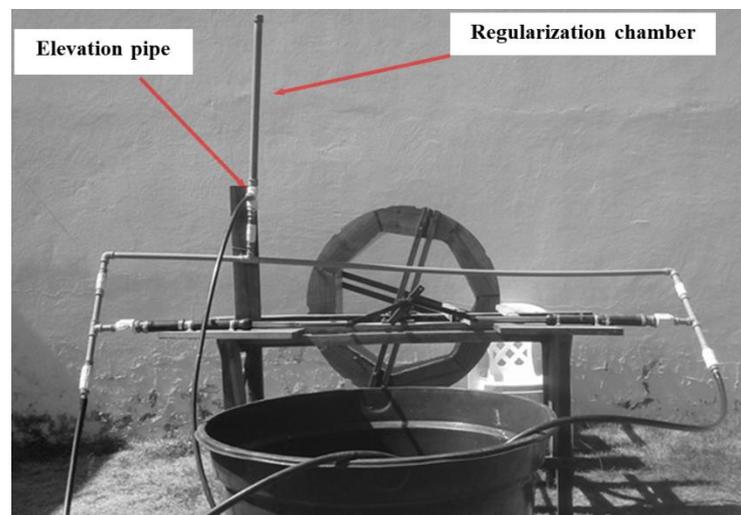

Figure 4. Proposed undershot water wheel prototype made of residual materials.

The cost of each part of the proposed water wheel was quantified, and an estimate was achieved for the total cost. The residual value of recyclable materials was considered.

Experimental layout, model proposal and equipment efficiency

The prototype was placed in an open grass area and attached (connection of bottom retention valves) to a 1 m3 water reservoir as a water supply. The elevation pipes were

extended 26 m horizontally from the water wheel to a water reservoir tower (8 m high), which was used to elevate the terminal pipe (1/2" diameter) into 10 elevation points. These points are placed 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.5, 5.5, 6.5, and 7.5 m higher than the surface water supply. MULLER et al., (2004) define very small head differences as 0.5–2.5 m, while QUARANTA (2018) explored 1–10 m as small head. Therefore, this experiment reaches a small head amplitude.

There are two velocities that rule the performance of water wheels. The water course velocity, which contains kinetic energy, transfers it to the blades of water wheel, resulting in a second velocity (Figure 5). Therefore, two velocities determine the performance of a water wheel. The water course velocity, which has kinetic energy, transfers it to the blades of the water wheel, resulting in a second velocity (Figure 5).
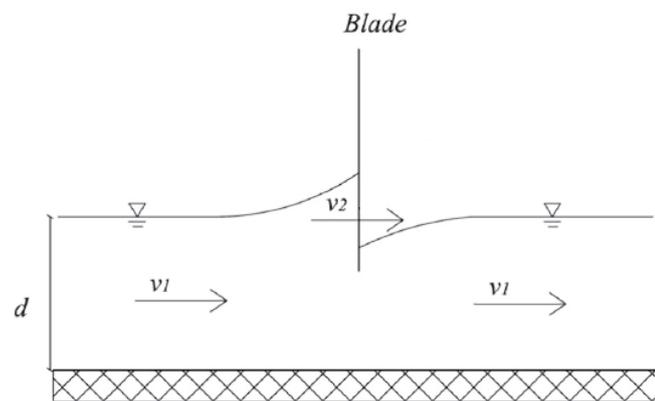

Figure 5. Hydraulic behavior of stream wheels and theoretical energy transfer between the water flow and the blades of the wheel, where v_1 is the undisturbed flow velocity, while v_2 is the blade velocity (adapted from Quaranta, 2018).

Energy transference depends on the canal design (PAUDEL & SAENGER, 2018), number of blades, blade angle, and water course depth (QUANRANTA, 2018; MULLER et al., 2004). Therefore, blade velocity (v2) is strongly dependent on v1. This study investigated v2, considering the scope of the proposed objectives.

An electrical battery analyzer sensor, based on the inductive proximity, was installed in the perimetric blade area (the fixed part in the chassis) to obtain and control the blade speed. The amplitude velocity variation was 0.5, 1.0, 1.5, 2.0, 2.5, and 3 m s-1. The electronic device could keep the velocity constant, probably because of the pressure head, although it did not pass 0.2 m s-1 of standard deviation.

The flow supplies were measured (thrice by volume-time method) for each elevation point and velocity, so that 60 sample points were quantified (flow-elevation-velocity).

Two empirical models were proposed to explain the flow supply (Q) as a variable response to v2 and head pressure (h). The first model (Model A), Equation 1, is remarkably simple and does not consider, effectively, the decrease in Q as a consequence of the increase in water elevation (h). The second model (Model B), Equation 2, reasonably accounts for the flow reduction as a function of the increase in elevation head.

$$Q = \alpha \frac{v_2{}^\gamma}{h^\omega} \tag{1}$$

$$Q = \frac{v_2}{\left(\lambda + v_2 \left(\varepsilon + \beta(h^\delta) \right) \right)} \tag{2}$$

where:
Q – flow supply ($_x10^{-3}.m^3.min^{-1}$)
v_2 – blade velocity ($m.s^{-1}$);
h – pressure head (m); and
$\alpha, \gamma, \omega, \lambda, \varepsilon, \beta, \delta$ – parameters (-)

The Levenberg–Marquardt algorithm was applied to obtain the parametrization by using the maximum reducing error of the estimate and measured flow. Additionally, the absolute error and the coefficient of correlation were used to evaluate the results. The proposed models are tested in a range of experimental data; consequently, their adjustment would only be reliable within that range. Despite this, some extrapolation was made to propose future work.

Kinetic power (Pkin) of the free flow was calculated as a function of Q where Q=Av1 is the flow rate, A is the blade area, and v1 is the river flow velocity considered here as v2=0.33v1. This assumes the maximum value from the momentum theory, according to Quaranta (2018), where power coefficient is 0.296, presented in Equation 3. The power output (water wheel power - Pww) is represented by Equation 4, where Q is the flow supply. The efficiency estimation (η) was obtained by the ratio of Pww by Pkin (Equation 5).

$$P_{kin} = \frac{1}{2}.\rho.Cd.Q.v_1{}^2 \tag{3}$$

$$P_{ww} = \rho.g.Q.\Delta h \tag{4}$$

$$\eta = \frac{P_{ww}}{P_{kin}} \tag{5}$$

where:
P – power (Watts)
Q – flow ($m^3.s^{-1}$)

v_1 – river velocity (m.s^{-1});

h – elevation pressure head (m);

ρ – water density (kg.m^{-3}); and

C_d – power coefficient (-).

RESULTS AND DISCUSSION

Equipment costs

The results of the economic cost are shown in Table 1. The total cost for a wooden water wheel like the one developed in this study (140.03 USD) corresponds to 52% of the Brazilian minimum wage, according to the Brazilian Economical Budget of 2018.

Table 1. Items applied to manufacture water wheels process construction, and the respective values.

ITENS	Units	Price (US$)*	Total Costs (US$)*
Motorcycle vibration**	1	16.95	16.95
Iron axe, connections and rolamentos	-	27.83	27.83
Blade material (zinco)	-	8.47	8.47
Screws, Washer & Nuts	-	9.10	9.10
Retention valves (1")	2	11.30	22.60
Retention valves (¾ ")	3	7.91	23.73
Hard wood**	-	-	-
PVC pipe and connections	-	15.54	15.54
Nautical lithium grease	1	1.70	1.70
Electrical wire spool**	1	-	-
Labor costs (weld and others)	-	14.12	14.12
Total			**140.03**

*dolar-real value in the last 6 months from the construction data 3.54 R$ (Brazilian Central Bank, 2018)

** residual value (scrap value)

Valves are the more significant investment, as they constitute 33% of all costs. The variation in investments presented here could be used as a developing country reference. Nevertheless, it can be a function of currency conversion, region of a given country, minimum wage in that locale, and unit cost of residual materials. Additionally, farmers could bargain (free-of-cost) for some of the residual values. In contrast, industrial water wheels are available in the central region of Brazil at a cost of approximately 847 USD.

Therefore, in terms of relative costs, the proposed water wheel represents 1/6 times the cost of industrial equipment. The simplicity of the construction process and the low-cost initial investment are probably very attractive for water pumping in subsistence farming.

Equipment performance

Both proposed mathematical models (A and B) can be used to describe the flow supply (10-3.m3.min-1) as a function of blade velocity (m.s-1) and head (m). Table 2 shows the parameterization and the statistic coefficient.

Table 2. Parametrization of flow hydraulic performance as function of blade velocity and pressure head

Model	Parameters (-)							R^2
	α	γ	ω	λ	ε	β	δ	
A	1.758	1.249	0.091	-	-	-	-	0.983
B	-	-	-	0.633	-0.084	0.017	0.535	0.980

*R^2 value of model A was 0.0983 and the Standard error was -0.002 $10^{-3}.m^3.min^{-1}$
** R^2 value of model B was 0.980 and the Standard error was 0.056 $10^{-3}.m^3.min^{-1}$

Model A is simpler, with better statistical adjustment than Model B. Nevertheless, Model B has broader applicability; and is recommended for higher speeds because of its better estimate of energy loss (friction) at high speed.

The flow-velocity-head curves are presented in Figure 6. The abscissa axis informs, as mentioned before, the blade perimeter velocity (v2). Therefore, a practical application of these equations is necessary to measure the real relationship among velocities v1 and v2. In the relation presented (v2=0.33v1), the angular coefficient could range from 0.33–0.70 (Quaranta et al. 2018). Considering the value of 0.33 as a reference and the river velocity of 0.5 m.s-1, the corresponding blade velocity would be 1.51 m.s-1. Values are taken as a reference (MULLER, 2010) for the following assumptions.

For the low elevation range, both models can predict the flow consistently well. For reference, river velocity is considered as 1.5 m.s-1, and at an elevation of 10 m the water wheel flow supply reached 1.160 m3.day-1 (estimation of Model B integrated in a day). This is enough to stock water to maintain 15 habitants.day-1 in rural areas in China (individual water consumption of 0.076 m3.habitants-1.day-1) according to FAN et al., (2013), or approximately 10 habitants.day-1 in Brazil (individual water consumption of 0.115 m3.habitants-1.day-1), according to the Brazilian Institute of Geography and Statistics, IBGE (2018).

Furthermore, the water wheel could be used to stock water to supply 200 m2 of gravity drip irrigation, considering a drip irrigation efficiency of 86% and evapotranspiration demand of 5.0 mm.day-1. This represents 20% of the areas irrigated by Alves et al. (2014), using an electric motor powered by solar energy under similar conditions.
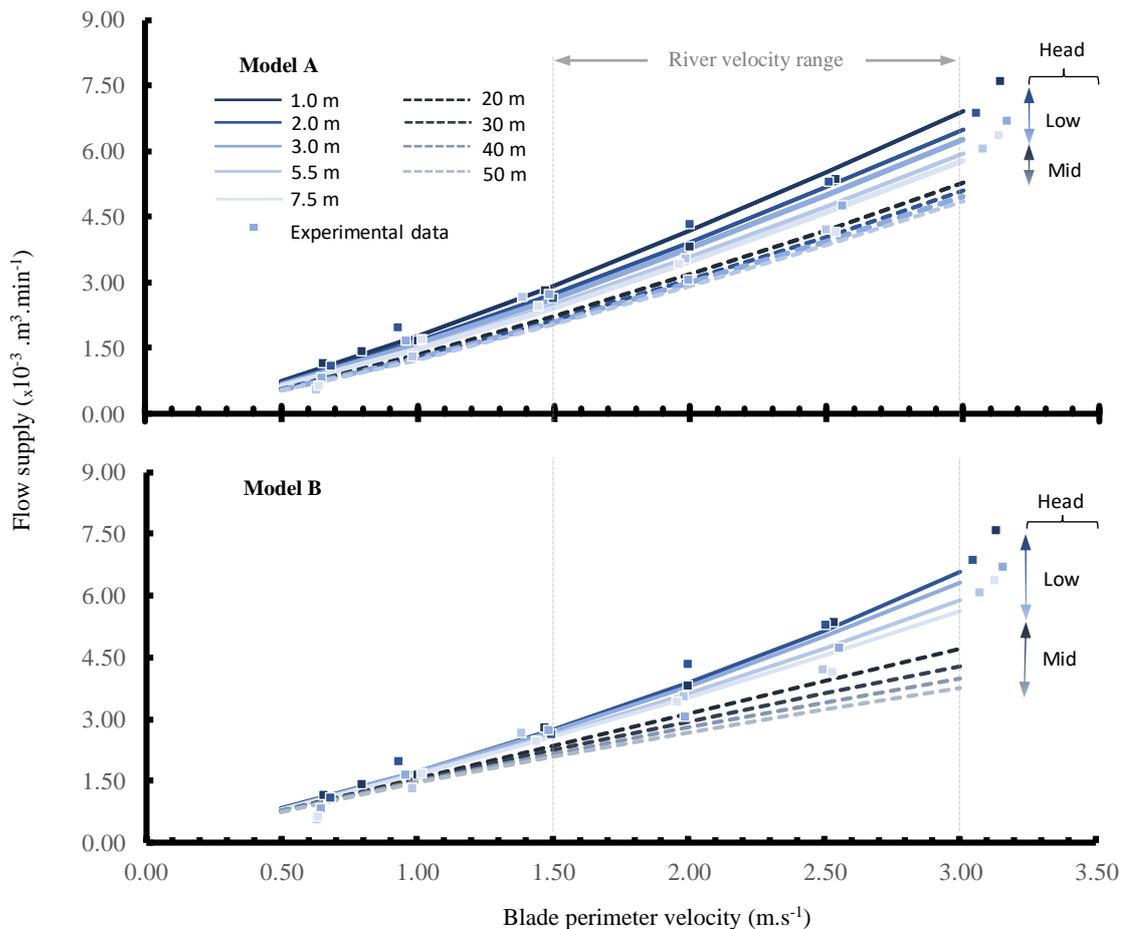
Figure 6. Water flow according to the specific rotation velocity and elevation head (low, 0 to 10 meters; and middle, 10 to 50 meters) for the models proposed.

Alves et al. (2014) studied the initial cost of a water pumping system for drip irrigation (area of 10000 m², and 5.6 L.m^{-2} of water plant demand) considering a total water elevation of 10 m (manometric pressure head of 22.9 m) from a photovoltaic and diesel pumping system, which costs 10,848–2,253 USD, respectively.

Considering the volume pumped per day divided for the initial costs, as a normalized flow/investment index, obtain 5.16 and 24.85−10^{-3}m³.US\$$^{-1}$.day^{-1} for the solar and diesel pumping systems, respectively. For the proposed equipment, considering an elevation of 22 m and the velocity of the watercourse of 1.5 m.s^{-1} (v_2=0.495 m.s^{-1}, Model B), we have the volume of water pumped per day, associated with the initial cost of 8.07 10^{-3}m³.USD[1].day^{-1}.

With respect to the initial investment range including photovoltaic applications and the use of diesel, the referenced water wheel is in the middle. Though not discussed in this study, it should be noted that maintenance and operation costs will tend to be relatively lower than those presented by Alves et al., (2014).

In terms of energy transformation, however, the wooden equipment performance is lower than the industrial water wheels (Fig. 7). Muller et al., (2010) exhaustively tested the undershot (floating) water wheel and concluded that the efficiencies reached 25%–42%, as a function of the numbers of blades. More efficient results were obtained when $v_2 = 0.33 v_1$.
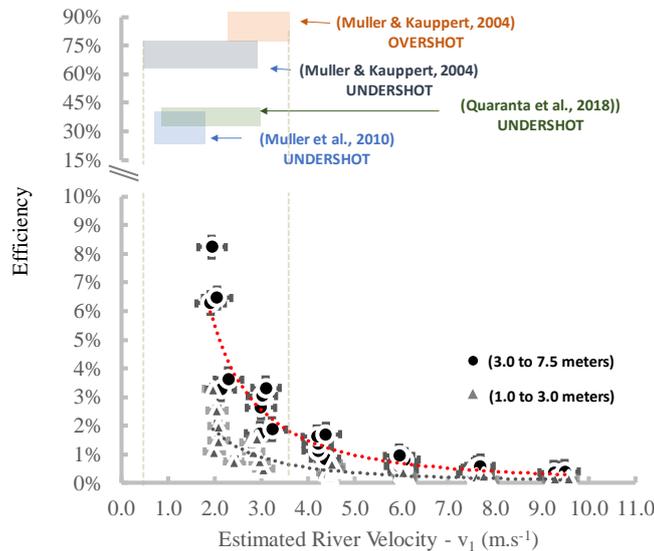

Figure 7. Efficiency comparison among proposed alternative water wheel and other industrials overshot and undershot models, considering a estimated river velocity as 67% higher than blade perimeter velocity.

Despite the low efficiency range, better performance was observed in lower estimated river velocities, which are more common (Muller et al., 2010; Muller & Kauppert, 2004). Quaranta et al., (2018) concluded in a review that the efficiency could double in cases of floating device usage. In that case, the relation among velocities could present values of v2=0.70v1. Therefore, if this assumption is applied in this work, the general efficiency estimation would be improved. The major energy leakage could be partially explained by the mechanical friction loss.

CONCLUSIONS

The initial investment was relatively low compared to the industrial water wheels; moreover, it represented 50% of the Brazilian minimum wage. These costs could be reduced by acquiring a free-of-cost pumping system. Furthermore, when relativity is compared to the electric motor powered by solar energy to pump water, it grants a similar attractive investment.

The hydraulic investigation revealed that the proposed mathematical model consists of a simple way to estimate the supply flow as a function of blade velocity and elevation head. The equipment can easily supply water to irrigate an area of 200 m2 with a 5.0 mm water column per day for approximately 15 habitants.day-1 in rural areas.

The undershot wheels developed in this study present a very low energy transfer efficiency, probably because of the mechanical friction loss.

Despite the enduring challenge of energy access for rural areas, the developed prototype represents an environmentally friendly, simple, and low-cost alternative for decentralized water pumping in remote locations, specifically, for low head sites.

ACKNOWLEDGMENTS

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