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DESIGN AND FABRICATION OF MANUALLY OPERATED RECIPROCATING TYPE PUMP USING SCOTCH YOKE MECHANISM FOR RURAL APPLICATION

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ABSTRACT

In the early 19th century, it was used extensively as a boiler feed water pump. Nowadays, it is used for pumping highly viscous fluids such as concrete, heavy oils etc. Normally it has relatively small capacities and large delivery head and is used in applications where low discharge is required at high pressure.

In this project, a weighted object acts as a pendulum which conserves momentum and swings with the application of human effort. It gives rotational motion to the shaft and the rear sprocket attached with it, which rotates the crank disc which in turn reciprocates the plunger. Because of that water is sucked in one stroke into the cylinder and is delivered out from the cylinder in the successive stroke.

The development for this project was prompted due to the need for pumping systems that do not use electricity as its power source in underdeveloped remote areas.

KEYWORDS: Scotch Yoke Mechanism, Freewheel Sprockets & Pendulum

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Original Article

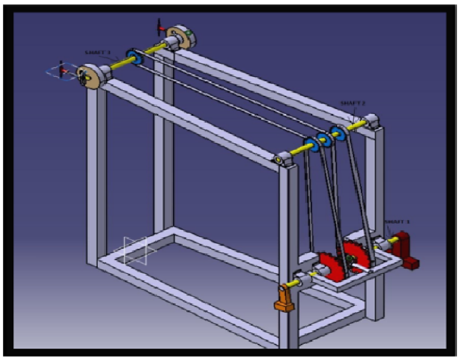
INTRODUCTION

A pump is a device that moves a fluid or sometimes slurries, by mechanical action. Pumps operate by some mechanism (typically rotary and reciprocating) and consume energy to perform mechanical work by moving the fluid. They may operate via many energy sources, including manual operation besides electricity, engines and wind power. A reciprocating pump is a class of pump which uses a backward and forward movement of the plunger or piston to move the fluid. Rome and ancient Greece, long back in 250 BC[1], they used the Archimedean screw device. As the name was suggested, the device was shaped similar to a giant screw. It worked by lifting water from inside of the pump for irrigation purpose. In the meantime, piston pumps were also available around as the Archimedean screw. Later on, in 1580, gear pumps were preceded by the invention of the sliding vane pump. The piston vacuum pump would come along in 1650[1]. One sort of pump once common worldwide was a hand-powered water pump, or 'pitcher pump'. It was generally installed in the days before piped water supplies over community water wells [2].

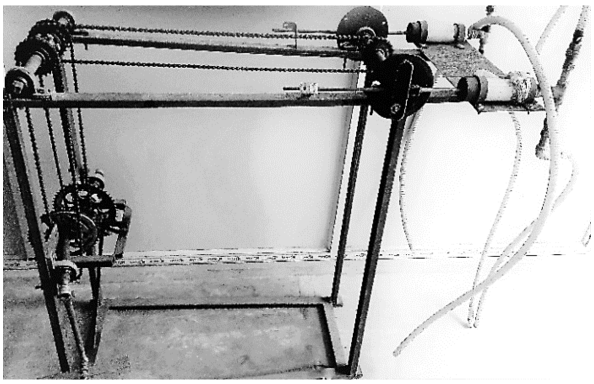
Modern hand-operated community pumps are considered the most economical and convenient option for safe water supply in rural areas in developing countries. A hand pump explored water from a deeper ground level that is often not polluted and also protects water source from contaminated buckets. Afridev pump sets are cheap to be designed to build and install, and easy to maintain for their simple parts. However, scarcity of spare parts for these types of pumps [3] in some regions of Africa has diminished their utility for these areas. C. A. Okoronkwo et al. [4] designed a hand water pump with quick return mechanism and a gear train drive which represents a modification to lift pump. In his results, it was found that the quick-return mechanism has a capacity of 15.2litres/min with a required effort of 102.7N.N.Tulasi Radha et al. [5] fabricated a mechanism which uses pedal power for generating electricity and at the same time for water pumping also. R. Praveen Kumar et al. [6] designed and developed a dual side water pumping system using scotch yoke mechanism where reciprocating motion of the plunger is achieved by a cam plate and the action is used to pump the water. Mogaji P. B. [7] developed an improved version of pedal-powered water pump machine which showed a discharge of 0.0016 m3/s at a head of 20m using a driving torque of 29.5 Nm with an estimated efficiency of 90%.Yathisha.N et al. [8] also designed and fabricated pedal powered reciprocating water pump with a scotch yoke mechanism. Mragank Sharma et al. [9] designed and fabricated a water pumping machine by using gym cycle to utilize and to convert the physical energy while cycling in the gym to lift the water in order to save the electricity. Biswas K. W. [10] examines the possible application of renewable energy for pumping water from geologically safe deep tube wells to overcome limitations in existing water technologies in the arsenic-contaminated villages in Bangladesh.

METHODOLOGY

Two sprockets are mounted on Shaft 1A and 1B between the two bevel gears connected by a third gear meshed with them perpendicularly. The third acts as tumbler gear that serves the purpose of reversing the direction of motion. The two sprockets are chained to two freewheel sprockets sitting on Shaft 2. Between them is mounted a third sprocket. Because of the system enabled due to the two freewheel; the shaft rotates in unidirectional motion. The middle sprocket is chained to another sprocket mounted on Shaft 3. This shaft receives constant unidirectional rotation because of the movement fed to it by the chain that wraps the sprockets on Shaft 2 and Shaft 3. Attached to the ends of the Shaft 3 are two circular crank discs. When the pendulum is oscillated by human effort, it gives rotation motion to the shaft. The rear sprocket connected with it gives rotational motion to the crank disc through the Scotch yoke mechanism and the plunger gets reciprocated.“Figure 1” shows the assembly of the pump set.



CATIA Drafted Model



Fabricated Model

Figure 1: Assembly of Pump Set

Some of the Parts fabricated and used in the system are shown in “Figure 2”

Figure 2: Some of the Parts Fabricated and Used for Assembling the Pump Set

Bevel Gear Mechanism

When the pendulum gets oscillated, it gives rotational motion to the shaft connected with it and the bevel gear connected with that shaft give rotational motion to the pinion mashed with it, which in turn give rotational motion to another bevel gear mashed with it which in turn gives the oscillating motion to the pedal. The "Figure3"shows the bevel gear mechanism with CATIA drafting.

For bevel gear, a material is Mild steel having yield strength, s_t = 268MN/m^2 and Young's modulus of elasticity, E= 200MN/m^2.Standard gear ratio is 6, Number of teeth on pinion, z_1 = 10, the ratio of width B_1 to pitch diameter D_1 for pinion = 0.5 and Pressure angle, a = $14\left(\frac{1}{2}\right)$ degree. So the calculated module, m=4.5mm and pitch diameter for pinion as well as gear is D1=4.5cm and D2=7.2cm.

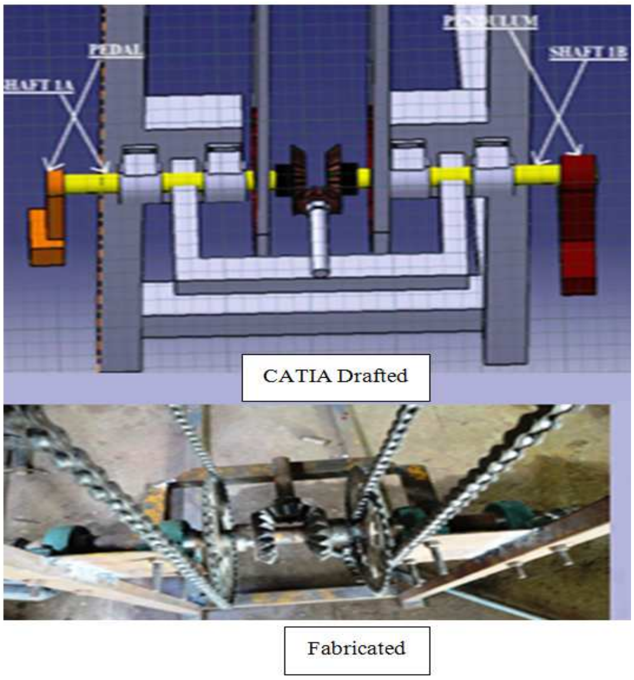


Figure 3: Bevel Gear Mechanism

Free wheel Mechanism and its Incorporation

Shaft 2 has mounted on it three freewheel sprockets. A freewheel is a type of bicycle hub that incorporates a ratchet mechanism, A ratchet is a mechanical device that allows continuous linear or rotary motion in only one direction while preventing motion in the opposite direction.

When the teeth are moving in the unrestricted (i.e., forward) direction, the pawl easily slides up and over the gently sloped edges of the teeth, with a spring forcing it (often with an audible 'click') into the depression between the teeth as it passes the tip of each tooth. When the teeth move in the opposite (backward) direction, however, the pawl will catch against the steeply sloped edge of the first tooth it encounters, thereby locking it against the tooth and preventing any further motion in that direction. Based on this principle the two sprockets work together to provide a unidirectional rotation to the shaft. The “Figure 4” shows the fabrication of free wheel sprocket.

For chain, Centre distance between two rear sprocket, a_1 = 86.5cm; rear and front sprocket, a_2 = 63.8cm and theoretical power to be transmitted, P_{th} = 27.05W. So on the basis of power to be transmitted; we have selected ‘08B’ chain drive. It has Pitch, P =12.70mm, roller diameter, D = 8.5mm, Rated power, P_r = 0.34KW at 50rpm. So calculated number of links are LN_1=168 & LN_2=132.

For sprocket, Pitch of chain, P =12.7mm; Number of teeth on rear sprocket, z_1 = 18,Speed ratio, $\frac{n2}{n1}$ = 2.5; so calculated value of Pitch diameter of rear sprocket, D_1 = 7.5cm & Pitch diameter of front sprocket, D_2 =17.8cm.

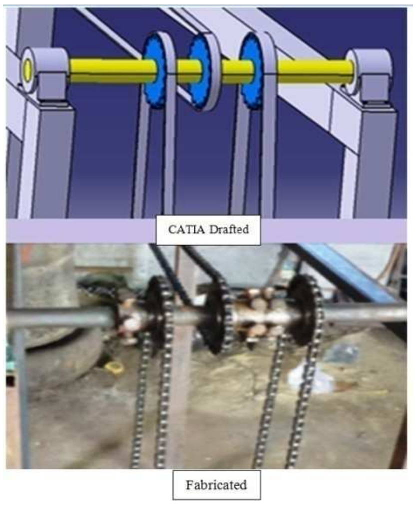


Figure 4: Free Wheel Sprocket

Yield strength for shaft material is 268MN/m^2. For a speed of 30 rpm, inside diameter of collar, d =2.5cm; theoretical power, P_{th} = 27.05W; τ_{max} = 0.3 of s_t=80.4MN/m^2. So, predicted value of standard diameter, D= d= 2.5cm.Bearing ISI No. 25BC02 deep grove ball bearing is used with a axial load on the bearing, F_a = 190N and no radial load. Dynamic load on bearing, p = 374.11 < 10690N.

Scotch Yoke Mechanism

This mechanism is used for converting rotary motion into a reciprocating motion through a slider which is connected with the crank disc by a pin. The “Figure 5” shows the scotch yoke mechanism developed in CATIA as well as fabricated one.

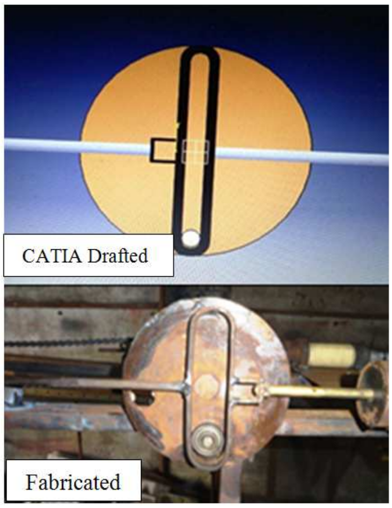


Figure 5: Scotch Yoke Mechanism

Design Parameters

Calculation of Inside Diameter of Cylinder

Discharge [11], Q=ANls *(Eq.20.1, page 994)*

Or $\frac{100}{1000\times3600} = \frac{\pi D^2\times30\times D\times2}{60}$

Or, D=3.14cm

Considering, D= 4.3cm

Calculated length of **Stroke**, ls = 2×4.3; Or ls = 8.6cm

Considering, ls = 9.5cm

Calculation of Pitch Diameter of Pinion and Gear

Theoretical **Power**[11], $P_{th}= \frac{\rho gAlsNh}{60000}$kW *(Eq.20.4, page 995)*

$=\frac{1000\times9.8\times\pi\times4.3^2\times9.5\times30\times4}{60000\times1000000}$

=2.704 W

For pinion, N= 48 RPM,

M_t[12] $= \frac{60P_{th}}{2\pi N}$

$=\frac{60\times2.704\times60}{2\times\pi\times48}$

or, M_t =0.538 N-m

Beam strength[12], $S_b = \frac{M_t}{R_m} = [1 - b/Ao]$

or, $S_b = mb\sigma Y[1 - b/Ao]$ *(Eq.19.11, page 721)*

For pinion,

R_m[12]= (D_1-bSinγ1)× 0.5 *(Eq.19.10, page 716)*

Here, $Sin\gamma_1 = \sin\{\tan^{-1}\left(\frac{10}{16}\right)\} = 0.53$

$b=0.5D_1$

So, $R_m = D_1 \times 0.5 \times \{1-(0.5\times 0.53)\} = D_1(0.3675)$

$A_o[12]=D_1\times 0.5 \times \sqrt{\frac{16^2}{10^2}+1}=0.94D_1$ *(Eq.19.6, page 715)*

Y=0.113

From equation

$$\frac{0.538}{D1\times 0.3675}=m\times 0.113\times D1\times 0.5\times \frac{268\times 10^6}{4}\times 0.137[1-\frac{0.5D1}{0.94D1}]$$

Or, $D^2 \times m = 1.3\times 10^{-6}$

Or, $m^3 \times 10^2 = 1.3\times 10^{-6}$

Or, m=2.4mm

Standard **Module**, m=4.50mm

Pitch Diameter, $D_1=10\times 4.50=45$mm

Pitch Diameter, $D_2=16\times 4.50=72$mm

Calculation of Number of Chain Links[12]:

$LN_1 = 2\times\frac{a1}{P}+\frac{(z1+z2)}{2}+(\frac{z1-z2}{2\pi})^2\times\frac{P}{a}$ *(Eq.14.6, page 548)*

Or $LN_1=2\times\frac{865}{12.7}+\frac{(44+18)}{2}+(\frac{44-18}{2\pi})^2\times\frac{12.7}{865}$

Or $LN_1=168$

$LN_2=2\times\frac{a1}{P}+\frac{(z1+z2)}{2}$

Or $LN_2=2\times\frac{638}{12.7}+\frac{(44+18)}{2}$

Or $LN_2=132$

Calculation of Sprocket Pitch Diameter[12, 13]

$D_1=\frac{p}{\sin\frac{180}{z1}}$ *(Eq.14.2, page 548; Eq.14.22n, page 301)*

$=\frac{12.7}{\sin\frac{180}{18}}=7.32$cm

Standard diameter, $D_1=7.5$cm

$D_2=\frac{p}{\sin\frac{180}{z2}}=\frac{12.7}{\sin\frac{180}{2.5\times 18}}=17.8$cm

Calculation of Shaft Diameter

$Mt = \frac{60Pth}{2\pi N}$

$= \frac{60\times2.704\times60}{2\times\pi\times30}$

=1.305Nm

τmax[13]=$\frac{16Mt}{\pi D^3}$ *(Eq.3.1, page 50)*

$268\times 10^6 \times 0.30 = \frac{16\times1.305}{\pi\times D^3}$

Or D=0.14cm

Standard diameter of the shaft, D=2.5cm

Calculation of Dynamic Loads on Bearing

Bearing Selection

- Assumption
  - Axial load on the bearing, F_a = 190N
  - Radial load on the bearing, F_r = 0
- Selection of Bearing
  - Bearing ISI No. 25BC02 deep grove ball bearing is used
  - The "Table 1" is for the parameter of the selected bearing:

Table1: Bearing Parameters[13] (Table 16.9, series 62. Page 387)

ISI No.	SKF	d(mm)	D(mm)	B(mm)	r(mm)	Basic	Capacity	Maximum Permissible Speed(rpm)
						Static	Dynamic	
25BC02	6205	25	52	15	1.5	6965	10690	13000

$\frac{F_a}{c_o}$[12] $=\frac{190}{6965}$=0.03 *(Page 573)*

Again for value of e, $\frac{0.056-.028}{0.26-0.22} = \frac{0.03-0.028}{e-0.22}$

Or e=0.223

For the value of thrust factor Y, $\frac{0.26-0.22}{0.223-0.22} = \frac{1.17-1.99}{Y-1.99}$

Or, Y=1.969

Dynamic load on the selected bearing[12], P=YFa *(Eq.5.3, page 572)*

Or, P=1.969×190

Or, P=374N< 10690N

Calculation of Theoretical Discharge

$Q = \frac{ALN}{60}$

$= \frac{\pi\times4.3^2\times9.5\times10^{-6}\times N}{4\times60} = 2.3\times 10^{-6}\times N$

At N_1 =15rpm, $Q_1 = 2.3\times 10^{-6}\times15$ = 21lit/min

At N_2 = 25rpm, $Q_2 = 2.3\times 10^{-6}\times25$= 3.4 lit/min

At N_3 = 35rpm, $Q_3 = 2.3\times 10^{-6}\times35$ = 4.8lit/min

At N_4 = 45rpm, $Q_4 = 2.3\times 10^{-6}\times45$ = 5.8lit/min

Calculation of Theoretical Power

$P = \frac{\rho gALNh}{60}$

$= \frac{10^3\times9.8\times\pi\times4.3^2\times9.5\times N}{60\times4\times10^6} = 0.0225\times N$

At N_1 =15rpm, P = 0.34W; At N_2 = 25rpm, P = 0.56W

At N_3 = 35rpm, P = 0.79W At N_4 = 45rpm, P = 1W

Calculation of Slip[14]

Slip = Q_{th}-Q_{act} *(Eq.20.10, page1244)*

At N_1= 15rpm, Slip = 2-1=1 lit/minAt N_2= 25rpm, Slip =3.4-2.4=2lit/min

At N_3= 35rpm, Slip 4.8-2.3=2.5lit/min At N_4= 45rpm, Slip = 5.8-2.7=3.1 lit/min

Calculation of Mechanical Efficiency

$\eta = \frac{P_{act}}{P_{th}}\times 100$ %

At N_1=15rpm,

$\eta = \frac{Pact}{Pth} = \frac{0.16}{0.34}\times 100 = 47\%$

At N_2=25rpm,

$\eta = \frac{Pact}{Pth} = \frac{0.23}{0.56}\times 100 = 41\%$

At N_3=35rpm,

$\eta = \frac{Pact}{Pth} = \frac{0.38}{0.79}\times 100 = 48\%$

AtN_4= 45rpm,

$\eta = \frac{Pact}{Pth} = \frac{0.44}{1}\times 100 = 44\%$

Results of discharge, power, slip, and efficiency against RPM of the crank disc are tabulated in "Table 2"

Table 2: Results Showing Discharge, Power, Slip, and Efficiency against RPM of the Disc

RPM of The Crank Disc (N)	Discharge (Q) in litre/min		Power (P) in Watt		Slip in lit/min	Efficiency (η)
	Theoretical (Q_{th})	Experimental (Q_{exp})	Theoretical (P_{th})	Operating (P_{opt})		
N_1=15	2	1	0.34	0.16	1	0.47
N_2=25	3.4	1.4	0.56	0.23	2	0.41
N_3=35	4.8	2.3	0.79	0.38	2.5	0.48
N_4=45	5.8	2.7	1.01	0.44	3.1	0.44

Graphical representation of RPM vs. Discharge, Power, Slip and Efficiency are shown in "Figure 6"

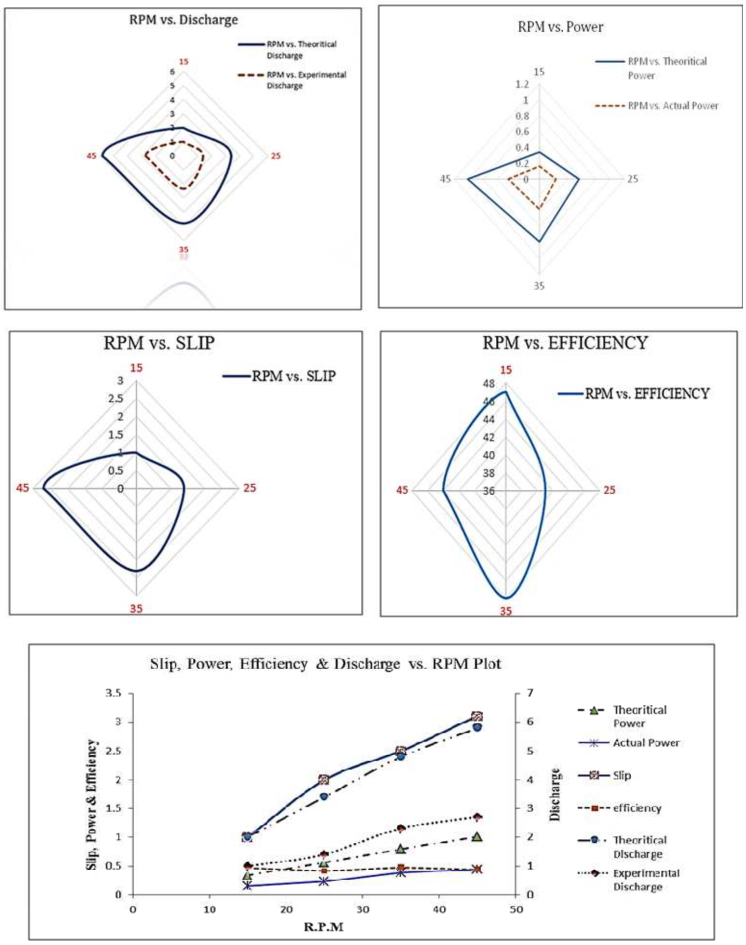


Figure 6: RPM vs. Discharge, Power, Slip, and Efficiency

DISCUSSIONS

Smooth running of the crank disc by giving it continuous reciprocating motion may reduce the factor 'slip' which causes a difference between the theoretical and practical discharge value which in turn depends on manual effort. On the other hand, by lubricating the rotating surfaces sufficiently, the difference in theoretical and practical values of power can be reduced to an extent. Around 15 RPM of the crank disc, the result was showing satisfactory value.

Materials of components used in the pump set and their specifications, no. of requirement and cost per unit were listed in 'Table 3'

Table 3: Materials of Components used and their Specifications, No. of Requirements and Cost Per Unit

Sl. No.	Components	Material	Specifications	Requirements	Cost per unit (Rs)
1	Bearing blocks	Mild Steel	Inside diameter=25 mm	8	480
2	Bevel gears	Mild Steel	Pitch diameter=mm	2	150
3	Pinion	Mild Steel	Pitch diameter=mm	1	100
4	Rare sprockets	Cast Iron	Pitch diameter=mm	4	260
5	Collar for rare sprocket	Cast Iron	Inside diameter=25mm	4	60

Table 3: Contd.,					
6	Front sprocket with pedal	Cast Iron	Pitch diameter=mm	2	320
7	Nut and bolt	Cast Iron	Length =70mm, Pitch diameter=15mm	16	30
8	Metal square plates	Mild Steel	Length(breadth)=17mm	2	50/plate
10	Shafts	Mild Steel	Diameter=25mm	3	360/unit length
11	Chains	Cast Iron	Pitch=12.7mm	3	180
12	Square metal bar	Mild Steel	Breadth(height)=40mm	12	55/kg
13	Pendulum	Mild Steel	Length=2540mm,heigth100mm	1	55/kg
14	Pedal	Steel	Length=15mm,Diameter=20mm	1	(Included with 6.)
15	Cylinder	UPVC	Inside diameter=43mm Stroke length=95mm	2	50/feet
16	Valves	Brass	Diameter=10mm	4	600
17	Tee joints	Cast Iron	Diameter=10mm	2	50
18	Pipes	Plastic	Diameter=10mm	4	40/feet
19	Scotch Yoke apparatus	Mild Steel	Length=14.7mm	2	50/kg
20	Crank discs	Mild Steel	Diameter=165mm	2	50/kg
21	Cylinder cap	Mild Steel	Inside diameter=8mm, Outside diameter=53mm	2	(Included with 15)
22	Small ball bearings	Mild Steel	Diameter=32mm	2	70

CONCLUSIONS

Dug wells located in the foothills zone, however, show deeper groundwater level ranging between 5 to 10 meters below ground level during pre-monsoon period, it is possible to construct a pump that is capable of reaching such depths and draw water with reasonable efficiency and that is not dependent on any external power source, but rather is operated by combining human effort with complex mechanisms.

The project is especially beneficial to those who are bereft of the access to electricity and sophisticated machines that rely solely on electricity or on fuel power.

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