

## **CHAPTER 4**

### **ENGINEERING RE DESIGN & PROTOTYPE**

#### **DEVELOPMENT OF WATERMILL SYSTEM**

*Chapter Overview*

- *To identify the watermill redesign basis and understand the parameters affecting its efficiency.*
- *To design various parts/ components and auxiliaries of importance.*
- *To develop a prototype with redesigned parameters, test the same and compare the results.*
- *To look for any possible value addition and multipurpose application of watermill.*

**Redesign Criteria:**

Main considerations for redesign criteria are:

- Low cost
- Local material
- Minimum maintenance yet better efficiency
- Focus on points gathered from survey i.e. penstock, nozzle, trash, water control etc.
- Selection of turbine is based on range of hydrology available in Uttarakhand and based on recommendation of lab testing.

# **Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand**

## **4.1 PARTS OF WATERMILL SYSTEM**

Main parts of overall watermill system include:

### 4.1.1 Penstock

Penstock is a closed conduit used for conveying water from intake to power house. We can use PVC, polyethylene, cast iron, stainless steel pipes for penstock. The selection of the material depends upon head loss due friction in pipe and economic consideration. In order to reduce costs, the pressure rating of pipe is varied along the length, so that the higher pressure ratings were only used when required, as these are more expensive.

### 4.1.2 Nozzle

A nozzle is a mechanical device designed to control the direction or characteristics of a fluid flow as it exits an enclosed chamber or pipe via an orifice. A nozzle is often a pipe or tube of varying cross sectional area and it can be used to direct or modify the flow of a fluid. Nozzles are frequently used to control the rate of flow, speed, direction, mass, shape, and/or the pressure of the stream that emerges from them.

### 4.1.3 Runner

Runner is the part of turbine where water comes and hits the turbine and it makes the turbine shaft to rotate.

### 4.1.4 Drive Shaft

Shaft is a device used to transfer energy from runner to other rotating part. Balancing of the shaft is an important criterion which affects the efficiency of the transmission. If shaft is not well balanced it will lead to vibration in the system.

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### 4.1.5 Bottom Bearing

A very simple bottom bearing having a ball which is press fitted at the lower end of the shaft, which rests on a piece of hard steel.

## 4.2 WATERMILL EFFICIENCY

It is really important to remember that the efficiency characterizes not only the ability of a turbine to exploit a site in an optimal manner but also its hydrodynamic behavior. A very average efficiency means that the hydraulic design is not optimum and that some significant problems may occur that can strongly reduce the yearly production and damage the turbine.

Efficiency of a watermill is defined as the ratio of power supplied by the turbine (mechanical power transmitted by the turbine shaft) to the hydraulic power, as

$$\text{Efficiency of watermill} = (\text{power output}) / (\text{power input})$$

Power input is also known as hydropower, hydraulic power or water power. This can be calculated using the equation given below

$$\text{Power available} = \rho * g * h * Q \dots \dots \dots (4.1)$$

[28]

Where

- $\rho$  = density of water (kg/m<sup>3</sup>)
- $g$  = acceleration of gravity (9.81 m/s<sup>2</sup>)
- $h$  = head (m).
- $Q$  = flow rate (m<sup>3</sup>/s)

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For still water, this is the difference in height between the inlet and outlet surfaces. Moving water has an additional component added to account for the kinetic energy of the flow. The total head equals the pressure head plus velocity head.

The overall efficiency can be classified as:

### 4.2.1 Hydraulic efficiency

When the flow deviates from that nominal discharge so does the turbine's hydraulic efficiency. The hydraulic efficiency of the turbine is the ratio of power developed by the runner to the net power supplied by the water at the entrance to the turbine. The two powers differ by amount of hydraulic loss.

Hydraulic efficiency = (Power supplied to runner / net power supplied at the turbine entrance)

### 4.2.2 Mechanical efficiency

Mechanical efficiency of the turbine is the ratio of power available at the turbine shaft to the power developed by the runner. These two powers differ by the amount of mechanical losses viz, bearing friction.

Mechanical efficiency = (Power available at the shaft end / Power developed by the turbine)

### 4.2.3 Volumetric efficiency

Volumetric efficiency is the ratio of quantity of water actually striking the runner and quantity of water supplied to the turbine. These two quantities differ by amount of water that slips directly to the tail race without striking runner.

Overall efficiency of the turbine can be represented by product of above three efficiencies.

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**4.3 EFFECT OF VARIOUS COMPONENTS ON EFFICIENCY**

4.3.1 Penstock

Conveying water from the intake to the powerhouse may not appear a difficult task. However deciding the most economical arrangement for a penstock is not so simple. Penstock can be of PVC, cast iron or steel. The material is determine by economic consideration

The diameter is selected as the result of a trade-off between penstock cost and power losses. The power available from the flow Q and head H is given by the equation:

$$\text{Power Available} = Q * H * \gamma * \eta \dots \dots \dots (4.2)$$

[29]

Where,

Q - The discharge in m<sup>3</sup>/s

H - The net head in m

γ - The specific weight of water in kN/m<sup>3</sup>

η - The overall efficiency.

The net head equals the gross head minus the sum of all losses, including the friction and turbulence losses in the penstock, that are approximately proportional to the square of the velocity of the water in the pipe. To convey a certain flow, a small diameter penstock will need a higher water velocity than a larger diameter penstock, and therefore the losses will be greater. Selecting a diameter as small as possible will minimize the penstock cost but the energy losses will be larger and vice versa.

A simple criterion for diameter selection is to limit the head loss to a certain percentage. Loss in power of 4% is usually acceptable.

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Actually the main head loss in a pressure pipe is friction losses. The head losses due to turbulence passing through the trash rack, in the entrance to the pipe, in bends, expansions, contractions and valves are minor losses. Consequently a first approach will suffice to compute the friction losses, using for example the Manning equation:

$$h_f/L = 10.3 n^2 Q^2 / D^{5.333} \dots\dots\dots(4.3)$$

[30]

Where,

- $h_f$  = Head loss due to friction
- $L$  = Total length of pipe
- $n$  = Manning constant
- $Q$  = Discharge
- $D$  = Diameter of penstock

### 4.3.2 Nozzle

The work of the nozzle is to increase kinetic energy at the expense of pressure energy. The efficiency of the nozzle means how effectively it converts potential energy to kinetic energy.

The velocity which is available at nozzle exit depends upon total head available.

The relationship is given as

$$C_0 = (2gh)^{1/2} \dots\dots\dots(4.4)$$

[31]

Where,

- $C_0$  = spouting velocity (ideal velocity)
- $H$  = Head available
- $g$  = gravitational constant

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Pipe friction loss is considered as external loss and not included in losses attributed to turbine system. This can be represented by nozzle velocity coefficient. Nozzle velocity coefficient is defined as the ratio of actual velocity at the exit to ideal velocity at the exit of the nozzle. The value varies from 0.98 to 0.99.

Other losses occur in nozzle and also because of windage and friction of turbine wheel. Nozzle efficiency is defined as energy at nozzle exit to energy at nozzle inlet.

$$\text{Nozzle efficiency} = \frac{C^2}{2gH} \dots \dots \dots (4.5)$$

[32]

Where,

- C = velocity at nozzle
- H = Head available
- g = gravitational constant

### 4.3.3 Diameter of runner

The diameter of blade has greater importance in efficiency of the watermill. If the diameter of water mill is high than designed value, then starting torque will be a problem. If the diameter of blade is less than designed value, then volumetric efficiency will be low. This can make less water which is coming from nozzle to hit the watermill surface, so overall efficiency will be low.

### 4.3.4 Material of blade runner

Roughness of the material has great importance in efficiency. Cast iron or stainless steel is preferred over wood due to more smoothness of surface.

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### 4.3.5 Bearing

Bearing efficiency will affect the mechanical efficiency of a watermill. If bearing efficiency is low, this will reduce mechanical efficiency also.

## **4.4 PENSTOCK**

Penstock can be installed over or under the ground, depending on the factors such as nature of ground itself, penstock material, the ambient temperature and environmental requirement.

A flexible and small diameter PVC pipes for an instance, can be laid on the ground, following its outline with sand and gravel surrounding the pipe to provide good insulation. Small pipes installed in this way do not need anchor block and expansion system.

Penstock installed above ground can be designed with or without expansion joint. Variation in temperature are especially important if the turbine does not function continuously, or when the penstock is dewatered for repair, resulting in thermal expansion or contraction. Usually the penstock is built in straight or nearly straight lines, with concrete anchor blocks at each bend and with expansion joint between each set of anchors. The anchor block must resist the thrust of the penstock plus the friction forces caused by its expansion and contraction.

### 4.4.1 Material for penstock

There is a wide choice of material for penstocks. For the larger heads and diameter, fabricated welded steel is probably the best option. Nevertheless, spiral machine welded steel pipes should be also considered, due to their lower price. If they are available in the required sizes, for high heads, steel or ductile iron pipes



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are preferred, but at medium and low heads still become competitive. The material used in penstock can be classified as following types:

a. Polyethylene

Plastic pipe PE 14 is very attractive solution for medium heads because it is cheaper, lighter and more easily handled than steel and does not need protection against corrosion. This can be used from .4m diameter to 200m diameter. Pipes of PE16 can be laid on the top of the ground and can accommodate bends of 20-40 times the pipe diameter. PE pipes can withstand pipe line freeze up without damage, may be not available in sizes over 300 mm diameter.

b. Polyvinyl chloride

PVC 15 pipes are easy to install because of the spigot and socket joints provided "O" ring gasket. PVC pipes are usually installed under ground with minimum cover of one meter. Due to their resistance to UV radiation they cannot be used on surface unless painted, coated or wrapped. The minimum radius of curvature of PVC is relatively large and its coefficient of thermal expansion is five times higher than that of steel.

c. Concrete

Concrete penstock, both pre stressed with high tensile wires or steel reinforced, featuring an interior steel jacket to prevent leaks, and furnished with rubber gasket and socket joints constitute another solution. Unfortunately their heavy weights makes transportation and handling costly, but are not affected by corrosion.

d. Steel

They are used in head of 50m to diameter of 5.5 m. the advantages include flexibility to conform to ground settlement, ease of laying on the ground with

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almost no grade preparation, no requirement for expansion joints and no necessity for concrete supports or corrosion protection.

<i>Material</i>	<i>Young's modules of elasticity</i>	<i>Coefficient of linear expansion</i>	<i>Ultimate tensile strength</i>	<i>Mann's coefficient</i>
Steel	206	12	400	0.012
Polyethylene	0.55	140	5	0.009
PVC	2.75	54	13	0.009
Cast iron	78.5	10	140	0.014

(Table 4.1: Properties of material, [33])

### 4.4.2 Design Of Penstock

Data from the site,

Head available at the site = 3 to 7m

The length of the pipe required = 15m

Various discharge condition are =

Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
0.1	0.103	0.106	0.108	0.116	0.12	0.13	0.145	0.15

For the design

1. Material is selected according to ground condition, accessibility, weight, joining system and cost.
2. Diameter is selected to reduce frictional resistance
3. Wall thickness is selected on the basis of maximum internal pressure.
  - a. Penstock diameter

Penstock diameter is selected by comparing cost and power loss. The main loss occurred in the pipe is frictional losses. All other minor losses are neglected.

Frictional loss can be calculated using following formula,

$$h_f/L = 10.3 n^2 Q^2 / D^{5.333} \dots\dots\dots(4.6)$$

[34]

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Where,

- $h_f$  = Head loss due to friction
- $L$  = Total length of pipe
- $n$  = Manning constant (refer table 1)
- $Q$  = Discharge
- $D$  = Diameter of penstock

Therefore the diameter is

$$D = (10.3 n^2 Q^2 .L/h_f)^{0.1875} \dots\dots\dots(4.7)$$

[35]

Where,

$h_f$  is taken as 4% of total head for the calculation,

The head loss due to friction,  $h_f$  = 0.28m

Calculation for PVC at a discharge of 1 m<sup>3</sup>/s

$$D = (10.3 n^2 Q^2 .L/h_f)^{0.1875} = 0.2237m$$

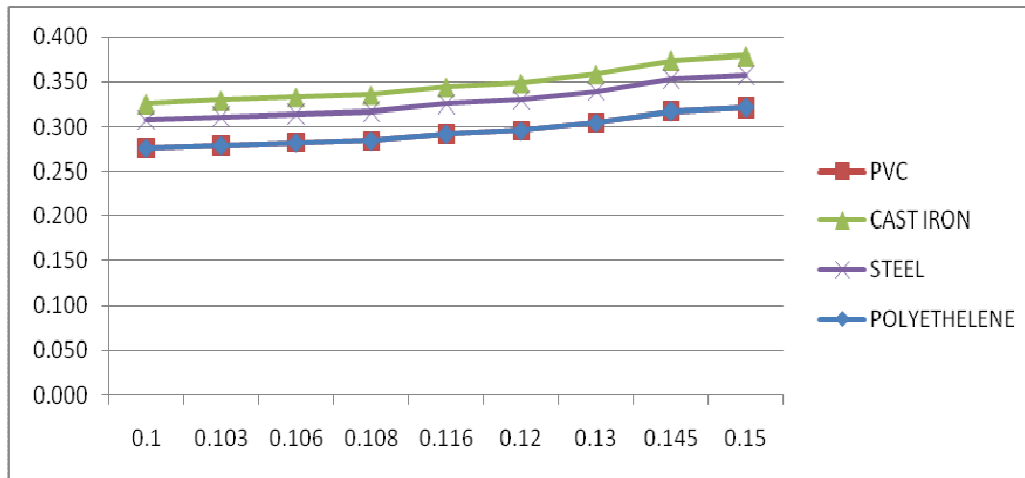
The values obtained according to this equation are summarized as follows,

<i>Head (m)</i>	<i>Discharge (m<sup>3</sup>/s)</i>	<i>Polyethelene</i>	<i>Pvc</i>	<i>Cast iron</i>	<i>Steel</i>
		<b>Dia (m)</b>	<b>Dia (m)</b>	<b>Dia (m)</b>	<b>Dia (m)</b>
3m	0.1	0.276	0.276	0.326	0.307
	0.103	0.279	0.279	0.329	0.311
	0.106	0.282	0.282	0.333	0.314
	0.108	0.284	0.284	0.335	0.316
	0.116	0.292	0.292	0.344	0.325
	0.12	0.296	0.296	0.349	0.329
	0.13	0.305	0.305	0.359	0.339
	0.145	0.317	0.317	0.374	0.353
	0.15	0.321	0.321	0.379	0.358

(Table 4.2: Design values for Penstock Diameter)

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Comparison of diameter of the different material is shown in the graph,



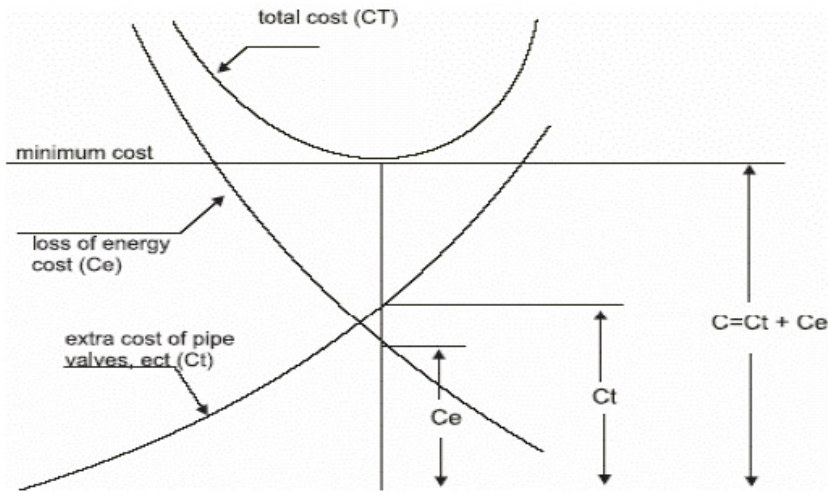
(‘Penstock Diameter v/s Discharge Curve for 3m Head)

Result obtained from the graph

1. Cast iron required highest diameter because the loss is highest in the cast iron.
2. PVC and PE requires same diameter because loss factor is same in both the case.
3. With increase in diameter of the pipe, the head loss due to friction decreases. So it is advised that to put high diameter pipe.

But cost is also a factor which determines the flow. So economics should be also seen before selecting diameter of pipe.

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**(Fig 4.1: Economic Curve for selection of Penstock Diameter)**

b. Wall thickness

The wall thickness required depends on the pipe material, its ultimate tensile strength, the pipe diameter and operating pressure. In steady flows the operating pressure at any point along a penstock is equivalent to the head of water above that point. The wall thickness is computed by equation

$$E = (P_1 * D / 2 * \sigma_f) \dots\dots\dots(4.8)$$

[36]

Where,

- e = Wall thickness in mm
- P<sub>1</sub> = Hydrostatic pressure in kN/mm<sup>2</sup>
- D = Internal diameter (refer **Table 4.2**)
- σ<sub>f</sub> = Allowable tensile strength in kN/mm<sup>2</sup> (refer **Table 4.1**)

Calculation for PVC:

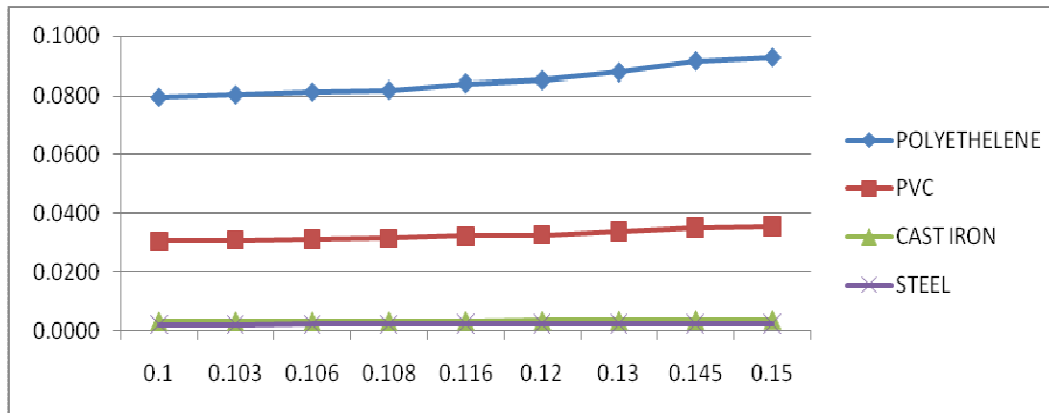
$$e = (P_1 * D / 2 * \sigma_f) = (7.28 * 0.2227 / 2 * 13) = 0.0626m.$$

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Head	Discharge	Polyethylene	PVC	Cast iron	Steel
	m <sup>3</sup> /s	Thickness(m)	Thickness(m)	Thickness(m)	Thickness(m)
3m	0.1	0.0795	0.0306	0.0034	0.0022
	0.103	0.0804	0.0309	0.0034	0.0022
	0.106	0.0812	0.0312	0.0034	0.0023
	0.108	0.0818	0.0315	0.0034	0.0023
	0.116	0.0840	0.0323	0.0035	0.0023
	0.12	0.0851	0.0327	0.0036	0.0024
	0.13	0.0877	0.0337	0.0037	0.0024
	0.145	0.0914	0.0351	0.0039	0.0025
	0.15	0.0925	0.0356	0.0039	0.0026

(Table 4.3: Design values for Wall thickness for different material)

Comparison of wall thickness:



(Penstock Wall thickness v/s Discharge Curve for 3m Head)

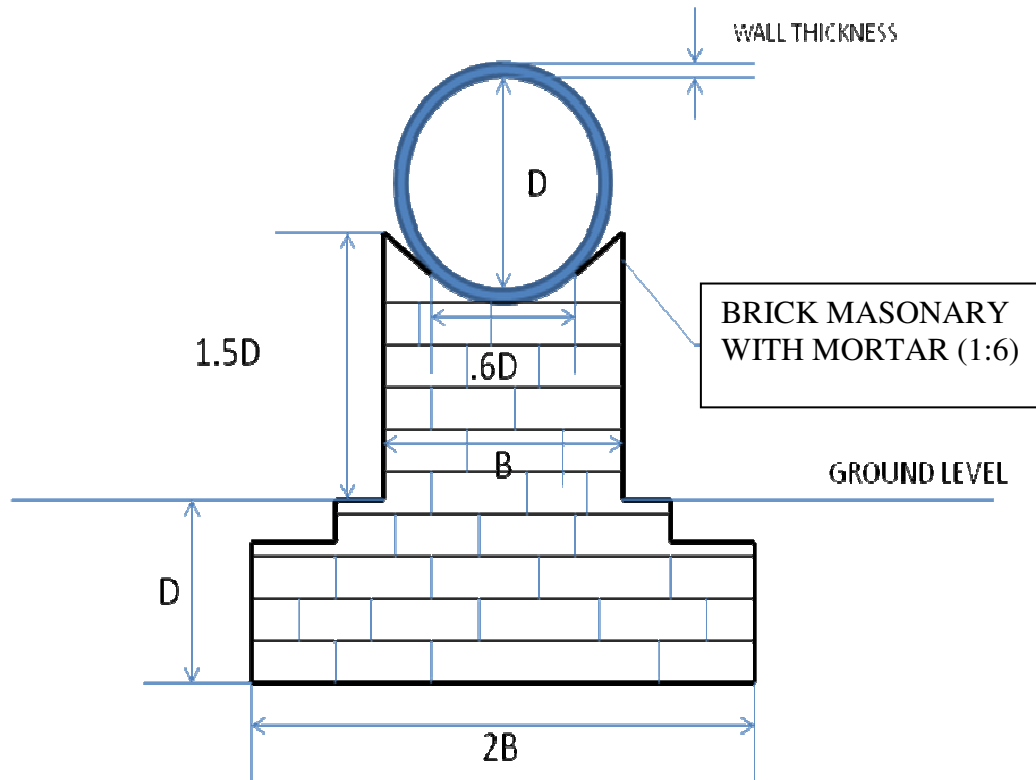
Result of Wall thickness against Discharge graph

1. It is found that steel requires lowest thickness since its tensile strength is very high compared to other material
2. Polyethylene which have lowest tensile strength have highest diameter for with stand high pressure generated by water flow.

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### 4.4.3 Penstock support

Penstock should be supported over either masonry structure or concrete structure. They should withstand the total stress produced by penstock. The design of penstock is given below.



(Fig 4.2: Design of Penstock)

### 4.5 NOZZLE

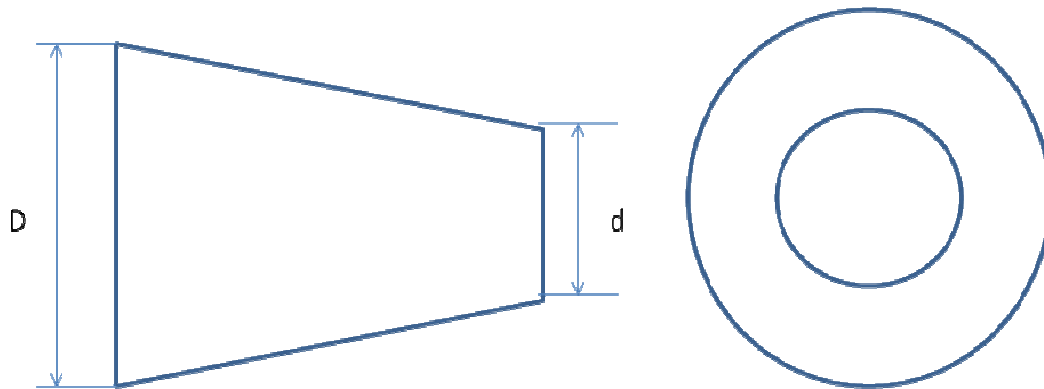
A nozzle is a mechanical device designed to control the characteristics of a fluid flow as it exits (or enters) an enclosed chamber or pipe via an orifice. A nozzle is often a pipe or tube of varying cross sectional area and it can be used to direct or modify the flow of a fluid (liquid or gas). Nozzles are frequently used to control the rate of flow, speed, direction, mass, shape, and/or the pressure of the stream that emerges from them.

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In case of hydraulic turbine jet nozzle is mainly used. A hydro jet is a nozzle intended to eject gas or fluid in a coherent stream into a surrounding medium. Nozzle is a device used for converting the pressure energy of jet into kinetic energy of jet.

Material for nozzle

- Stainless steel
- High strength micro alloy
- Heat treatment steel
- Plastic



(Fig 4.3: Design of Nozzle)

Diameter of jet from the nozzle:

Least diameter of jet is given by,

$$D = (4Q/\pi K\sqrt{2gh})^{1/2} \dots\dots\dots(4.9)$$

[37]

Where,

- Q = Discharge
- K = Nozzle coefficient (0.98)
- g = Gravitational constant
- H = Head available
- d = Diameter of jet

$$d = 0.542(Q/\sqrt{h})^{1/2} = 0.542(0.1/\sqrt{3})^{1/2} = 0.108m.$$

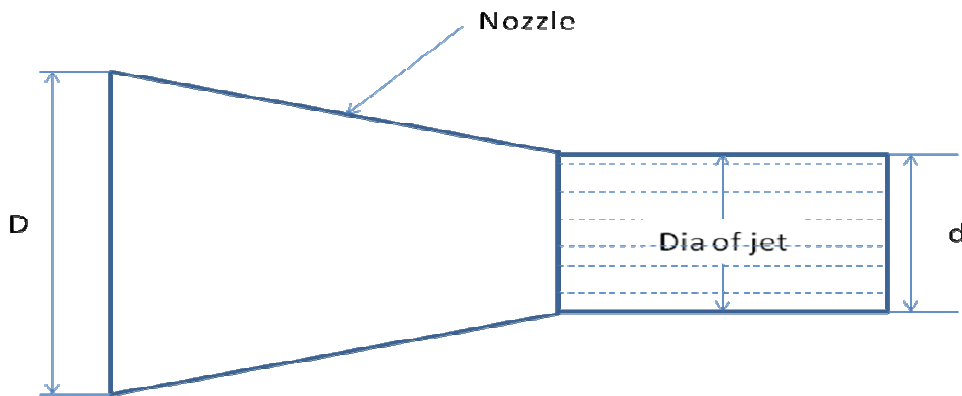


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As the discharge changes the value of diameter of jet, will also increases. (Refer **Table 4.4**)

<i>Head</i>	<i>Discharge(<math>M^3/S</math>)</i>	<i>Diameter Of Jet(<math>M</math>)</i>
3m	0.1	0.108
	0.103	0.110
	0.106	0.111
	0.108	0.112
	0.116	0.117
	0.12	0.119
	0.13	0.123
	0.145	0.130
	0.15	0.133

(Table 4.4: Design values for Diameter of Jet)



(Fig 4.4: Design of Jet)

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**4.6 DESIGN OF WATER MILLS**

In order to design standard water mill, the available data of water mill sites were analyzed and characterized into 3 categories depending on the head as (a) upto 3 m (b) 3 to 7m and (c) 7 to 15 m. based on the site data available a database is prepared. To utilize the potential of these water mill sites and to cover entire range of water mill site, 3 different systems are suggested to fulfill various needs of local people.

<i>Sr. No</i>	<i>System</i>	<i>Head Range</i>	<i>Speed (rpm)</i>	<i>Power Output</i>
1	For grinding cereals only	Upto 3m	70-100	Upto 1 kW
2	For cereal grinding and electricity generation	3 to 7	125-225	2Kw
3	For electricity and other agro processing	7 to 15 m	350 -550	Upto 5 kW

**(Table 4.5: Application of Standard Watermill [38])**

In the range of low head (around 3m to 7m) inward flow impulse turbine (Pelton) is suggested as per testing results in previous chapter. For developing a mechanical power of 5 kW cross flow turbine is recommenced.

4.6.1 Design of turbine runner

The ideal velocity of jet is known as spouting velocity =  $(2gh)^{1/2}$ , But actual velocity is slightly less, due to friction loss in the nozzle.

$$V = \phi^* (2gh)^{1/2} \dots\dots\dots(4.10)$$

[39]

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Where,

H = Net Head

$\phi$  = Coefficient of velocity for the nozzle = 0.98

For maximum efficiency the velocity of the wheel is 0.5V. However in actual practice the maximum efficiency occurs when the value of u is about 0.46V

Therefore,

$$U = 0.46 \times \phi \times V \dots\dots\dots(4.11)$$

[40]

$$U = .45 \times (2gh)^{1/2}$$

Where

U = Tangential Speed of Blade

But,

$$U = \frac{\pi DN}{60}$$

D = Diameter of blade

N = Speed (RPM)

g = Gravitational constant

H = Head available

Comparing both the above equation the diameter is obtained as

$$\text{Diameter of Runner (D)} = 38.9(H/N)^{0.5} \dots\dots\dots(4.12)$$

$$\text{Radial width of the rim (a)} = 0.17D \dots\dots\dots(4.13)$$

[41]

Where,

D = Diameter of Runner

H = Head available

N = Speed (RPM)

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Design of turbine diameter for given discharge:

$$\begin{aligned} \text{Diameter of Runner } D &= 38.9(6/225)^{0.5} \\ &= 0.423\text{m} \end{aligned}$$

$$\begin{aligned} \text{Radial width of rim, } a &= 0.17*0.294 \\ &= 0.07191\text{m} \end{aligned}$$

<i>Head</i>	<i>Rpm</i>	<i>Diameter Of Runner(m)</i>	<i>Radial Width Of Rim(m)</i>
3m	225	0.299	0.05083
4m	225	0.345	0.05865
5m	225	0.386	0.06562
6m	225	0.423	0.07191
7m	350	0.294	0.04998
8m	350	0.314	0.05338

(Table 4.6: Turbine Design values for different site conditions)

### 4.6.2 Number of blade

The number of blades should be such that jet is always completely intercepted by the bucket so that volumetric efficiency is close to one. The formula used to find the number of blade is given by

$$Z = D / 2d + 15 \dots \dots \dots (4.14)$$

[42]

Where

D = Diameter of Runner

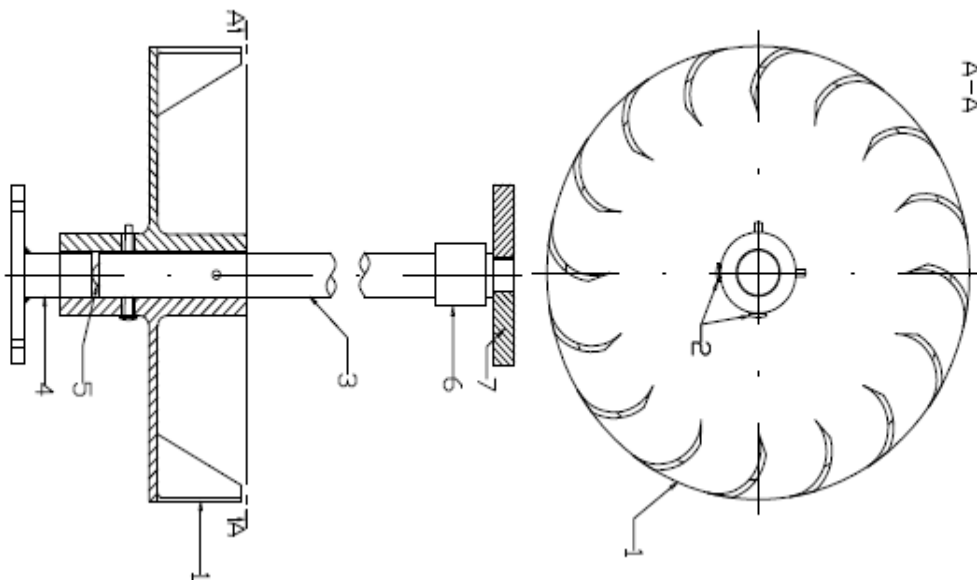
d = Diameter of Jet

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The number of blades changes from site to site. The different requirement is given below under an average discharge of  $0.12\text{m}^3/\text{s}$ .

<i>Head(m)</i>	<i>Discharge(<math>\text{m}^3/\text{s}</math>)</i>	<i>Number of blade</i>
3m	0.12	20
4m	0.12	21
5m	0.12	22
6m	0.12	24
7m	0.12	21
8m	0.12	22

(Table 4.7: No of Blades required for different Head)



(Fig 4.5: Design of Runner Assembly)

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### 4.6.3 Design of shaft

Shaft is a device used to transmit power. Here shaft is used to transmit power from runner to electric generator or grinding machine.

Material used

- High strength micro alloy
- Heat treatment steel
- Steel

As far as cost is concern steel (ASTM A36) is considered good for watermill application.

$$\text{Design of the shaft (d)} = 10.2(C*T)/t \dots\dots\dots(4.15)$$

[43]

Where

$$t = \text{yield stress (MPa)} = 80 \text{ Mpa (Material used: Steel)}$$

$$C = 1(\text{for belt drive})$$

$$T = \text{torque transmitted}$$

$$\text{Yield stress of material} = 250\text{Mpa}$$

$$\text{Power input} = \rho * g * Q * H / 1000 \dots\dots\dots(4.16)$$

[44]

Where

$$\rho = \text{Density of water} = 1000\text{kg/m}^3$$

$$g = \text{Gravitational constant}$$

$$Q = \text{Average discharge} = 0.12\text{m}^3/\text{s}$$

$$H = \text{Head available} = 7\text{m}$$

$$\text{Power input} = 9810 * 0.12 * 7 / 1000 = 8.24\text{kW}$$

$$\text{Power output} = \text{Power Input} * \text{Efficiency}$$

$$\text{Let, Efficiency} = 80\%$$

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Therefore, Power output = 6.59

But also, Power output =  $2\pi NT/60$

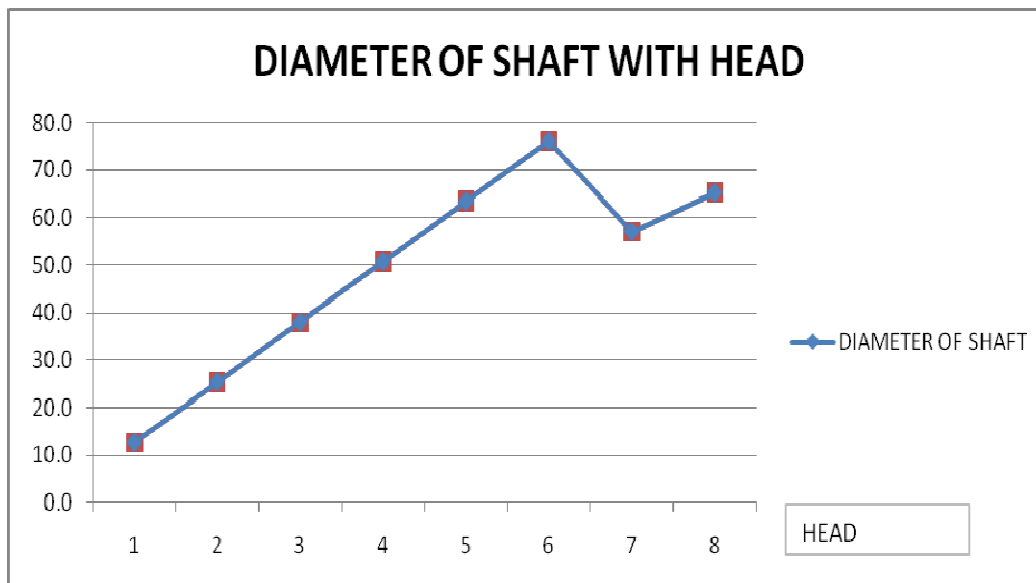
Therefore, Torque transmitted

$T = \frac{6.6 \times 60 \times 1000}{(2\pi \times 350)} = 180 \text{ N/mm}^2$

Diameter of shaft =  $10.2 \times 1 \times 180 / 80 = 57 \text{ mm}$

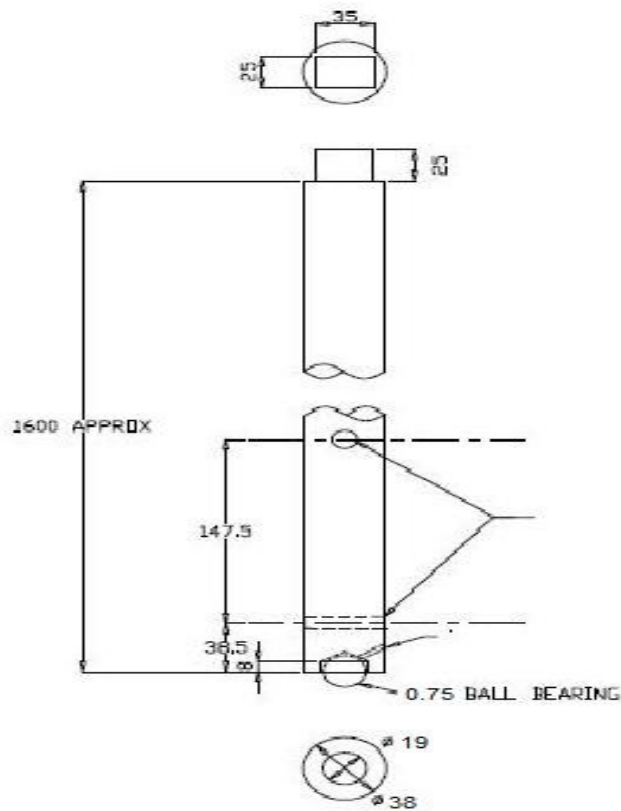
<i>Head(m)</i>	<i>Discharge(m<sup>3</sup>/s)</i>	<i>Torque</i>	<i>Diameter of shaft (mm)</i>
1	0.12	199.1	12.7
2	0.12	398.2	25.4
3	0.12	597.3	38.1
4	0.12	796.4	50.8
5	0.12	995.6	63.5
6	0.12	1194.7	76.2
7	0.12	896.0	57.1
8	0.12	1024.0	65.3

(Table 4.8: Design values for Diameter of Shaft)



(‘Diameter of Shaft v/s Head Curve’ for different Heads)

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(Fig 4.6: Design of Shaft)

### 4.6.4 Material used in Turbine

<i>Component</i>	<i>Material used</i>
Runner	Wood
	Stainless steel
Turbine shaft	High strength micro alloy
	Stainless steel
	Carbon steel
Nozzle material	Stainless steel
	High strength micro alloy

(Table 4.9: Material used in Turbine [45])



## **Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand**

### a. Stainless steel

In metallurgy, stainless steel, also known as inox steel or inox, is defined as a steel alloy with a minimum of 11% chromium content by mass. Stainless steel does not stain, corrode, or rust as easily as ordinary steel. It is also called corrosion-resistant steel or CRES. There are different grades and surface finishes of stainless steel to suit the environment to which the material will be subjected in its lifetime. For turbine application we used 13Cr 4Ni type of stainless steel.

Stainless steel differs from carbon steel by the amount of chromium present. Carbon steel rusts when exposed to air and moisture. This iron oxide film (the rust) is active and accelerates corrosion by forming more iron oxide. Stainless steels have sufficient amounts of chromium present so that a passive film of chromium oxide forms which prevents further surface corrosion and blocks corrosion from spreading into the metal's internal structure. Apart from this, Mild Steel with following properties is advised as raw material

Carbon Percentage:	0.15-0.45%
Density:	7.85 gm/cm <sup>3</sup>
Melting Point:	15100C
Thermal Conductivity:	0.12 cal/cm/0C/s
Coefficient of Linear Expansion:	11.1 Cm/m/0C at 200C

### b. High strength micro alloy

Higher strength steel is fine grained steel with high yield point. This steel is made stronger by increasing the proportion of manganese and by using micro alloy elements of vanadium and niobium. Advanced rolling method also creates rolling steel. This can be welded easily. The main advantage is weight reduction.

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### c. Carbon steel

Carbon steel may be produced with chemical composition (carbon, manganese, phosphorus, sulfur, and silicon) within the specified limits of a given grade and still have characteristics that are dissimilar. Carbon steel may be obtained in a number of fundamental qualities that reflect various degrees of the quality conditions mentioned before. Some of those qualities may be modified by imposing such requirements as Limited Austenitic Grain Size, Specified Discard, Special Heat-Treating, Maximum Incidental Alloy Elements, Restricted Chemical Composition, and Nonmetallic Inclusions.

#### 4.6.5 Factors effecting selection of material

##### a. Roughness of material

Hydraulic energy conversion into mechanical energy in a hydro turbine is inevitably associated with energy losses. Energy losses depend upon the type of turbine, its design, size (dimensions) of the turbine and regime of operation. To improve the performance of such efficient turbines, it is necessary to investigate all the hydraulic elements and runner in particular, to study the nature of losses and to find means of reducing them. Fluid friction losses – especially in the runner where the relative velocities are the greatest – need special consideration. The flow conditions in a hydraulic turbine, especially the prototype turbine, are such that the friction factor is a function of the relative roughness only. Therefore the roughness protrusions of the runner surfaces in contact with the flow are very important and should be the least.

In scaling up hydraulic efficiency of turbine from model to prototype, it is generally accepted as a standard practice that the hydraulic losses can be divided into two parts: the part due to kinetic losses arising from vortices etc, which needs

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no scaling up and the other due to fluid friction which is to be scaled up. Hydraulically smooth flow can be achieved in the model turbines at the velocities generally prevailing by limiting boundary surface roughness ( RMS – root mean square - value of roughness protrusions )  $R_a$  typically to 0.4 microns in runner and guide wheel achievable through suitable surface finish. Limiting roughness for hydraulically smooth flow through other components is about 2.5 times this value.

Strength of material

In materials science, the strength of a material is its ability to withstand an applied stress without failure. Material selection of runner blade should be such that the water jet which is coming from the nozzle should not affect the runner.

### b. Corrosion resistance

Corrosion is the disintegration of an engineered material into its constituent atoms due to chemical reactions with its surroundings. Cast iron has more corrosion resistance than mild steel. So cast iron is used for this purpose.

### c. Life

Life of the material depends upon corrosion, strength of material etc. cast iron have more life than mild steel due to its corrosion resistance property.

<b>Material</b>	<b>Strength of material (Design strength)</b>
a. Stainless steel	Good
b. High strength micro alloy	Excellent
c. Wood	Poor
d. Carbon steel	Very good Corrosion resistance
a. Stainless steel	Good
b. High strength micro alloy	Very good
c. Wood	Excellent
d. Carbon steel	Good Life (more than stainless steel)
a. Stainless steel	Good

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b. High strength micro alloy	Excellent
c. Wood	Poor
d. Carbon steel	Very good Price
4.1 Stainless steel	Reasonable
4.2 High strength micro alloy	High
4.3 Wood	Low
4.4 Carbon steel	Reasonable

### **4.7 BEARING**

A bearing is a device to allow constrained relative motion between two or more parts, typically rotation or linear movement. The various type of bearing used in watermill is:

#### 4.7.1 Ball bearings

Ball bearings use balls instead of cylinders. Ball bearings can support both radial (perpendicular to the shaft) and axial loads (parallel to the shaft). For lightly-loaded bearings, balls offer lower friction than rollers. Ball bearings can operate when the bearing races are misaligned.

#### 4.7.2 Thrust bearings

Thrust bearings are used to support axial loads, such as vertical shafts. Spherical, conical or cylindrical rollers are used; and non rolling element bearings such as hydrostatic or magnetic bearings see some use where particularly heavy loads or low friction is needed.

#### 4.7.3 Water lubricated bearing

Water lubricated bearing of wood , lignum vitae, rubber, or special composition are sometimes preferred particularly for small and medium turbine where bearing is located bottom of the head cover cone where packing box and lubricated bearing is inaccessible , and where water contamination is unavoidable.

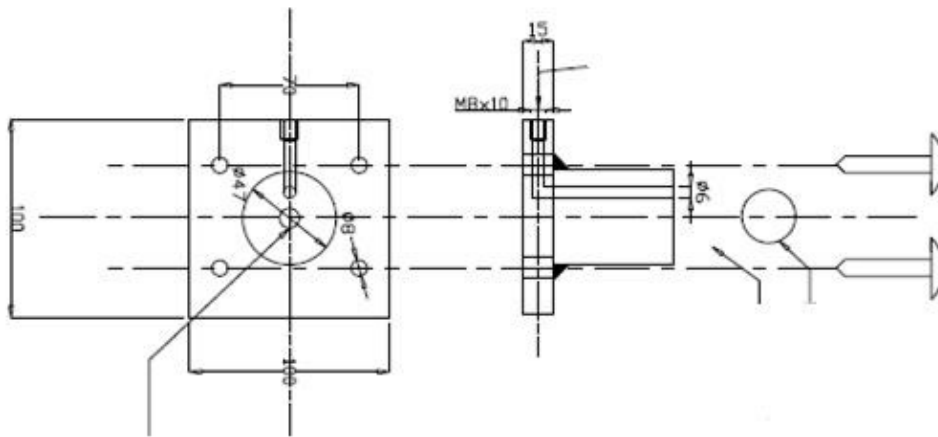
## Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand

### 4.7.4 Self lubricating bearing

To maximize bearing life at today's increased speeds and higher temperatures, lubrication is the key and self-lubricating bearings are best for this. These bearing are cylindrical or spherical in shape.

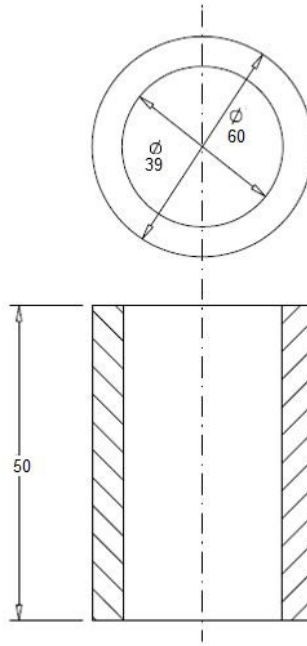
The different advantages are,

1. Self lubricating
2. Good friction resistance  
It is being tested under wet and dry conditions, yielding a coefficient of friction in the range of 0.04-0.10 depending on the conditions.
3. Good abrasion resistance
4. Good load carrying capabilities
5. Good corrosion resistant
6. Easy handling & installation



(Fig 4.7: Design of bearing plate & Greasing arrangement)

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**(Fig 4.8: Design of Shisham bush for bearing Cap)**

### 4.8 OTHER FACTORS EFFECTING EFFICIENCY

#### 4.8.1 Effect of Jet Ratio on specific speed

Specific speed of the turbine

Specific speed of any turbine is the speed in rpm of a turbine geometrically similar to the actual turbine but of such a size, that under corresponding condition it will develop 1-kilowatt power when working under unit head. A significant point about specific speed is that it is independent of the dimension of both actual turbine and specific turbine. Therefore, specific speed of both the turbine is equal. There exist a general trend to select a turbine of higher specific speed because higher specific speed of a turbine result in reduction of runner diameter as well as the overall size of the runner, due to which weight and cost of runner is reduced.

$$\text{Specific speed } (N_s) = 207.5/m \dots\dots\dots(4.17)$$

[46]

This gives the relationship between specific speed and jet ratio m.

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Where,

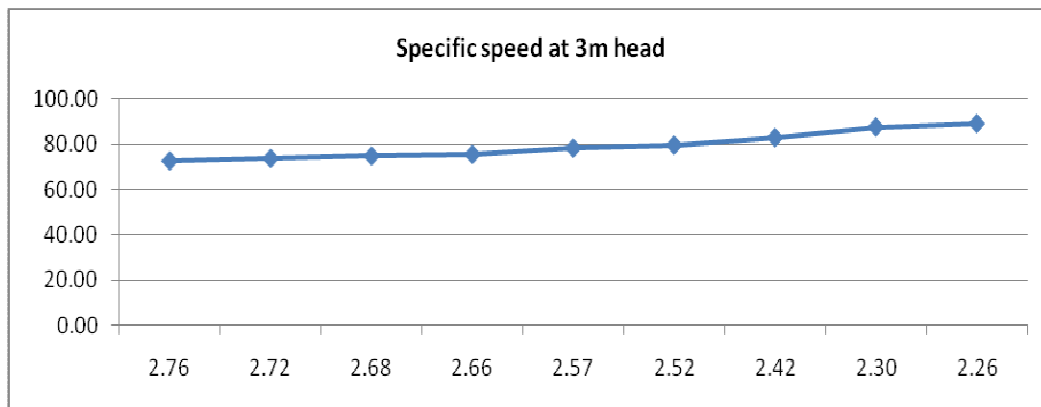
$$m = \text{Jet ratio} = \frac{\text{Diameter of blade}}{\text{Diameter of jet}}$$

So the value of specific speed at various discharges and head is given as,

**Table 24:** values of specific speed at various discharges and head

<i>Head</i>	<i>Discharge</i> ( $m^3/s$ )	<i>Diameter of jet</i> ( $m$ )	<i>Diameter of blade</i> ( $m$ )	<i>Jet ratio</i>	<i>Specific speed</i>
3m	0.1	0.108	0.299	2.76	72.73
	0.103	0.110	0.299	2.72	73.81
	0.106	0.111	0.299	2.68	74.88
	0.108	0.112	0.299	2.66	75.58
	0.116	0.117	0.299	2.57	78.33
	0.12	0.119	0.299	2.52	79.67
	0.13	0.123	0.299	2.42	82.93
	0.145	0.130	0.299	2.30	87.58
	0.15	0.133	0.299	2.26	89.08

(Table 4.10: Specific Speed At Various Discharges And Head)



(‘Specific Speed v/s Jet Ratio’ Curve)

Result obtained from the graph

1. As the value of jet ratio increase the specific speed of the turbine decreases.

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### 4.8.2 Effect of specific speed on efficiency

The relationship between specific speed and efficiency are given below

$$N_s = 3.13 * N_u * (Q_u * \eta)^{0.5} \dots\dots\dots(4.17)$$

[47]

Where

$$N_u = \text{Unit speed of rotation} = N/\sqrt{H}$$

$$Q_u = \text{unit discharge} = Q/\sqrt{H}$$

$$\eta = \text{efficiency of turbine}$$

Therefore

$$\text{Efficiency } (\eta) = N_s^2 / 10.95 * N_u^2 * Q_u \dots\dots\dots(4.18)$$

[48]

<i>Head(m)</i>	<i>Speed (rpm)</i>	<i>Unit speed</i>	<i>Discharge</i>	<i>Unit discharge</i>	<i>Specific speed</i>	<i>Efficiency</i>
3m	225	129	0.1	0.058	72.7	50.2
			0.103	0.060	73.8	50.2
			0.106	0.061	74.9	50.2
			0.108	0.062	75.6	50.2
			0.116	0.067	78.3	50.2
			0.12	0.069	79.7	50.2
			0.13	0.075	82.9	50.2
			0.145	0.084	87.6	50.2
			0.15	0.087	89.1	50.2

**(Table 4.11: Specific Speed at Various Discharges & Head)**

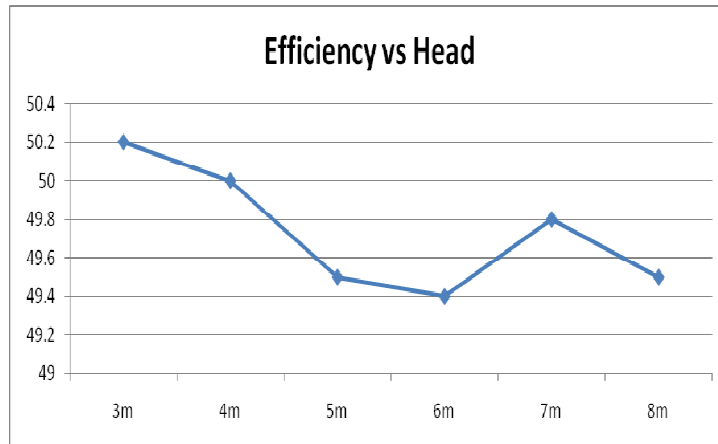
Comments on results of table

As the discharge changes the diameter of jet will also changes. So this will affect the specific speed to keep changes efficiency will remain constant. As the head changes the efficiency the turbine also get affected. This can be formulated as follows.



## Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand

<i>Head</i>	<i>Efficiency (%)</i>
3m	50.2
4m	50
5m	49.5
6m	49.4
7m	49.8
8m	49.5



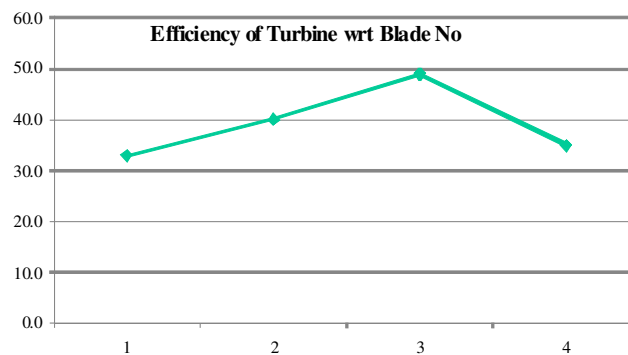
(Table 4.12: Impact of Head on Efficiency of turbine)

(Head v/s Efficiency of Turbine Curve)

### 4.8.3 Impact of blade angle on Efficiency

<b>Blade No</b>	<b>Efficiency of Turbine (%)</b>
1	33.0
2	40.0
3	49.0
4	35.0

(Table 4.13: Impact of blade angle on Efficiency)



(‘Efficiency of turbine v/s No of blade’ Curve)

## Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand



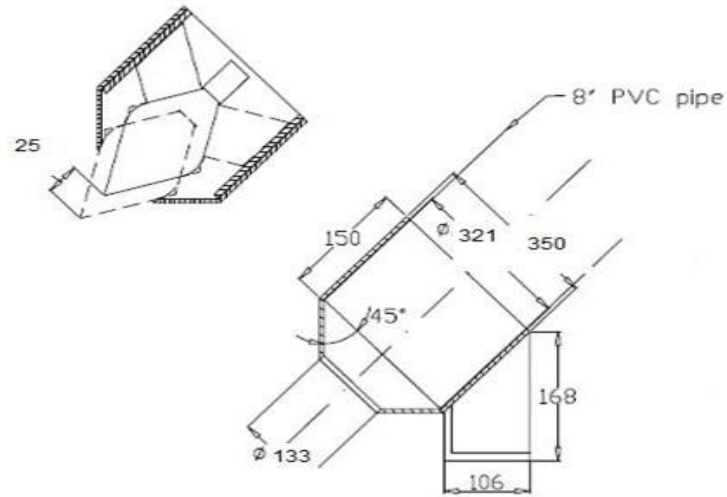
(Fig 4.9: Impact of blade angle)

### 4.9 IMPROVEMENTS

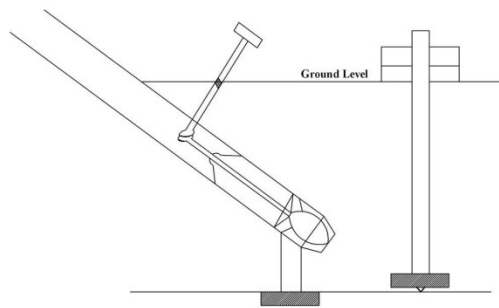
#### 4.9.1 Controlling diameter of Jet

Diameter of jet should be controlled according to discharge. It is done through a spear valve at the nozzle. This can improve the efficiency of the system because as it effect specific speed of the turbine. In auto controlling system, the discharge can be measured by flow meter sensor and signal can be supplied to motor. The motor rotates the needle valve according to the discharge and the needle valve can control flow.

## Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand



**(Fig 4.10: Design of Jet Diameter)**



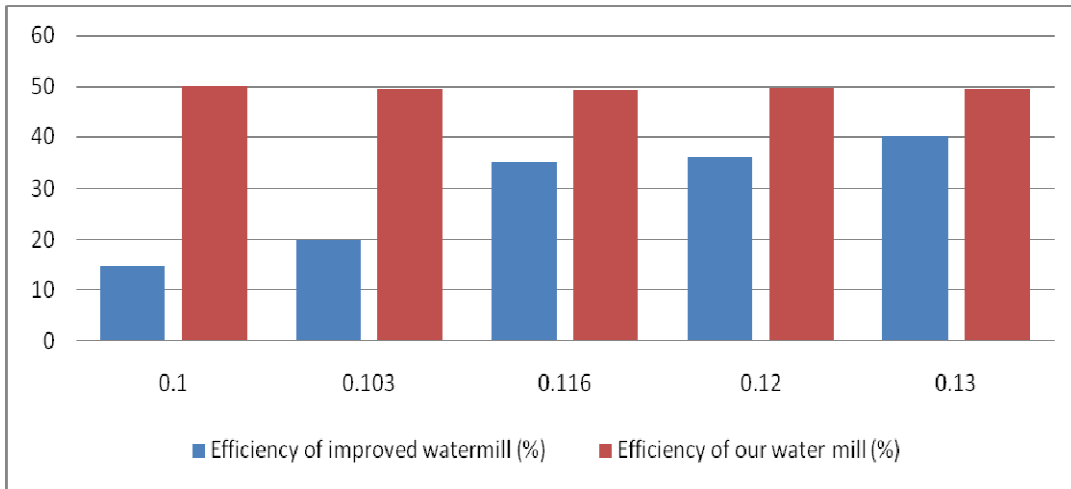
**(Fig 4.11: Control of Jet Diameter)**

By adopting this method in expert watermill improved efficiency of watermill is given below,

<i>Head</i>	<i>Discharge(<math>m^3/s</math>)</i>	<i>Efficiency of existing improved watermill (%)</i>	<i>Efficiency of our watermill (%)</i>
4m	0.1	15	50
5m	0.103	19.9	49.5
6m	0.116	35	49.4
7m	0.12	36.1	49.8
8m	0.13	40	49.5

**(Table 4.14: Comparison of Efficiency of Watermill)**

## Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand



(Efficiency of Improved and our Watermill for different discharge conditions)

Comparison of turbine with and without nozzle control,

Condition of watermill

- Head available = 7m
- Maximum discharge available,  $Q_m = 0.15\text{m}^3/\text{s}$
- Diameter of runner = 0.294m
- Diameter of jet = 0.107m
- Jet ratio = 2.74
- Number of blade = 21
- Rotational speed = 350rpm

Let the discharge variation of site is measured and is given in the table below

Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9
0.1	0.103	0.106	0.108	0.116	0.12	0.13	0.145	0.15

### ■ Calculation of Efficiency

$$Q_m / Q_1 = 350 / N_1 \dots\dots\dots(4.19)$$

[49]Where,

$$\text{Speed available } (N_1) = 350 * 0.1 / 0.15 = 233\text{rpm}$$

$$\text{Power output} = 2 \pi [NT / 60] \dots\dots\dots(4.20)$$

[50]

## Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand

Where

$N$  = Speed of rotation

$T$  = Torque available

Efficiency = power output/power input

From above two relationship, Efficiency  $\propto$  speed of the runner

$$\epsilon_1/\epsilon_2 = N_1/N_2 \dots\dots\dots(4.21)$$

[51]

Where

$\epsilon_1$  = Efficiency with outlet jet control

$\epsilon_2$  = Efficiency without outlet jet control

$$\epsilon_2 = 49.8 * 233 / 350 = 33.2\%$$

<i>Discharge (m<sup>3</sup>/sec)</i>	<i>Designed Speed (rpm)</i>	<i>Speed Achieved (rpm)</i>	<i>Efficiency (%)</i>
0.1	350	233	33.2
0.103	350	240	34.2
0.106	350	247	35.2
0.108	350	252	35.9
0.116	350	271	38.5
0.12	350	280	39.8
0.13	350	303	43.2
0.145	350	338	48.1
0.15	350	350	49.8

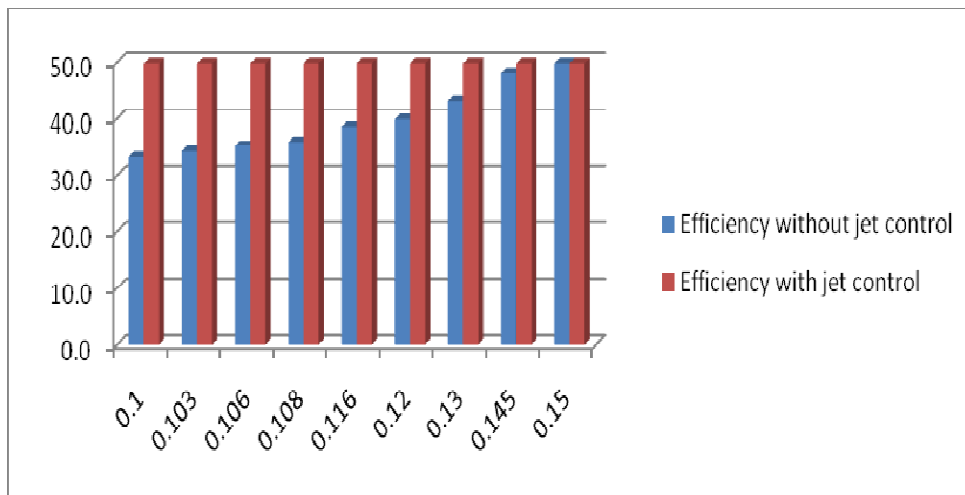
**(Table 4.15: Efficiency calculation for Watermill)**

<i>Efficiency Without Jet Control</i>	<i>Efficiency With Jet Control</i>
33.2	49.8
34.2	49.8
35.2	49.8

## Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand

35.9	49.8
38.5	49.8
39.8	49.8
43.2	49.8
48.1	49.8
49.8	49.8

**(Table 4.16: Comparison of Turbine Efficiency (7m Head))**



(Efficiency Curve with & without Jet control)

### 4.9.2 Nozzle control

Based on the design watermill with jet control was manufactured and tested. (MNRE accredited manufacturers of watermills). Watermill was tested with and without jet control and results were compared with that of existing improved watermill.

Basis for the Design:

Head = 3m  
 Flow = 0.12 m<sup>3</sup>/s  
 Length of penstock = 15m

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<b>Penstock</b>	Material	PVC
	Diameter	0.296m
	Wall thickness	0.0327m
<b>Nozzle</b>	Material	PVC
	Exit diameter	0.119m
	Nozzle control	Needle valve
<b>Runner</b>	Material	Cast iron
	Diameter	0.299m
	Radial width	0.05083m
	Number of blade	20

**Results are as per follows:**

### 1. Test Report on Existing Improved Watermill

HEADING	DISCHARGE (m <sup>3</sup> /S)	INPUT POWER (9.8*Q*H) KW	DYNAMOMETER READING			TORQUE (T1-T2)*R (Nm)	SPEED (rpm)	OUTPUT POWER (2π*NT/60*1000) KW	EFFICIENCY
			TENSION AT TIGHT SIDE T1 (N)	TENSION AT SLACK SIDE T2 (N)	TENSION AT TIGHT SIDE (N)				
3	0.1	2.94	0	0	0	0.00	225	0	0
			166	0	0	12.04	210	0.265	8.999
			156.8	0	0	31.91	195	0.651	22.15
			235.6	9.8	0	48.31	170	0.860	29.239

**(Table 4.17: Test Report on Existing Improved Watermill)**

### 2. Test Report on Our Improved Water Mill (Without Nozzle)

S.NO	HEAD (m)	DISCHARGE (M <sup>3</sup> /S)	INPUT POWER (9.8*Q*H) KW	DYNAMOMETER READING		TORQUE (T1-T2)*R (Nm)	SPEED (N)	OUTPUT POWER (2π*N*T/60*1000)	EFFICIENCY
				TENSION AT TIGHT SIDE	TENSION AT SLACK SIDE				

## Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand

				TIGHT SIDE T1 (N)	SLACK SIDE T2 (N)			KW	
1	3	0.1	2.94	0	0	0.00	220	0	0
2				380.3	0	19.60	215	0.77	26
3				525.1	9.8	35.11	200	0.97	33
4				733.9	17	48.79	190	1.28	44

**(Table 4.18: Test Report on Our Improved Water Mill (Without Nozzle))**

### 3. Test Report on Our Improved Water Mill (With Nozzle)

S.N O	HEA D (m)	DISCHA RGE (M3/S)	INPUT POWER (9.8*Q*H) KW	DYNAMOMETER READING		TORQ UE (T1- T2)*R	SPEE D (N)	OUTPUT POWER (2 $\pi$ *N*T/60* 1000) KW	EFFIEN CY
				TESION AT TIGHT SIDE T1 (N)	TESION AT SLACK SIDE T2 (N)				
1	3	0.1	2.94	0.0	0	0.00	225	0.00	0
2				604.7	19.5	56.18	225	1.32	45
3				640.5	39.2	61.17	225	1.44	49
4				718.1	44.8	68.66	225	1.62	55

**(Table 4.19: Test Report on Our Improved Water Mill (With Nozzle))**

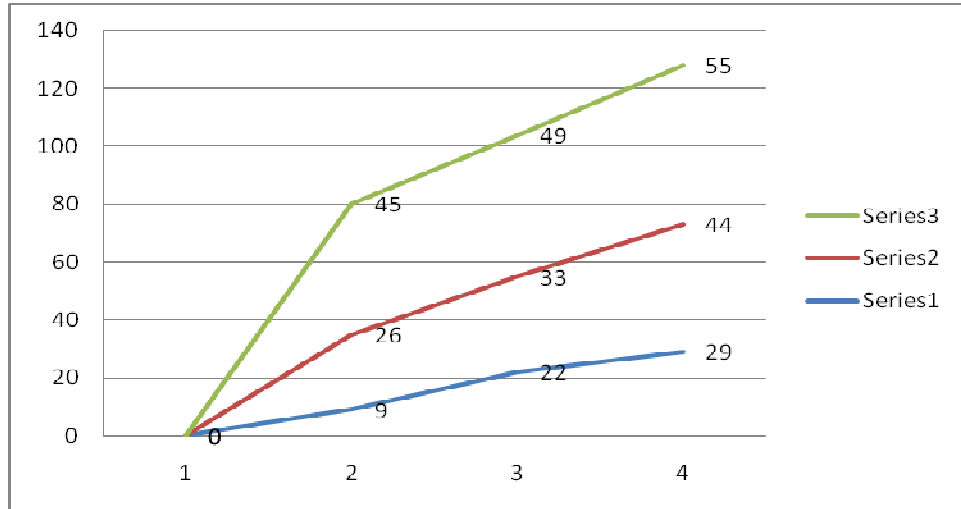
### 4. Efficiency at 3 m Head and 0.1 m3/s Discharge

<i>Efficiency Of Improved Watermill (%)</i>	<i>Efficiency Of Our Watermill (Without Nozzle) (%)</i>	<i>Efficiency Of Our Watermill (With Nozzle) (%)</i>
0	0	0
9	26	45
22	33	49
29	44	55

**(Table 4.20: Comparison of Efficiency of Watermill)**

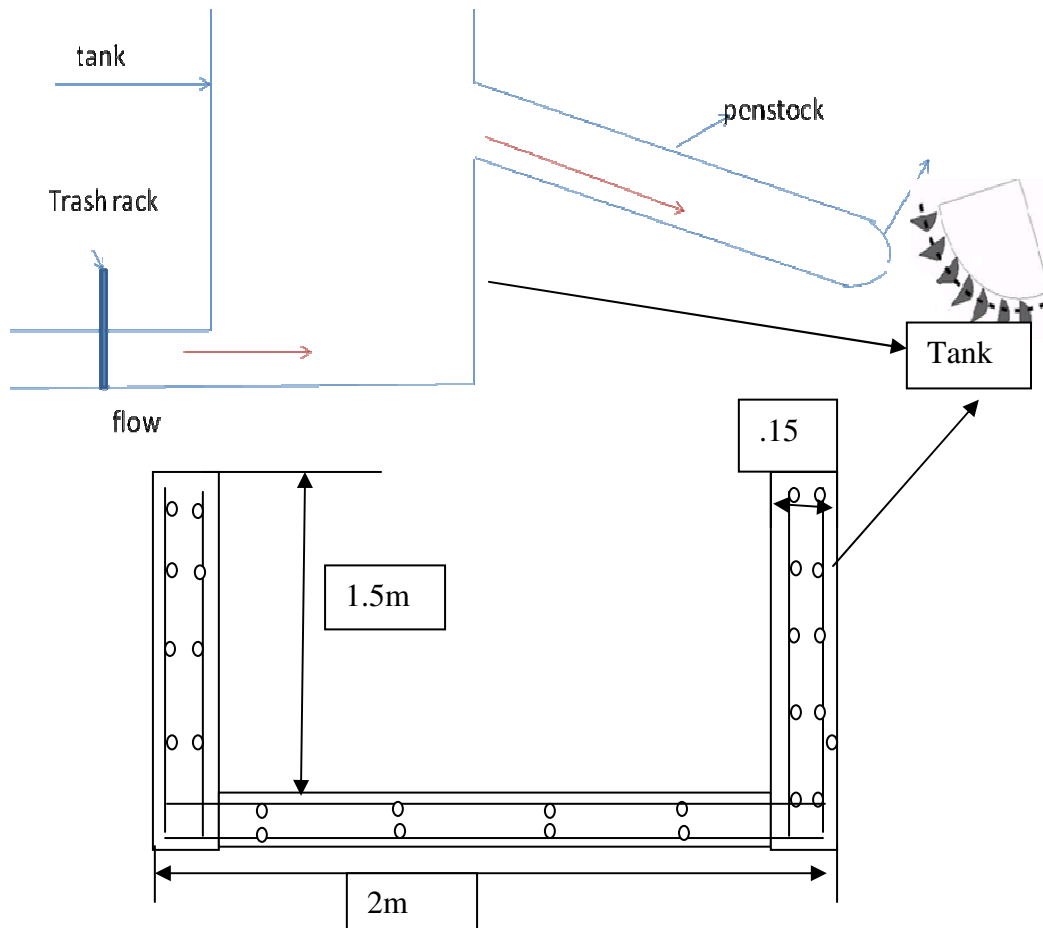


## Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand



(Comparison curves for Efficiency of Watermill)

### 4.9.3 Putting one trash rack and a tank (de siltation tank) before penstock



**(Fig 4.12: Trash and De siltation Tank)**

## **Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand**

One of the major functions of the intake is to minimize the amount of debris and sediment carried by the incoming water, so trash racks and a tank are placed at the entrance to the intake to prevent the ingress of floating debris and large stones.

A trash rack is made up of one or more panels, fabricated from a series of evenly spaced parallel metal bars. Trash racks are fabricated with stainless steel or plastic bars. Since the plastic bars can be made in airfoil sections, less turbulence and lower head losses result. The tank removes debris and stones which coming along with water through bottom sedimentation.

A fine trash rack may be provided before the tank. Bar spacing should be 5 depending on of trash size. The trash rack may consist of thinly spaced vertical steel bars or rods. The distance between bars or the width of wholes or slots shall not be larger than 0.5 times the nozzle diameter in case of impulse turbine with fixed nozzle. Structurally, the trash rack shall withstand the full water pressure of a completely blocked rack with maximum water level upstream and no water downstream. The trash racks should be placed at an angle of around  $70^\circ$  to the horizontal for eases of cleaning and end above water level. A suitable trash-cleaning tool must be provided.

## **Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand**

### **4.10 MULTI PURPOSE WATERMILL**

Today, much of these mountainous regions remain unelectrified despite the interest in and demand for basic electricity. The aim is to create an opportunity for an individual entrepreneur to provide electricity to his immediate community by leveraging part of his indigenous infrastructure: the water mill.

Even the smallest amount of electrical power could have a big impact on this part of the world. For most Himalayan homes, kerosene is the only available source of light after sunset. Houses are rarely well-ventilated, and kerosene inhalation poses a real health threat. New lighting technology can completely replace the use of kerosene for lighting. Both Compact Fluorescent Lights and the more exotic white LED lights are available today in the local market. There is enough power in the traditional water mill to power these kinds of lighting systems as well as other small household appliances or even small incandescent lighting systems. Extending the mill's functionality to include electricity generation also has the added benefit of providing an entrepreneurial mill owner with an additional source of income.

When engineering a product for the individual entrepreneur in the Himalayan region, low cost becomes the dominate criteria. For a mill owner, expensive induction generators and transmission lines are simply out of the question. A battery charger is a much more viable solution. The mill owner bears the cost of the inexpensive charging system, while the individual households bear the cost of batteries, as they are able. Even the more remote and isolated homes are able to participate in this scheme, as long as they are within walking distance of a mill. Although issues of transportation and disposal remain, battery usage seems the quickest and most economical path to bring basic electrical lighting to the mountains.

## **Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand**

Batteries simply can go where a transmission grid cannot. A battery-charging extension to the mill could both alleviate the need for these long trips and make such a strategy available to other, more remote areas of the mountains.

The mill is also an ideal site for a battery-charger. During much of the year, steady streams of people arrive at their local mill with grain and leave with flour, as has been done for centuries. It will not be a dramatic change of routine for rural villagers to bring their batteries to the mill as well. They can have a battery charged and their grain ground in the same trip. The battery charger extension can also be operated during the unutilized time of the mill, which varies by season. The availability of a battery-powered light also allows the mill to operate at night, either for grinding or battery charging.

An inexpensive battery charger can be made using a car alternator, a bicycle rim, a belt, and a mill "key". The key sits on the rotating turbine shaft and supports the top grinding stone. By attaching a small square post to its top, the turbine shaft can effectively be extended. The bicycle rim has a square pipe welded to its axle that can be slipped over the square post. The turbine thus drives the bicycle rim, and the rim in turn drives the smaller alternator pulley using the long car v-belt. With the top stone raised up, the water mill's energy goes not into grinding, but into powering the alternator.

### **Watermill battery charger**

A car alternator is an excellent choice for a battery charger as is it has been specifically engineered to provide a regulated voltage ideal for recharging 12V batteries. It can supply up to 500W of power, which is conveniently the maximum estimated power output of most traditional water mills. Although the alternator needs a fairly high rpm to generate electricity, it can be run below car idle speeds.

## Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand

The bicycle rim and alternator pulley provide enough of a ratio to allow the alternator to produce power at water mill speeds (60-90 rpm).

The most significant advantage to using an inexpensive mill add-on to bring electricity to the mountains is sustainable maintenance. Maintenance is always a large concern when introducing new energy technology to remote areas of the world. Typically it cannot be maintained without additional infrastructure and technical expertise.

### Specifications:

Cost	Rs 3540
Power	Upto 0.5 kW
Voltage	14.4VDC
Pulley ratio	13:1
Belt type	V belt
Generator	Car alternator



(Fig 4.13: Battery Charging arrangement of watermill)

## **Analysis & Redesigning of Watermills for Sustainable Development of Rural Areas of Uttarakhand**

### *Summary*

- *It is identified that most important design basis is to have a system which is low cost, made up of easily available material, simple in concept, well-engineered and sophisticated enough to be maintenance-free & efficient for longer period.*
- *Based on commonly available hydrology equipment and material selection was made.*
- *Various components like runner, shaft, penstock and nozzle are designed for the available range of hydrology.*
- *Flow control is suggested by means of spear valve with manual adjustment which can give almost constant efficiency at various levels of discharge.*
- *A prototype is developed and tested suggesting that a possibility of 15 – 20% efficiency improvement is there over existing improved watermills.*
- *A carry home type battery charging arrangement was also suggested to take care of some of lighting requirement.*
- *A user friendly software is made to give the manufacturers a readymade design for different hydrology to bring standardization in design and thus performance.*