MicroHydro Turbine

A Feasibility Study

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1 Introduction

In the Fall of 2006 a feasibility study was presented as a senior design project. The objective of the study was to determine if it would be feasible to install a micro-hydro turbine or any other small scale hydro-electric source, at Minors Millpond in Reynolds, Georgia. The idea for the project was proposed by our sponsor, Leo Lovel, who was interested in developing the site for a small community around which the hydropower would be the drawing feature. The project team was initially presented with documents from the sponsor, indicating some initial measurements and a sketched diagram of the site. The Minors Millpond consists of two spillways and covers approximately 35 acres. The water source for the Minors Millpond is Panther Creek, which is a watershed for approximately 4,000 acres and is supplemented by numerous artesian springs. The Minors Millpond has two spillways, one of which is significantly wider than the other. Both spillways have significant leakage problems. Some initial dimensions of one spillway along with a rough estimate of the flow rate were provided. The project sponsor also indicated that in middle Georgia, September and October were seasonal dry months. The area was also in the midst of a five year drought. The objective of the study is to collect data, calculate the expected flow rate, and determine through economic analysis if it would be feasible to install a micro-hydro turbine or any other small scale hydro-electric source.

2 Site Visit

On September 30th, 2006 the FSU Micro Hydro Turbine Project Team traveled to Reynolds, Georgia. The goal of this visit was to observe the site and collect the necessary data. The objectives for the day were as follows:

Measure the dimensions of each spillway and the levy dimensions
Measure the head or height the water falls
Collect data that would be necessary to determine flow rate
Find out where the water from the spillways flowed
Locate a power hookup (grid)
Basic site survey
Determine the conditions of the dams

2.1 Site Description

The Minors Millpond is located in middle Georgia and is approximately 35 acres. It is supplied by Panther Creek, which is a water shed for approximately 4,000 acres and is supplemented by several artesian springs. The Minors Millpond eventually runs to the Flint River via the Patsiliga Creek. The millpond has two separate spillways; one which was previously used as grist mill (when the mill was in operation) and the other spillway was used as an overflow when the mill was not in use. Shown in Figure 2.1is a satellite image from Google Earth of the Minors Millpond. Shown on the image are both of the spillways. Also shown in blue is the direction of runoff from the spillways.

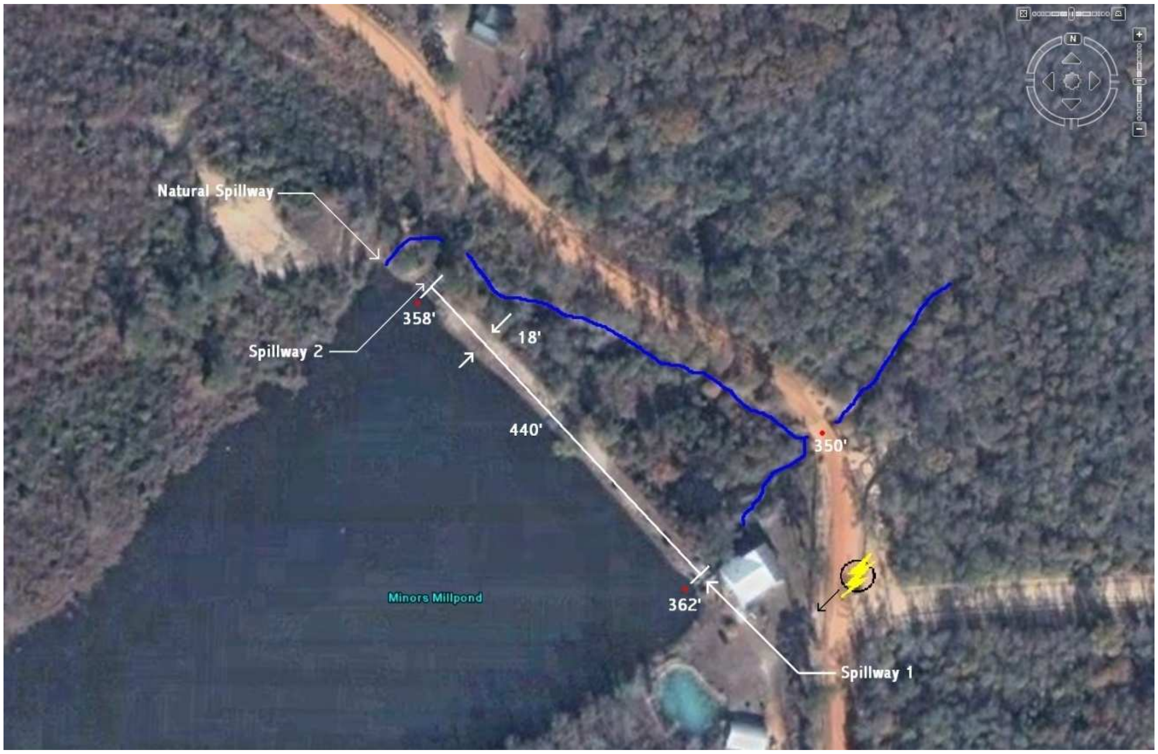

Figure 2.1– Satellicapture Image of Minors Millpond [Google Earth]

Spillway one Figure 2.2 is the primary spillway with the mill house in close proximity (which housed the inner workings of the mill). Spillway two Figure 2.2 is approximately 440ft. northwest of spillway one and was strictly used as overflow, or control. A third natural spillway about 30ft. away is 2ft. higher than spillway two and was possibly used for flood control. The width of the top of the levy is 18ft. Figure 2.1 shows red pin points indicating elevations of three locations upstream and downstream of the spillways provided by Google Earth. Figure 2.1also indicates where a possible power hookup is located denoted by a lightning

Figure 2.2 Power Hookup Location, Spillway Two, Spillway One

bolt. This hookup can be seen in Figure 2.2 at left.

The grist mill is no longer in use and has obvious signs of deterioration. The dams are constructed of wood planks, all of which are rotting in both spillways.

In the case of spillway two, no water is actually flowing over the dam but is instead leaking through the wood planks. Spillway one is not in as bad of a condition, but there is still a substantial amount of leakage from the dam.

2.2 Dimensions and Use of Spillways

2.2.1 Spillway One

Spillway one Figure 2.4 consisted of two rectangular chambers both about 14ft. high. The larger chamber [App. A.1] is approximately 55ft. long and 12ft. wide. The large chamber has a small rectangular exit leading to the smaller chamber where the water would then flow out of the spillway. Historically, during the grist mill operation, the small rectangular exit would be blocked, allowing the first chamber to fill to its highest point. The exit would then be opened and the power of the flow would be captured in the second chamber.

2.2.2 Spillway Two

Spillway two was not the primary spillway used for the operation of the mill but was instead used for overflow. Spillway two had an average width of 31ft. measured in 7 different locations along the spillway and had an average length of 28.2ft measured in 5 different locations [App. A.2].

2.2.3 Natural Spillway

The natural spillway is not actually a natural spillway but a canal dug out of the ground for the purpose of flood control. Although there is no significance to the dimensions of the natural spillway, the height of the entrance to it, relative to the water level is. Using basic surveying techniques, we established a transit location between spillway 2 and the natural spillway and from that location the height difference from the water level to the natural spillway was measured. The method of surveying is depicted below in Figure 2.3.

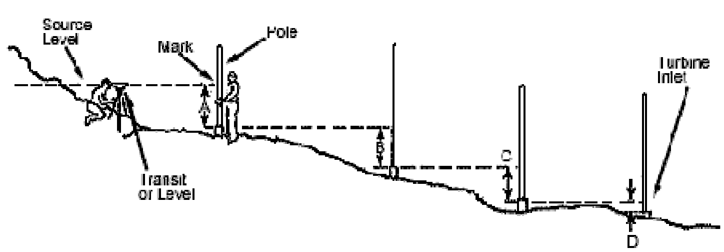

Figure 2.3 – Surveying Method

2.3 Measuring Flow Rate

The most important aspect of this visit was to determine the total flow rate through both of the spillways. After measuring all the dimensions of each spillway, the project team was able to proceed with the proper measurements for determining velocity. There are several methods for determining the velocity in an open channel, which are outlined in the Layman's guide. The method the team preferred was the *float method*. By using a small floatation device (in our case we used a small square of foam), one can record the time it takes for the floatation device to travel a defined distance. Velocity is a function of time and distance, and both were collected in the float measurement. This method, however, will result in a value for surface velocity which is not constant for the entire cross-section of the flow. To determine the average velocity, the surface velocity can be multiplied by a correction factor ranging from 0.60 to 0.85, depending on the depth of the channel and the surface roughness.

Figure 2.4, below, is the cross sectional area that was measured for our flow calculations at spillway one.

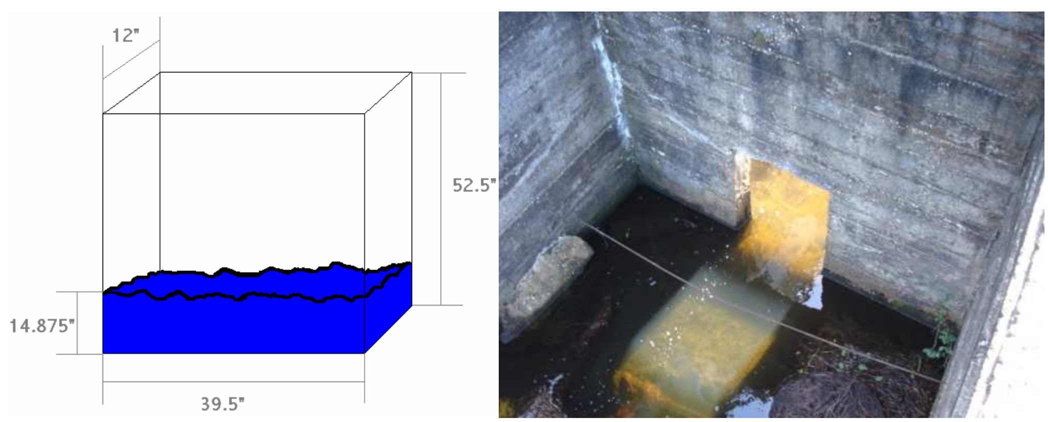

Figure 2.4 – Spillway One Dimensions

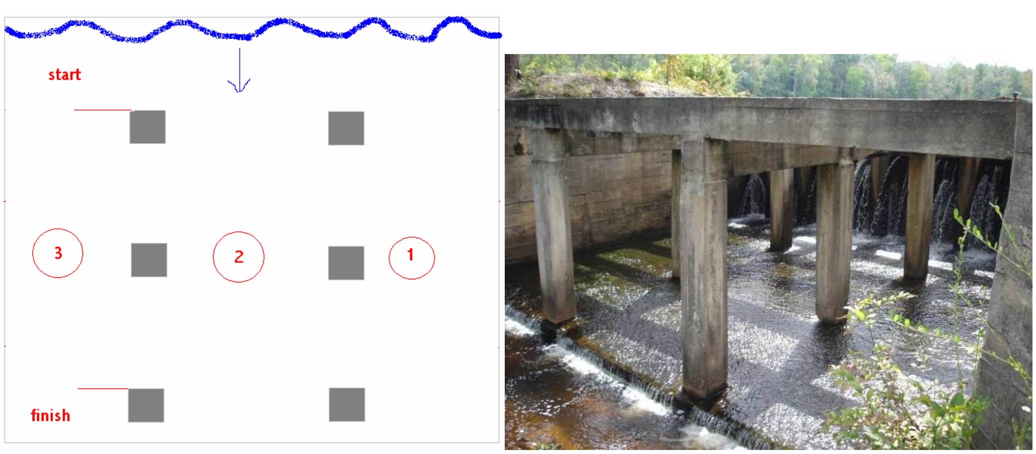

Figure 2.5 – Spillway Two Dimensions

Figure 2.5 shows a diagram of the distance the flotation device traveled in spillway two and a picture of spillway two. Both spillways have rectangular cross sections, making the cross section a simple measurement [App. A.1, A.2]. For both spillways, we defined a distance for the measurement and tabulated the time it took to traverse that distance [App. A.1, A.2]. At spillway one, the distance traveled was the thickness of the wall the water was passing through (the exit from chamber one to chamber two) and the distance traveled at spillway two was from one column to another. All of the depth measurements and time measurements used in the calculations were averages of several measurements taken, in order to produce conservative values for each [App. A.1, A.2]. From the distance and time measurements, the surface velocity was calculated [App. A.3]. Spillway one had a velocity of .199m/s and spillway two had a velocity of .559m/s. By knowing the cross sectional area and velocity, we were then able to determine flow rate. The flow rate for spillway one was 1,203 gallons per minute and spillway two was 2,792 gallons per minute [App. A.3]. The correction factor has not been factored into these values of flow rate to generate an average flow rate for the cross section. To determine the correction factor the flow properties must be known. It was important to determine whether the flow was laminar or turbulent for the correction factor. By calculating the Reynolds numbers for both spillways we were able to determine the flow was turbulent [App. A.3]. The team also consulted Dr. Wenrui Huang, Associate Professor of Hydraulics, at the FAMU/FSU College of Civil Engineering about determining turbulence in open channel flow. An alternative way of determining turbulent flow, he informed us, is to drop an object in the water. If the waves move up stream then the flow is laminar. This method also confirmed that our flow was turbulent. In the case of turbulent flow, the correction factor can be ignored because the surface velocity is very close to the average velocity of the flow. In our case, we opted to use a correction factor of .85 (highest in the range) to produce a conservative value for average velocity and flow rate. The total flow rate for both spillways, with the correction factor applied, was 3,395 gallons per minute or 7.564 cubic feet per second (cfs).

2.4 Measuring Head

The water pressure, or head, is the distance between the surface of the water in the reservoir and the surface of the water at the bottom of the spillway. We only measured the head from spillway one since this is the most probable location for the turbine. Also, all of the flow would be diverted into spillway one to maximize power output. The head measured was 100in or 8.33ft. Raising the head 1.5 ft is also a consideration to further increase the head and available power. If spillway two can be closed off, the pond height would then reach the height of the natural spillway. For all of the calculations using head, we combined the flow rates from both spillways and then used the head from spillway one.

3 Flow

3.1 Flow Energy

The energy of flowing water has been utilized for the advancement of mankind long before engineering was a profession. Intimate understanding of the basics, though, was not formalized until the seventeen hundreds with the development of the Bernoulli equation Equation 3.1 developed by Daniel Bernoulli and Loenhard Euler. The Bernoulli equation can be thought of as the mechanical energy associated with a flowing fluid. If the mechanical energy is conserved in the fluid, then the Bernoulli equation will always give a constant value, that is to say the energy just changes form.

$$gh + \frac{P}{\rho} + \frac{v^2}{2} = c$$

Equation 3.1

g	Acceleration due to gravity
P	Pressure
ρ	Density of water
v	Velocity
h	Elevation

Applying the Bernoulli equation to two points on a waterfall, as shown in Figure 3.1 would yield an equation for the theoretical available power represented in Equation 3.2

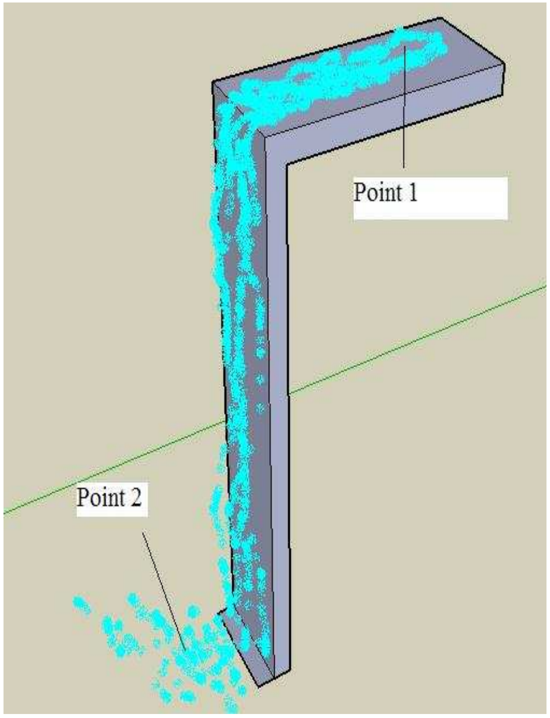

Figure 3.1 – Bernoulli Waterfall Example

$$P_1 = P_2 = 1\ atm$$

Equation 3.2

In the power equation above, the pressure term will go to zero because both pressures are equal to atmospheric pressure. The velocity term could introduce some error but its energy contribution is three orders of magnitude smaller than the contribution that comes from the elevation term. Therefore, in the interest of simplicity and with an understanding that the other terms are insignificant, we will pull these terms out of the equation and add another term, η, for efficiency. As stated before, the Bernoulli equation shows a maximum theoretical power. In practice, this maximum power output is not attainable so there is an efficiency factor added to give accurate power generation estimates.

$$Power_{generated} = g(h_1 - h_2)\dot{m}\eta$$

$$\dot{m} = Q\rho$$

Equation 3.3

Where $Q =$ volumetric flow rate

The acceleration due to gravity can be considered a constant everywhere on the earth's surface so there is no need to find this. The change in elevation from the top of the waterfall to the bottom is easily measured in a site survey. The mass flow and the efficiency factors are more difficult and will be addressed throughout this document. Calculation of the flow rate "Q" is complex enough to warrant its own section in this document, and will be the content of the rest of this section.

3.2 Flow Correlation

3.2.1 Site Overview

Before launching into a discussion about estimating mass flow rates, let us consider an overview of our specific site. Our site is situated in middle Georgia near Macon. The Closest USGS gauging stations are on the Flint River; one upstream near Carsonville, Georgia and one downstream near Montazuma, Georgia.

Figure 3.2 – Site Overview

It is not a difficult feat to measure flow. There are several methods that can be employed that give various degrees of accuracy. The problem is that it is not satisfactory to measure one flow since it only applies to a single point in time. If someone is developing a hydroelectric site, the real question is what the average flow will be over the life of the site. This is a trivial problem if the sight has been gauged for several years. One would simply assume that the historical data for the site would continue to be valid.

The strength of distributed power generation, like that of micro-hydro electric sites, is in its low environmental impact. The downside of this distributed nature is that the obscurity of the various sites can make finding information a difficult task. This is the case with the Minors Millpond. Panther Creek and its various springs are the feeders for Minors Millpond. This creek flows into Patsiliga creek which in turn feeds into the Flint River. The Flint River is not only a very large river, but it is also important in an interstate commerce conflict between Atlanta, Georgia and Apalachicola, Florida. Because of this, the Flint River is very accurately gauged. If we wanted to develop a hydro site on the Flint River, the data would be readily available. Our hydro site is separated from the Flint by two streams. There is readily available and accurate flow data for the Flint River[App. B], but what we would like to do is develop a valid way to correlate the Flint River flow data to the flow at the Minors Millpond site. If we take the Flint River basin as a control volume, we can write the steady state continuity equation for the control volume as shown in Equation 3.4

$$\frac{dm}{dt} = Q_{carsonvill\dot{e}} - Q_{Montezuma} + Q_{regionsTotalContribution}$$

$$\therefore Q_{regionsTotalContribution} = Q_{montazuma} - Q_{Carsonville}$$

Equation 3.4

3.2.2 Base and Rain Contributions

The flow in any given stream can be thought of as a combination of two parts; a contribution that comes from rain and varies with time, and a contribution that comes from springs and other sources, perhaps flowing in from outside the control volume. We call this contribution the base contribution. Equation 3.5 is the mathematical representation of what has already been stated. From this point forward, this regional contribution will be referred to as total Flint. Given this new information we can write equations for the flow rates that are important to our problem.

$$Q_{totaFl\,\mathrm{int}} = Q_{rainFl\,\mathrm{int}} + Q_{baseFl\,\mathrm{int}}$$

$$Q_{totaPanther} = Q_{rainPanther} + Q_{basePanther}$$

Equation 3.5

3.2.3 Base and Rain Contributions for the Flint River Basin between Carsonville and Montezuma

Consider the hydrograph in Figure 3.3. The red line represents the Flint

River's Base contribution to the flow rate. If we subtract the base from the total, we have the rain contribution to flow as a function of time (Figure 3.4).

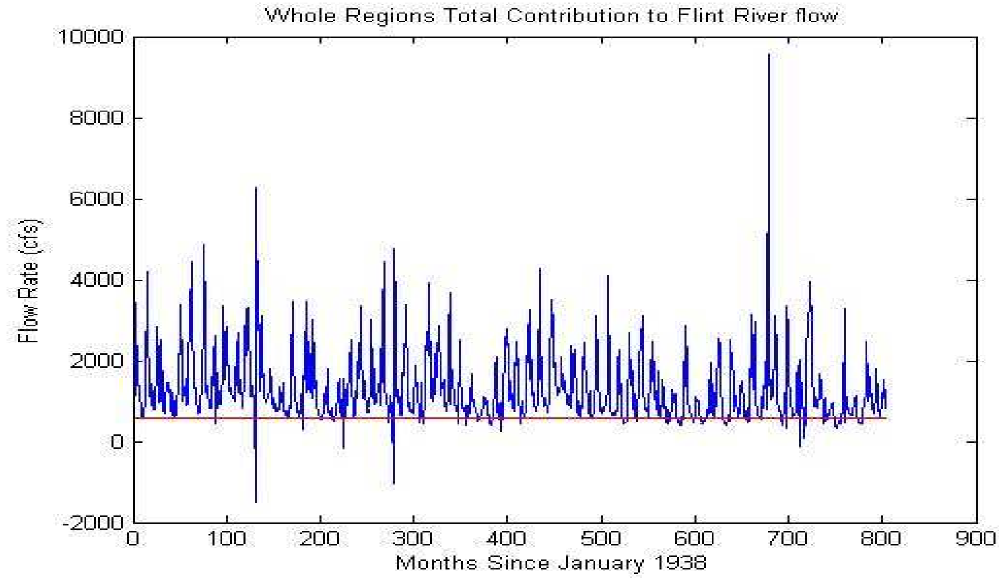

Figure 3.3 – Total Flow in the Flint River

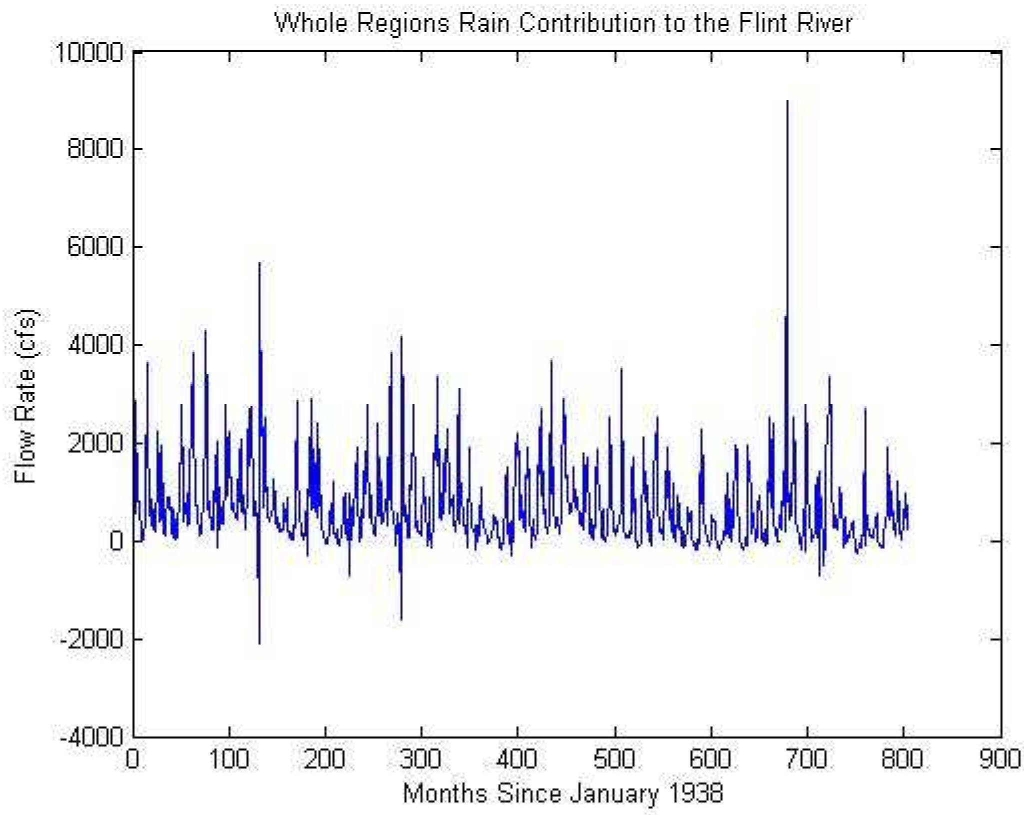

Figure 3.4 – Rain Contribution to the Flint River

3.2.4 Base and Rain Contribution to Flow in Panther Creek

It is admissible to state that the ratio of rain contribution to Panther Creek to the ratio of rain contribution to the Flint River is equal to the ratio of the Panther Creek watershed area to the Flint River watershed area. If we rearrange this equality, we can arrive at an equation for rain contribution to flow in Panther creek as shown in Equation 3.6.

$$\dot{V}_{rainPanther} = \frac{Area_{PantherWaterShed}}{Area_{FlintWaterShed}} \dot{V}_{rainFlint}$$

Equation 3.6

This is very encouraging because all of these parameters are easy for us to determine. The area of the Panther Creek watershed can be estimated from the topographic map of the site in Figure 3.5.

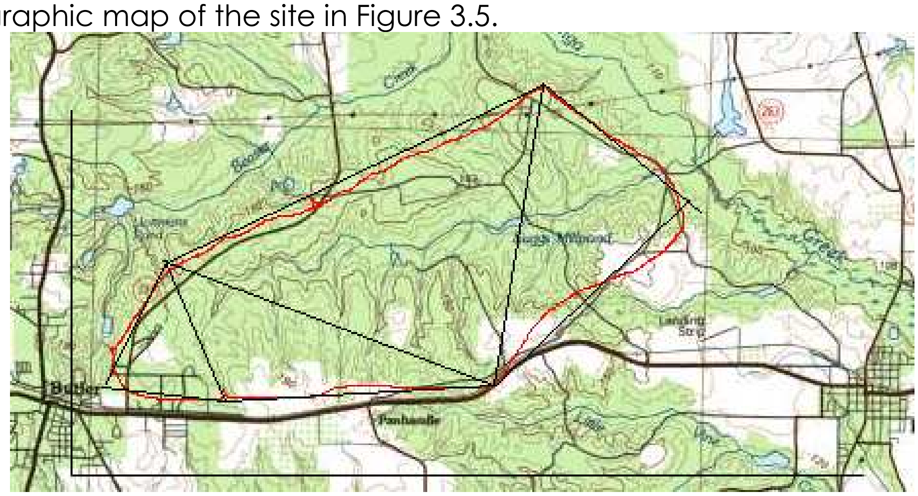

Figure 3.5 – Topographic Map of Panther Creek Watershed

The red boundary represents the estimated water shed boundary and the black triangles represent a triangular mesh used to estimate its area. This image was opened in MS Paint where the coordinates of the corners of the triangle were determined. Then Matlab (App. B) and Heron's formula were used to calculate this area in pixels. The straight line distance between Butler, on the bottom left, and Reynolds, on the bottom right, was used to convert the area in pixels into an area in square miles. The area of the Flint River basin between Carsonville and Montezuma (Figure 3.6) was determined in a similar way.

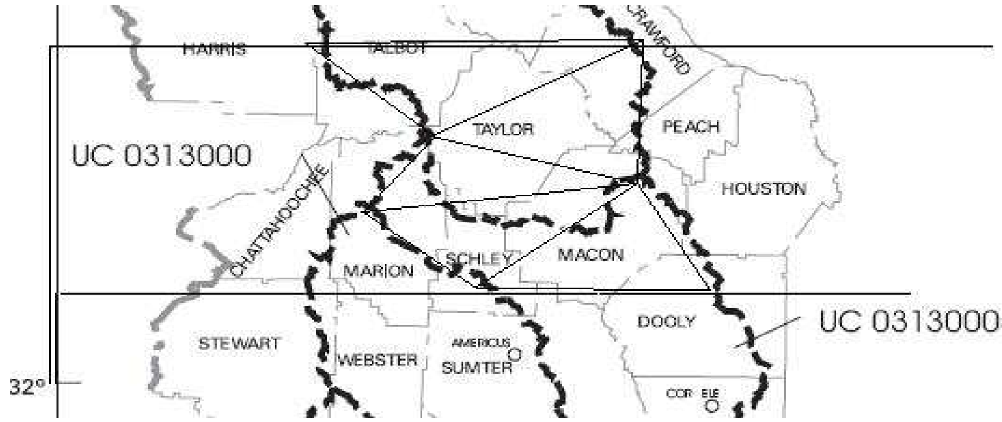

Figure 3.6 – Flint River Watershed for Area of Interest

Having determined the areas of the two watersheds we see from equation 3.6 that we can now find the volumetric flow rate in panther creek due to rain.

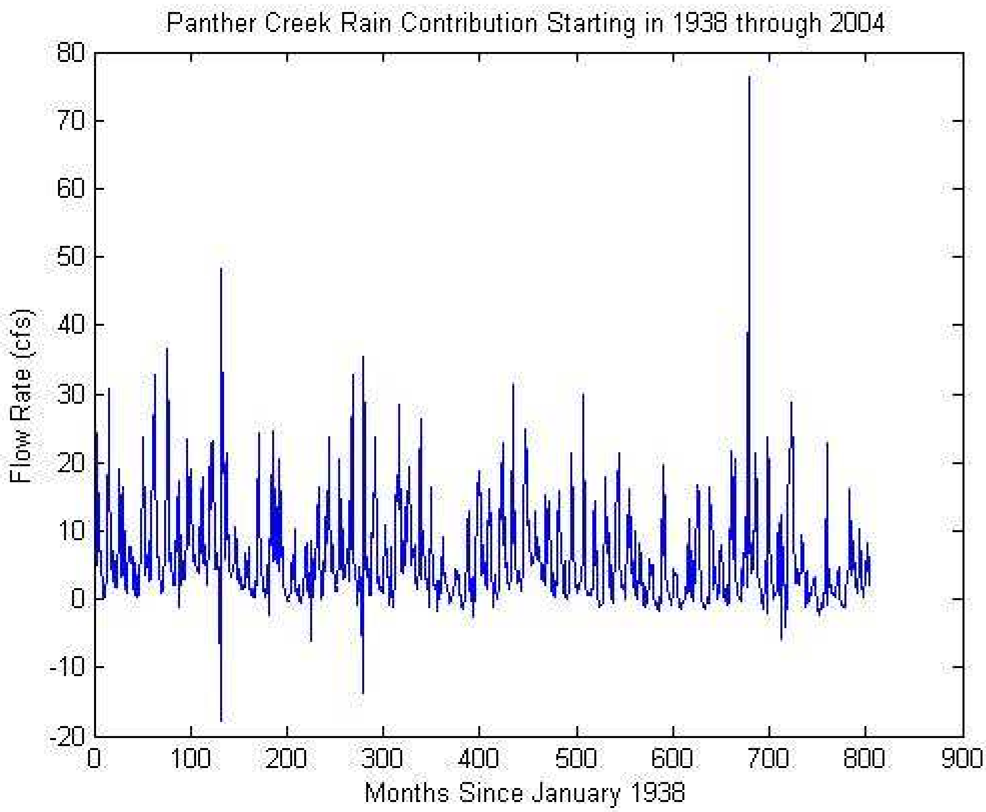

Figure 3.7– Flow Rate at Panter Creek Due to Rain

Referring back to Equation 3.5, we now have all the parameters needed to arrive at a hydrograph of Panther Creek, except for one. The missing parameter is the base flow contribution to Panther Creek that comes from springs and is fairly constant. A site survey was conducted in September which is the low flow period in middle Georgia (see Figure 3.9). We can assume that whatever flow we calculated that day is a base flow. Methods for determining the flow rate from the measured data will be discussed elsewhere. For now, we will take the results of the site survey to finish developing the hydrograph of Panther Creek. According to Equation 3.5, we add the base onto the contribution due to rain to get a hydrograph for Panther Creek.

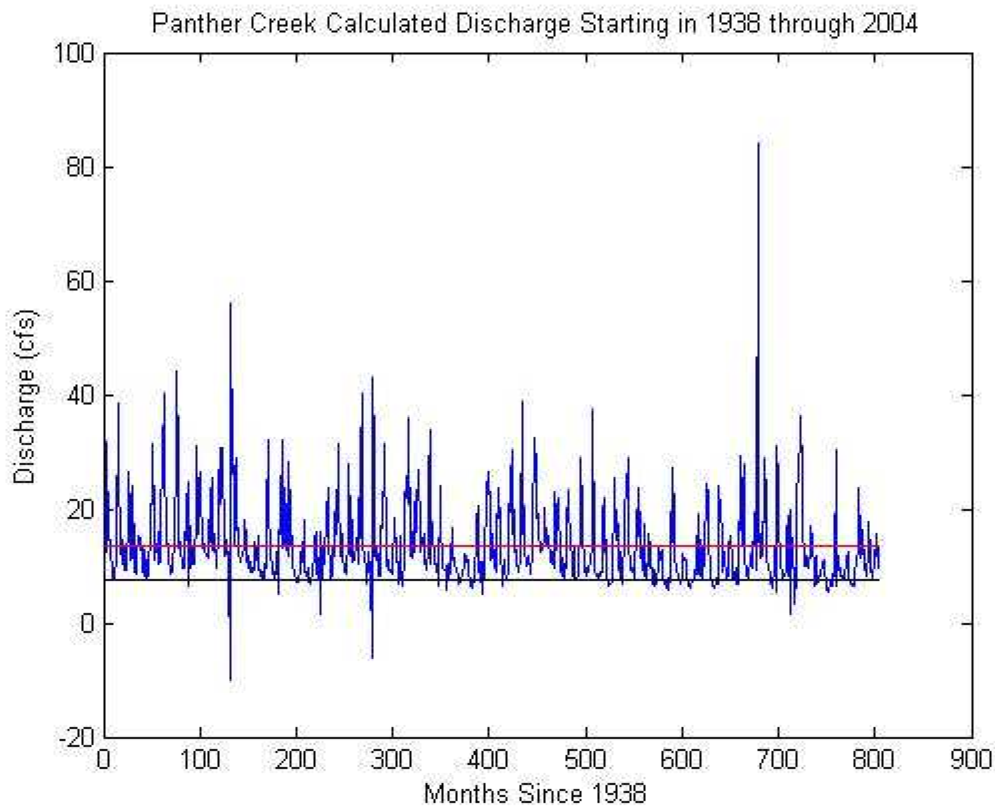

Figure 3.8– Historical Hydrograph for Panther Creek

From this hydrograph we can see that our historical average flow rate is about 13 cubic feet per second. This is the flow rate that all of our design and selection data will have to take into consideration. The hydrograph in Figure 3.8 starts in January of 1938 and ends in December of 2004.

3.2.5 Single Year Hydrographs

If we wanted to see what the flow rate does over a single year, then the plot of all the years on top of one another would yield the hydrograph in Figure 3.9.

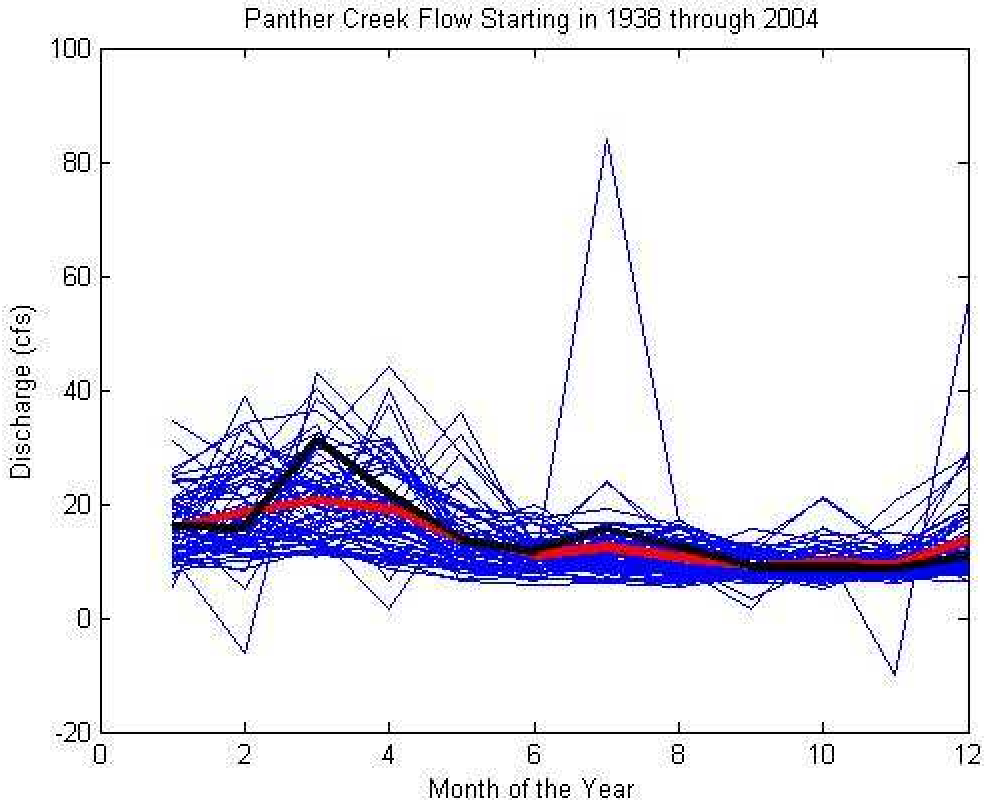

Figure 3.9 – Single Year Hydrograph

There are several things to point out about Figure 3.9. First, the flow is generally high and unpredictable throughout the first part of the year. Second, around June the flow begins to taper off and becomes more predictable. The red line represents average flow rates for the year and the black line is actual data for the year of 1958. This year was found to have the smallest deviation from the average. The month of March, 1958 has a lot of deviation but the rest of the year was very typical. If it becomes necessary, the year of 1958 will be expanded for further research.

3.2.6 Flow Duration Curves

A flow duration curve is another way of representing the data contained in a hydrograph. The Y axis of the plot has increasing percentages and the X axis has increasing discharge values. For any point on the line, the Y value of that point is the percentage of the time the flow meets or exceeds the value on the X axis. Matlab code was used to generate the graph shown in Figure 3.10.

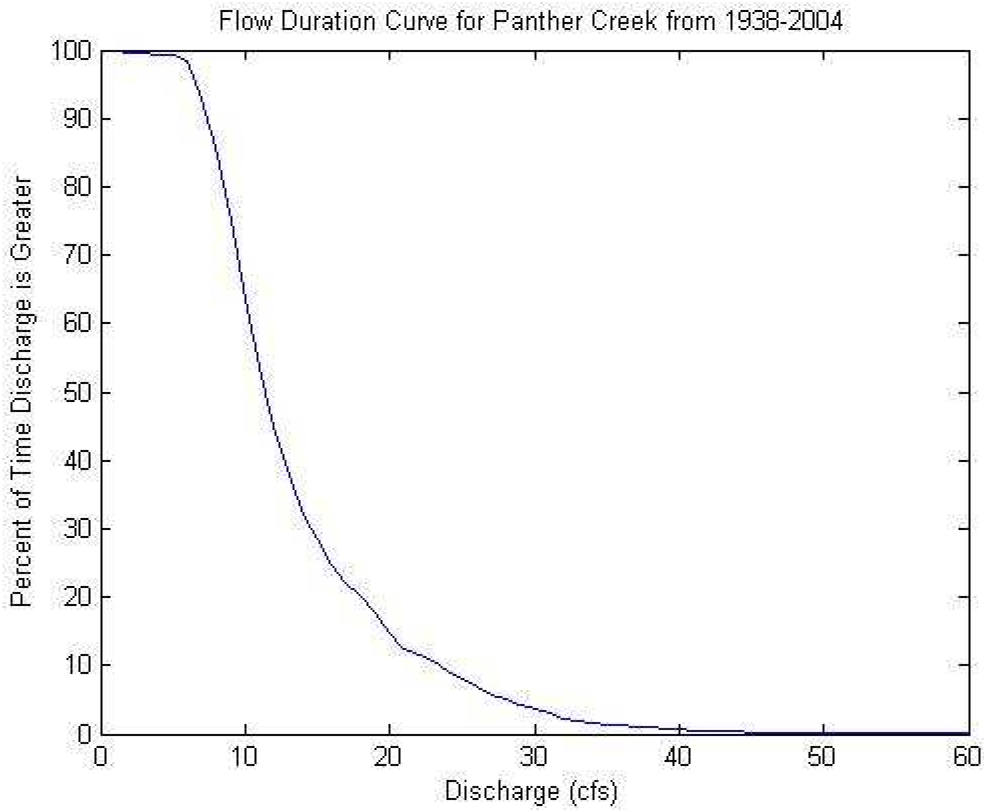

Figure 3.10 – Flow Duration Curve

The steep drop off at about 9cfs represents a base contribution that the flow should never fall below. The average flow rate that has been determined to be about 13cfs has a Y value of 50%, as expected. This means that 50% of the time the flow is greater than 13cfs and 50% of the time the flow is less than 13cfs. Lastly, the maximum flow that the site should be designed to handle is in the range of 40cfs and realistically, the flow should never go above 40cfs. If the site was designed to be able to handle 60cfs, it should be more than sufficient to handle 99.999% of the flow situations that the site will ever encounter.

3.3 Flow control

In order to reduce the environmental impact of the hydro site, it is necessary not to divert all of the flow through the turbine power system. In the interest of not diverting all of the flow, it is required that we be able to control how much flow goes over spillway two and spillway one.

Some of the proposed configurations for the hydro site would benefit from the ability to easily store up flow and then let all the water flow at once. This is beneficial both for the on demand nature of power generation and the added benefit of boosting the apparent flow rate at the turbine, which allows for the selection of larger and more efficient turbines.

3.3.1 General Control Theory

A transducer is any device that converts the nature of a signal. An example of a transducer is a potentiometer, which has the property of converting a displacement (either linear or angular), which is a mechanical signal, into an electrical signal such as voltage, which can be easily detected. Transducers are important to the field of control because they allow the state of a system to be compared to a reference.

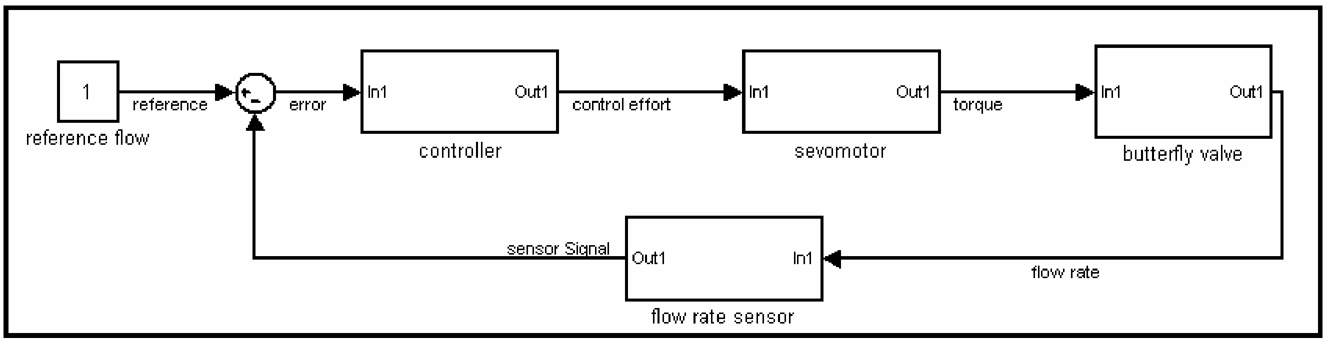

Figure 3.11 – Control Theory

In the controller in Figure 3.11, we have a reference flow rate that we would like to maintain. Assume that the situation being controlled is the flow at spillway two. In that case, the reference is the minimum flow that needs to be flowing through spillway two in order to support that ecosystem. Assume also that spillway two has been renovated and the timbers currently there have been replaced by a concrete bulkhead with a large butterfly valve installed like the one pictured in Figure 3.12.

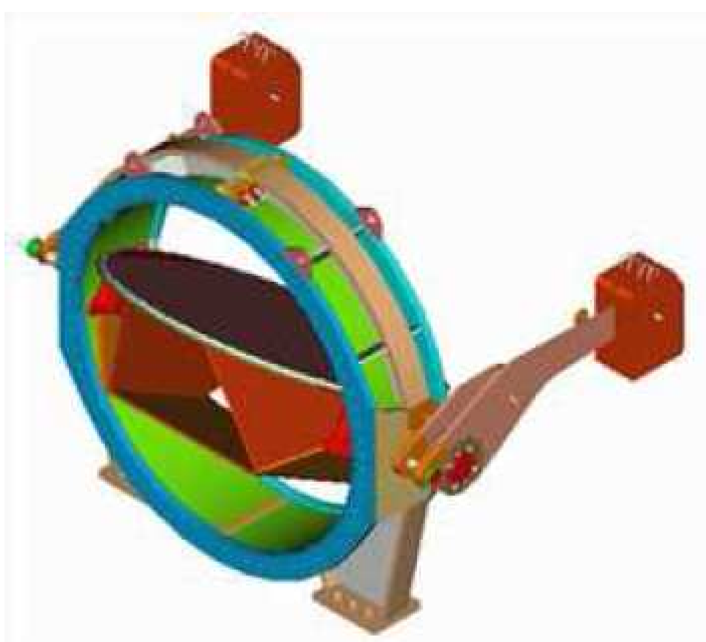

Figure 3.12 – Butterfly Valve

While the turbine system is operational, the butterfly valve would need to be wide open in order to maintain the minimum flow rate, but when the turbine system is offline and the water volume is charging back up, then the valve would only need to be cracked open. An electronic control system would be able to handle all of these things automatically with no interference from the owner/operator of the hydro site. A fully automated electronic control system would be much too expensive to implement for a project of this scope, but that does not mean that control is irrelevant. It simply means that the more expensive components will have to be replaced by a human operator that can check on the system daily and make necessary changes.

3.3.2 Options for Flow Control Over Spillway One

3.3.2.1 General

Without going into too much detail, we have essentially four options for the configuration of spillway one. Some of the designs require intermittent flow, that is, the flow will build up until enough volume is reached. Then the flow will run out at a high rate until the set volume is exhausted. At this point, the flow through the turbine will go to zero and the volume will recharge for another cycle.

3.3.3 Intermittent

If a design calls for intermittent flow, then there are two options that could be used to create the intermittency. One is what is called a siphon system. The other would be similar to a toilet tank assembly

3.3.3.1 Siphon

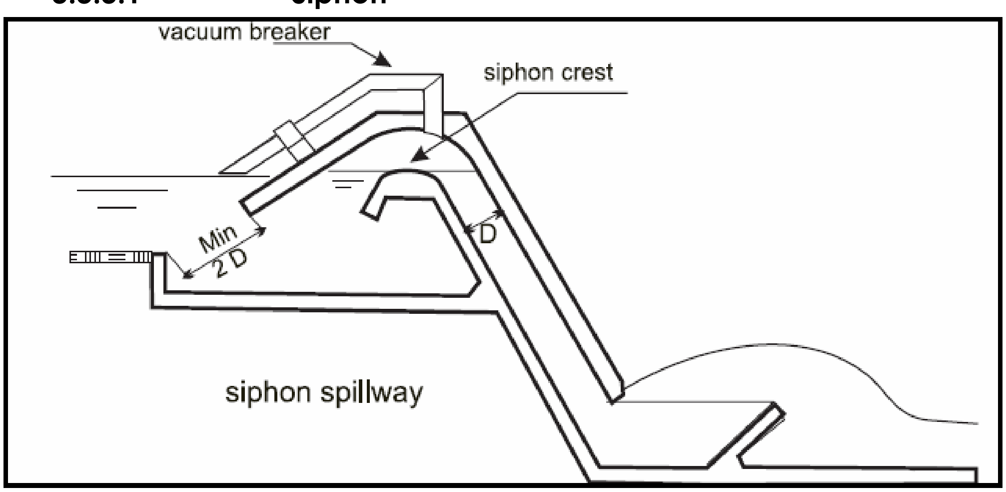

Figure 3.13 Siphon Spillway [6]

When the water level breaks, the siphon crest will begin to move at a very high flow rate. This flow rate would continue until the water level falls below the submerged surface of the vacuum break. The siphon spillway has the advantage of being completely self regulating. The disadvantage is considerable and that is that if the siphon is not designed properly, then it will have a tendency to create cavitation bubbles, which drastically reduces the life and efficiency of the turbine.

3.3.3.2 Toilet Tank

This design option would utilize the existing reservoir and a scaled version of a toilet tank. The only modification, other than scaling, would be the addition of an automatic flusher, such that as soon as the water level reaches maximum, then an actuator would automatically flush the reservoir.

3.3.3.3 Manual Control with Valves

This would be the most labor intensive option and also the cheapest intermittent flow option. In this scenario, a human operator acts as the controller from Figure 3.11.

3.3.3.4 Continuous

Several of the turbine options allow for continuous flow through the turbine. In these scenarios, there is no controller necessary. The lack of a controller makes the system much cheaper. The problem with these options is that they tend to be of a lower quality and are not very efficient.

3.3.4 Options for Flow Control Over Spillway Two

Flow over spillway two needs to be adjustable in response to the changing river discharges. Any intermittent control solution for spillway one would be acceptable, as well as two additional schemes: an inflatable spillway crest and flashboards.

3.3.4.1 Inflatable Spillway Crest

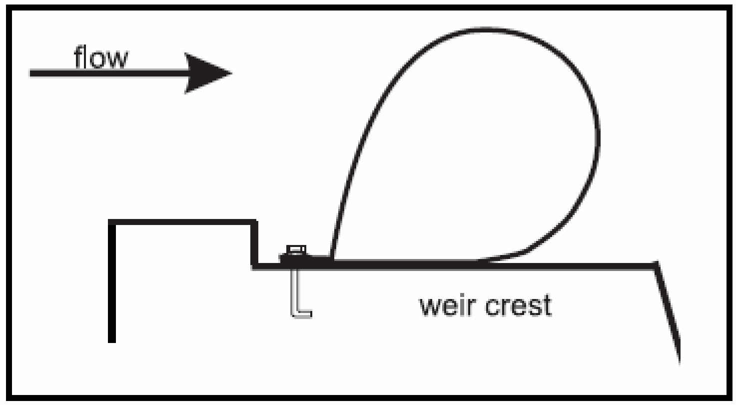

Figure 3.14 [6]

Figure 3.15 [6]

If the inflatable spillway scheme is chosen for spillway two, then the minimum height of the spillway would be sized to give the minimum flow during the driest part of the year. The inflatable bladder would need to be large enough to inflate enough to limit the flow in all but the highest 10-5% of the flow rates.

3.3.4.2 Flashboards

Flashboards accomplish the exact same thing that the inflatable bladder does that is to raise and lower the spillway crest. This option would likely be comparable to the inflatable option in terms of price but would be significantly less variable and more dangerous to adjust in high flow situations

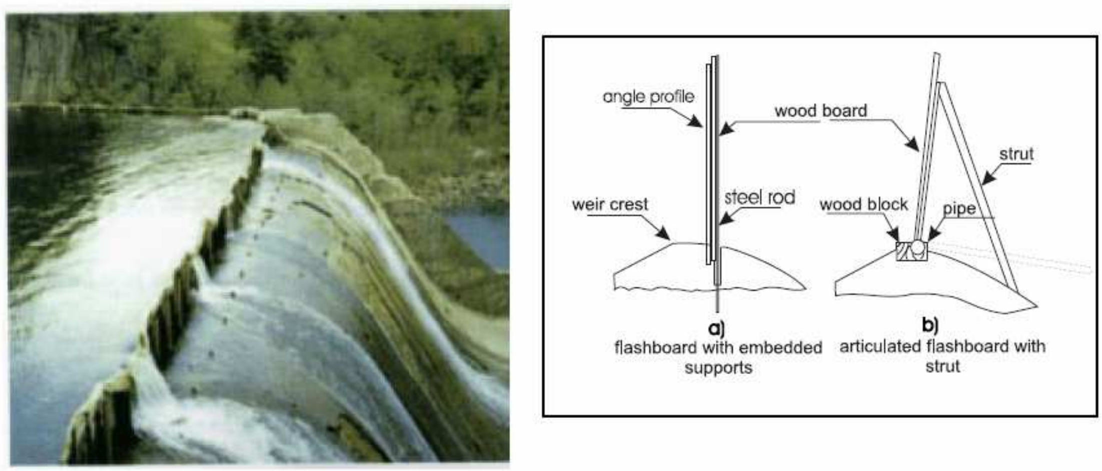
angle profile
wood board
strut
weir crest
steel rod
wood block
pipe
a)
flashboard with embedded supports
b)
articulated flashboard with strut

Figure 3.16 [6]

4 Hydraulic Structures

Inherent to the control of any flow for the generation of electricity is the need for various mechanical and civil structures associated with optimizing power production. The scheme shown in Figure 4.1 shows a typical run-of-river setup where flow is diverted very far upstream and routed to a forebay tank where energy can be stored for times of high demand. It is worthwhile to consider the function of a typical site and then consider how it relates to the more specific project at hand.

The first component in the chain which connects the upper river to the power house, and thus returning the water to the river, is the intake weir. The intake weir's purpose is to divert a certain fraction of the total flow from the main stream, and to remove some of the debris that is entrained in the flowing water. Once the water is taken from the stream, it is conveyed under force of gravity through a channel with just enough slope to bring the water to the forebay tank. From the forebay tank the water enters a power intake which has essentially the same function as the intake weir; the main difference is that the power intake does a more thorough job of filtering the water. Next, water flows into a penstock, which is a glorified pipe, to carry high volumes of water at pressure to the powerhouse. The powerhouse is the structure that contains the turbine and generator. The final link to return the water to the river is the tailrace, a pipe that starts at the turbine exit and extends to the river.

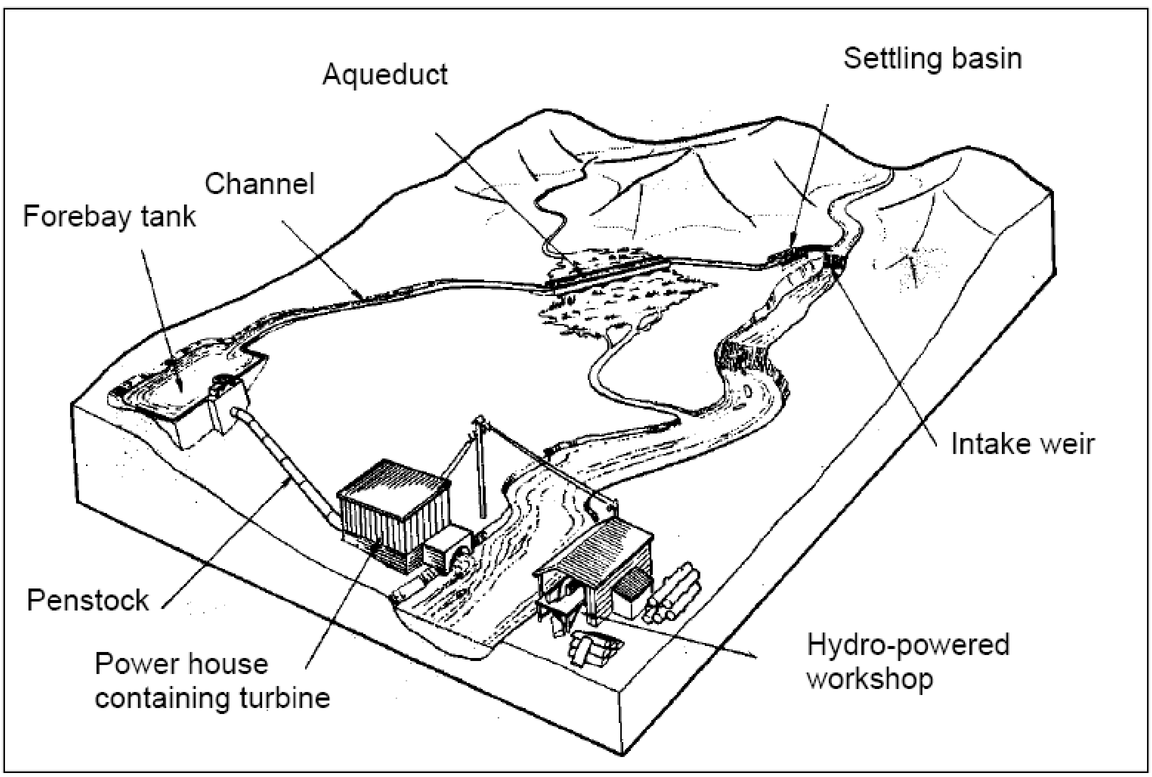

Figure 4.1 - Typical Small Hydro Scheme [10]

All of the functions represented in this typical hydro site diagram will have to be reproduced at Minors Millpond. The purpose of this study is to present options about how these various functions can be fulfilled and then explore the feasibility of each.

4.1 Dams

Dams do two things that are desirable for power production: increase the head of the flow and store potential energy in the form of still water. The problem with dams is that the water level behind the dam rises until it reaches the crest of the dam, thus flooding the region behind the dam, which leads to the destruction of habitat and the displacement of people and animals. Therefore, given that the purpose of small hydro is the mitigation of environmental impacts, the typical small hydro site does not include a dam.

Dams may be hard on the environment, but they are still very useful, and Minors Millpond already has one, so it will introduce no further disturbance to continue using it. We should however consider options for renovation. Both spillway one and spillway two have water retaining walls built from old timbers. These timbers are rotten and leaking. There are several options for renovating these retaining walls. It is necessary that the renovations made to spillway one include the capability of installing a penstock and some way to control the flow rate. Spillway two need only have the capability of controlling flow rate. The earth structure dam has been in place for a long time and should be fine for another 50 years provided that the water never breaches the top of the dam. If the spillways are designed properly and kept in good repair, the dams should be fine as they are. The spillways will be considered in greater details in a separate section.

4.2 Water Conveyance

In any hydro scheme there is an issue of moving water from place to place. This problem has been addressed for hundreds of years and the methods are proven and reliable. Each component in the hydro system will have some conveyance device to connect it either to another member of the system or to the world. The problem we face at Minors Millpond is greatly reduced from the general case since there is no intake weir, and the forebay is already in existence. All this really leaves is moving water from the reservoir side of the dam to the turbine side, and returning the water from the dam to the rest of the world via a tailrace.

4.2.1 Tower Type

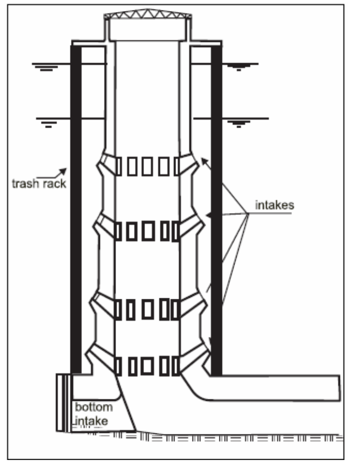

Figure 4.2 - Tower Type Intake [6]

The tower intake is what is normally seen in a situation like Minors Millpond where the water is stationary and the task of the intake is reduced to keeping debris and fish from entering the power system. This should not be too costly an item as it could easily be constructed from PVC pipe and chicken wire. The Ideal design would have a trash rack system that could be pulled up from somewhere onshore for cleaning. The Tower Intake has the disadvantage of being difficult to clean, an activity that would become very frequent.

4.2.2 Through Bottom Scheme

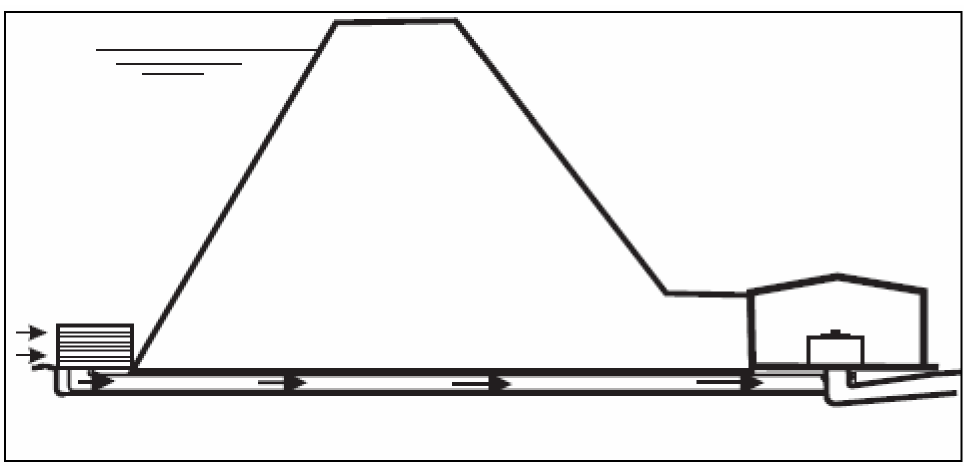
Figure 4.3 - Through Bottom Type Intake [6]

The through bottom scheme takes the water from one side of the dam and pipes it at a constant elevation to the turbine side. This setup has the benefit of simplicity and a disadvantage of having no real method for easy cleaning.

The Intake Structure serves two purposes one is to preventing debris from entering the turbine. The second is to control how much water actually enters the power generation system and how much will go down the river uninterrupted. The problem of flow control is complex and will have to be addressed in several places, but certainly it is a consideration in choosing the diameter of the intake. Trash accumulation is the most important function of the intake structure and will require frequent maintenance.

4.3 Power intake

The power intake is similar in function to the conveyance intake; the idea is to provide a transition for the flow, where in the conveyance intake the transition is from a natural water course to a channel. For the power intake, the transition is from the forebay to the penstock. There are several ways in which the power intake differs from the conveyance intake:

Must include a support for the trash rack and easy cleaning thereof

Guide vanes to distribute flow uniformly

The sides of the intake entrance must be designed to minimize K losses due to rapidly changing the direction of the water and flow separation.

Trash rack approach must be designed to minimize K losses and flow separation

Provide a smooth transition from conveyance channel geometry to penstock geometry

Must be designed to reduce vortices

4.3.1 Intake Water Filtering

There are two main portions of filtering: debris management and sediment management.

4.3.1.1 Debris Management

Trash racks are used to limit the debris that enters the hydro power system. Usually this rack consists of more than one panel of bars. The number of panels needed to adequately filter the water will depend on the specific application. The material used depends on how much load will be exerted on the panel. If the load on the panels is sufficiently high it becomes necessary to use stainless steel. If the loading is not too extreme then it is permissible to use plastics, which have the added benefit of being available in airfoil shaped cross sections so as to reduce the head loss across the grate.

Another important parameter to be considered in the design of the trash rack is the spacing between the bars. Typically this distance is between 100-300 mm for the first panel and 12-150 mm [Layman's pg119] for the second panel. The upper range of bar spacing is for a low head high volume flow such as what is seen at Minors Millpond. Kirchmer's Equation (4.1) can be used to calculate the head loss across a trash rack which should be very small.

$$h_{screen} = K_t \left(\frac{t}{b}\right)^{\frac{4}{3}} \left(\frac{V_0^{\,2}}{2g}\right) \sin\Phi$$

Equation 4.1

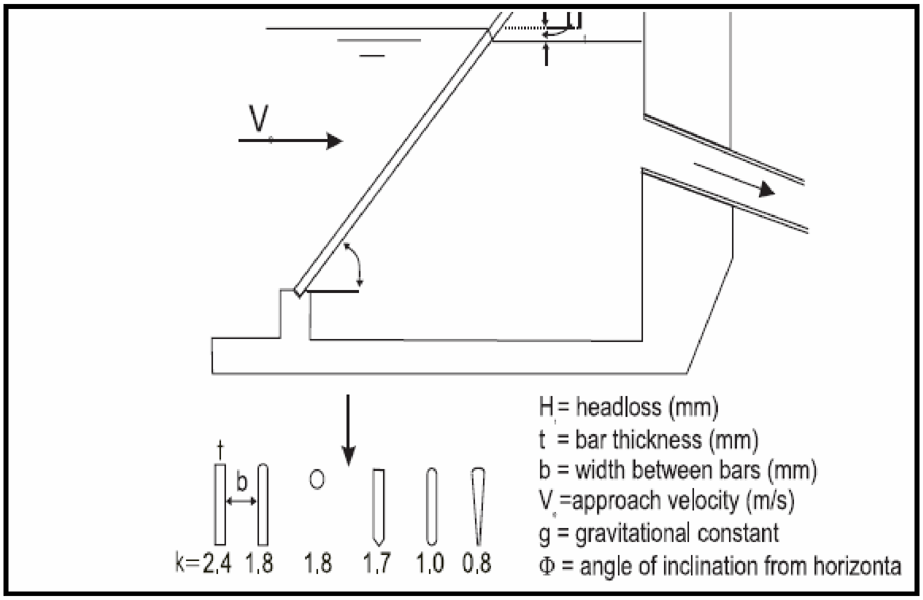

Figure 4.4 - Head Loss Parameters [6]

Cleaning the trash racks is an important task for two reasons. In some cases the trash rack will fill up quite often and generate a considerable amount of refuse that will need to be dealt with. Also the head loss across the grate will increase significantly if garbage accumulates on the bars. There are two basic options for trash removal: Manual and autonomous. Manual cleaning is an option for trash racks at a depth of up to four meters. A special above water platform should be installed to allow for easy cleaning of the trash rack if the manual cleaning option is chosen. If the Autonomous cleaning option is chosen then there are several designs available, the simplest of which is shown in Figure 4.5. In the pictured design, flexible rakes pull the trash from the trash rack and deposit it onto a conveyer belt at the surface for removal.

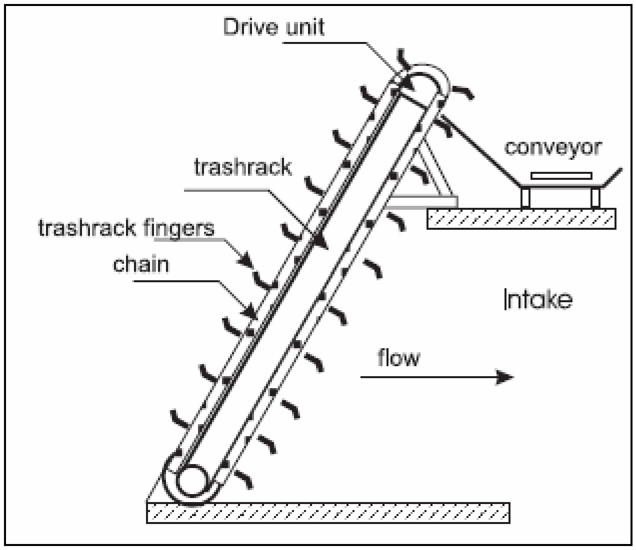

Figure 4.5 - Trash Rack Rake [6]

4.3.1.2 Deposition Management

Deposition begins in a flow where a quickly flowing fluid transitions from a high speed to a lower one. Deposition is especially problematic in the channels to connect an intake weir and a forebay. At the Minors Millpond site we have a large volume of roughly stationary water already. In this case most deposition that is going to occur has already happened. Therefore, it makes sense to not be too concerned with deposition, yet design the system in such a way that if deposition buildup becomes a problem it can be built into the system at a later date.

One difference between power and conveyance intakes is the degree to which the power intake must filter debris out of the water. All water that enters the power intake will go through the turbine, thus a well designed power intake can extend the life of the rest of the system.

4.3.2 Loss Minimization

Anytime fluid is rapidly accelerated there are energy losses. In the interest of reducing these losses it is important to pay close attention to the velocity profile of any transition taking place in the hydro power system. In the case of the intake at Minors Millpond there will be essentially stationary fluid sitting behind the dam accelerated to very high velocities inside the penstock. This liminal transition is susceptible to grievous losses if the transition point is not designed correctly

The research department of “Energy, Mines and Resources” of Canada has performed a study to compare the losses associated with extending the length of the intake and the savings associated with smoothing out the transition. the following quotation is a distilled version of their findings:

"The results showed that economic benefits increase with progressively smoother intake geometrics having multi-plane roof transition planes prepared from flat formwork. In addition, it was found that cost savings from shorter and more compact intakes were significantly higher than the corresponding disbenefits from increased head losses." [6]

A more quantitative result of this study (Fig. 4.4) is a determination of optimum scalable dimensions for a power intake. Note that the dimensions are given in a European standard format with commas as decimal points this is not really important since these results would be scaled down or up as needed for any given design. This design was found to have a K loss coefficient of 0.19.

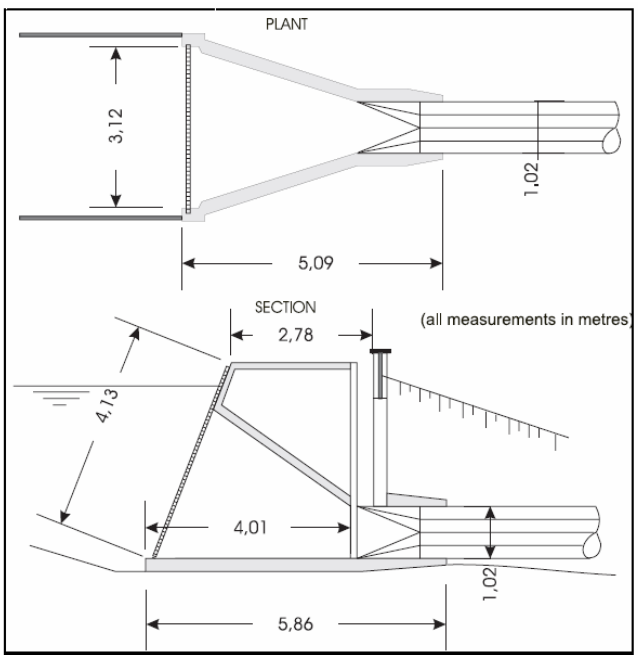

Figure 4.6 - Optimized Power Intake [6]

4.3.3 Precluding Vortices

A vortex is a turbulent rotational flow about an axis that can be observed in many natural systems. One common example is the swirling water leaving a bathtub drain. This is called a free or irrotational vortex and is common in situations where a fluid is being sped up to maintain a given mass flow rate, as is the case in the power intake.

Vortices have these adverse effects on a micro hydro system:
Create cavitation inside the turbine
Reduce the efficiency of the turbine
Introduce vibration
Increase the head loss of the intake
Entrain depositions back into the flow
Reduce the life of the turbine
The following factors increase the likelihood of vortex creation
Asymmetrical power intake sides
Power intake not sufficiently far below the surface of the water
Flow separation of any kind especially trash rack induced
fluid velocities in excess of 0.65 m/sec
excessive acceleration of fluid

Gulliver, Rindels and Liblom, of St. Anthony Falls hydraulic Laboratories, [6] provide the diagram in Figure 4.5 and suggest that if the parameters in Equation (4.2) are met, the vortex formation is unlikely.

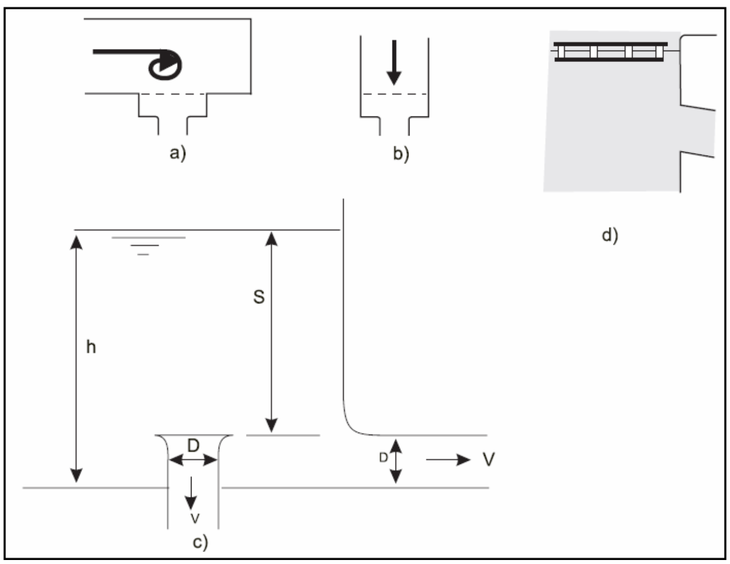

Figure 4.7 - Vortex Reduction Parameters

$S > 0.7D$ and $N_f = \frac{V}{\sqrt{gD}} < 0.5$

Equation 4.2

4.4 Gates and valves

Maintenance is necessary on all turbine setups, whether for repair or preventative. Flow to the turbine must be first cutoff to the turbine to do this. This is typically done through the use of gates and or valves located before the turbine. When determining the gate or valve to be implemented, it is important to make sure that all of the pressure created from the flow can be withstood.

Ball and butterfly valves are usually used to cutoff and regulate flow in the penstock. Ball valves (Fig. 4.6) produce minimal pressure loss when fully open, but tend to become very expensive as the penstock diameter increases. Butterfly valves (Fig. 4.7) consist of a rotating flange. Because they are used in many areas of industry, they are less expensive. However, since the flange stays in the flow, the pressure loss is greater than that of the ball valve.

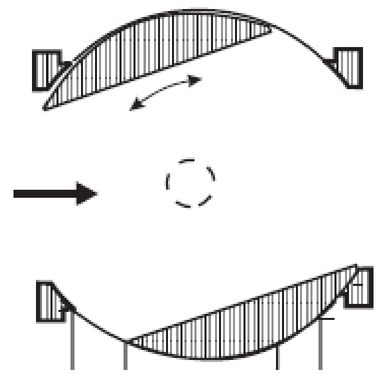

Figure 4.8 – Ball Valve [6]

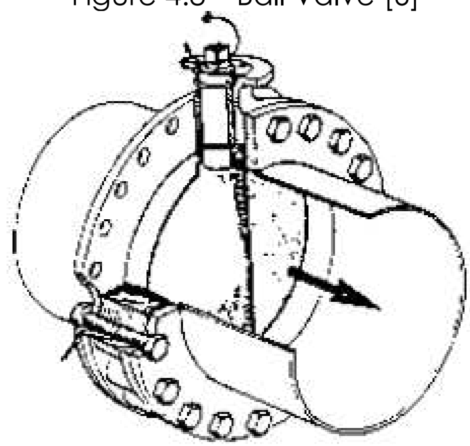

Figure 4.9 – Butterfly Valve [6]

Gates are used to cut off the flow to the power intake. This stops all flow through the penstock, allowing any maintenance that may be necessary. Gates typically slide up and down in tracks and can be operated electronically or simply by hand. Figure 4.8 shows a small hand actuated gate used for low pressure systems, and Figure 4.9 shows a much larger gate that must be opened using an electric motor.

Figure 4.10 – Hand Gate [5]

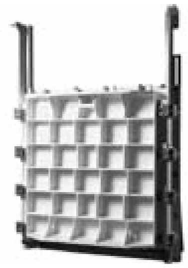

Figure 4.11 – Cast Iron Slide Gate [5]

4.5 Penstock

The purpose of the penstock is to transport the water from the forebay to the turbine. This can done using several different materials. Depending on the site, the penstock can take up as much as 40% of the total cost. Material selection must therefore be considered to minimize cost as much as possible while still keeping safety in mind.

When deciding what material to use, many factors must be taken into account. Corrosive environments, freezing temperatures, and ease of installation and assembly all depend on the site. High density polyethylene (HDPE) resists corrosion better than steel, but can withstand less pressure. If there are high changes in temperature, pipe length can change significantly. Expansion joints and anchor blocks (Fig. 4.10) must be used to compensate for this fluctuating length.

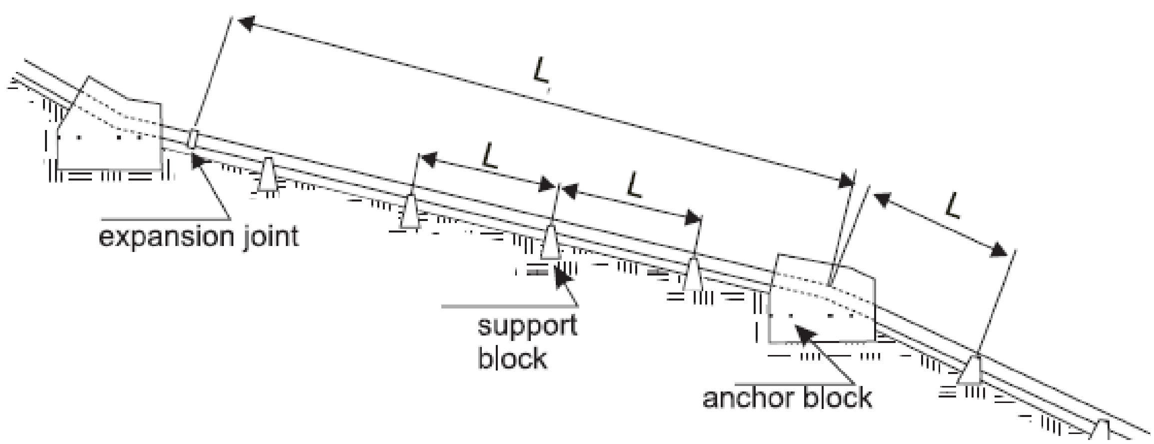

Figure 4.12 - Typical Penstock Support Layout [6]

It is preferable to bury the penstock. This reduces the likelihood of freezing damage and environmental impact. Burying can also eliminate the need for expansion joints, support blocks, and anchor blocks.

Diameter plays a key role in the losses from the penstock. By increasing the cross-sectional area of the penstock, the water velocity will decrease. With a decrease in velocity, there will be a decrease in friction losses; however there will also be an increase in cost of the penstock. Figure 4.11 shows a typical graph used to optimize the diameter of the penstock.

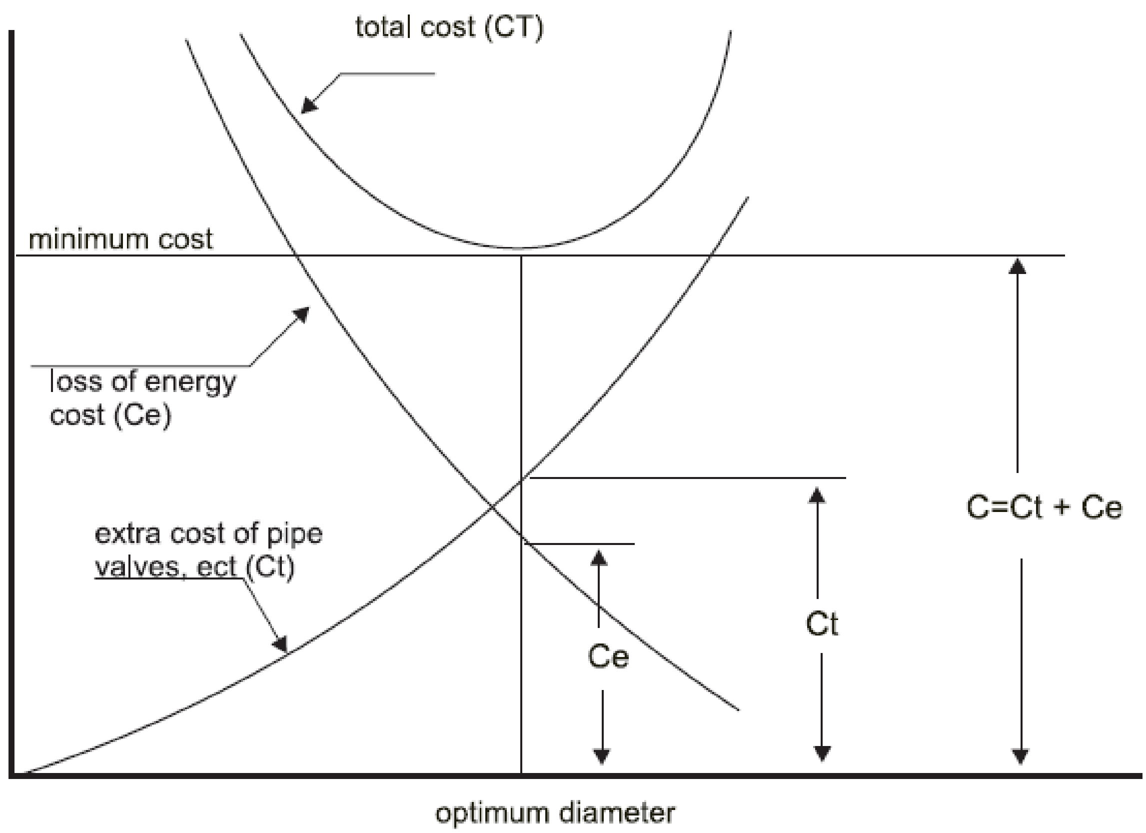

Figure 4.13 - Diameter Optimization [6]

The hydrostatic pressure created from the head must be determined so that a suitable wall thickness can be determined. This pressure is given by Equation (4.3).

$$\text{Pressure} = \rho \cdot g \cdot h$$

ρ = density of water
g = acceleration due to gravi
h = head

Equation 4.3

With the pressure calculated, the minimal wall thickness can then be calculated from Equation (4.4).

$$t = \frac{P \cdot D}{2 \cdot \sigma}$$

t = wall thickness
P = hydrostatic pressure
D = diameter
s = allowable tensile stre

Equation 4.4

A great deal of pressure can be created from the rapid opening or closing of a governing device such as a valve. This sudden pressure wave is called a waterhammer. Calculations must be done to determine, in the event of a waterhammer, whether or not the penstock can withstand the impulse. The Equation for the pressure wave created is simplified in Equation (4.5).

$$c = \sqrt{\frac{10^{-3} \cdot G}{1 + \frac{G \cdot D}{E \cdot t}}}$$

c = pressure wave (m/s)
G = bulk modulus of water ($2.1x10^{9}$ N/m^{2}
E = modulus of elasticity of penstock mate
D = penstock diameter
t = penstock wall thickness

Equation 4.5

5 Turbines

A turbine is a mechanical device that obtains energy from a fluid flow. Essentially, a turbine can be thought of as a reverse fan; drawing energy from the fluid that flows past it, instead of using energy to cause a fluid to move. Water turbines, also called hydro turbines or hydro-electric turbines, extract energy from moving water and convert it directly into electricity by means of a generator. A *micro-hydro* turbine is a turbine that typically generates less than 100kW of power. In the past, similar devices called *water wheels* (see Figure 5.1) were used to draw energy from water; with the energy extracted being purely mechanical in nature.

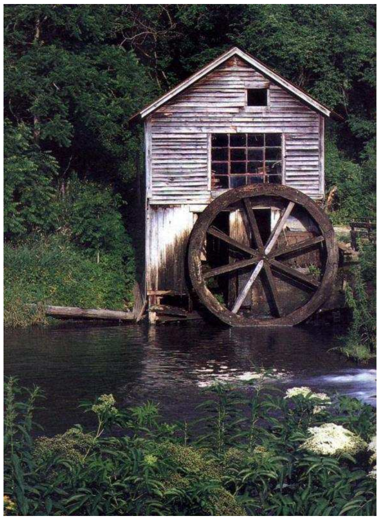

Figure 5.1 – A Water Wheel [11]

The potential and kinetic energies contained in a water flow can be expressed by two terms. The head, or distance that the water can "fall," is the pressure in the water, and a measure of the potential energy in the water flow. The velocity of the flow, when multiplied by the mass of the water flow, is the mass flow rate, and a measure of the kinetic energy of the flow. Hydro-electric generation can only take place when there is an explicit distance that the water flow falls. [6] Thus, we do not only desire a large flow of water for power generation, but also an area where there is a measureable distance that the flow will fall. The spillway of a dam is an ideal location for a hydro-electric turbine due to the ease of measuring the height of the fall and the concentration of water flow in that area. An example of gross head can be seen below in Figure 5.2:

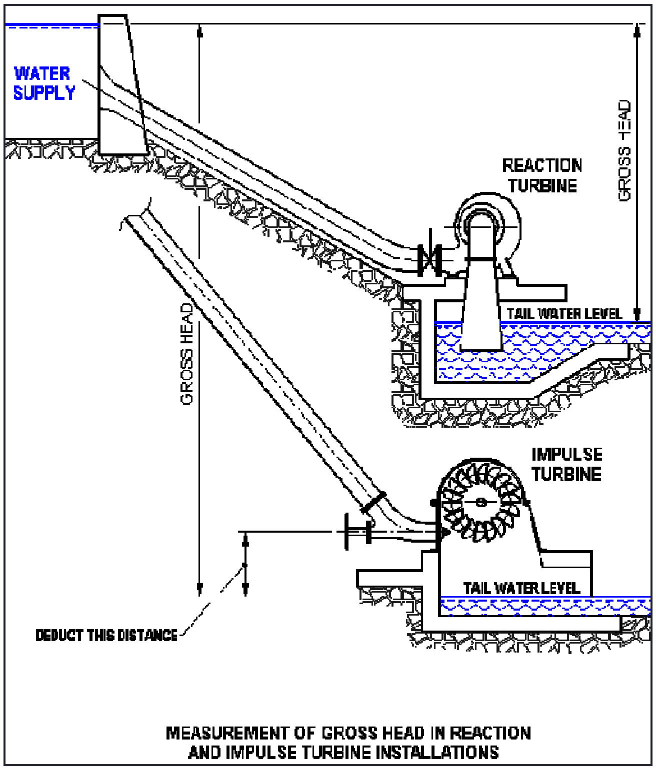

Figure 5.2 [6]

Micro-hydro turbines can extract power in two different ways. An *impulse* turbine converts a high head flow into a jet of water. This jet is directed onto the blades of the turbine which are shaped like cups. The force of the jet hitting the blades turns the turbine and strips the jet of its kinetic energy. So, an impulse turbine converts the water's potential energy to kinetic energy in the jet, then the water's kinetic energy into kinetic energy in the spinning turbine. The blades of this turbine are open to the outside atmospheric pressure and are simply struck by the high velocity flow.

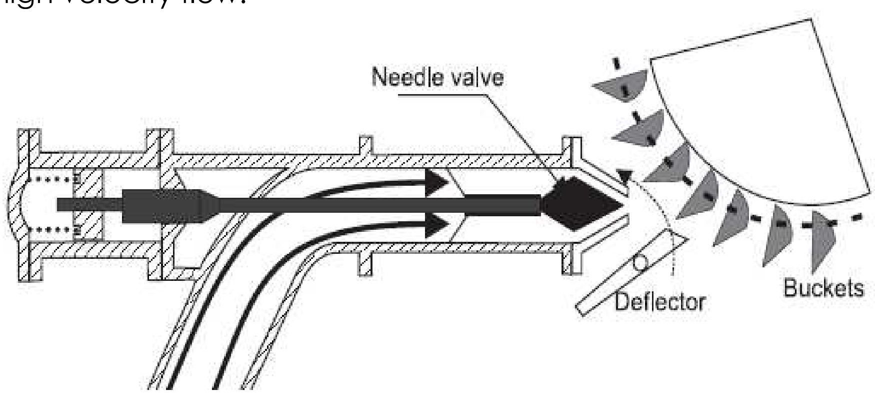

Figure 5.3 – Impulse Turbine Jet Configuration [6]

Consequently, a *reaction* turbine creates power by "reacting to the fluid's pressure or weight" [16]. These types of turbines look and operate much more like reverse fans. Essentially, this type of turbine extracts energy from the water by lowering the water's pressure as it passes through the turbine. The blades in this type of turbine are closed to the outside pressure and are fully immersed in the water flow. A *casing* is used to direct the water flow through the turbine and to contain the pressure of the flow.

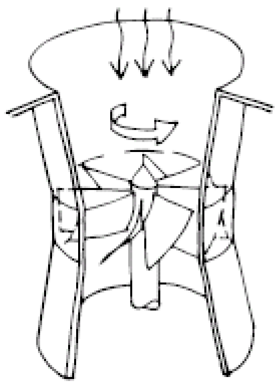

Figure 5.4 – Reaction Turbine [6]

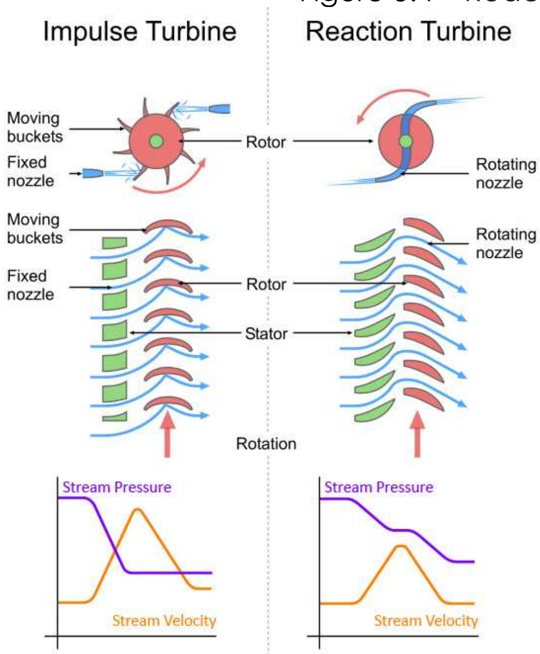

Figure 5.5 – Comparison of Impulse and Reaction Turbines [16]

Though impulse and reaction turbines are the two most widely used methods of obtaining energy from water, there is another version which is a hybrid of the two. Called a *Crossflow* turbine (or a Banki-Michell, or an Ossberger turbine), it converts energy from both the kinetic energy of water flow *and* the pressure loss of the flow. It does this by forming the flow, at the entrance of the turbine, into a rectangular jet (much like an impulse turbine) and forcing this jet onto the blades of the turbine. The orientation of the turbine axis is perpendicular to the flow, and the turbine itself is hollow. Therefore, after the flow has struck the blades of the turbine, it falls through the center axis and strikes the blades again on the bottom side of the turbine. This imparts a loss of pressure in the flow and thus imparts more energy into the turbine (much like a reaction turbine).

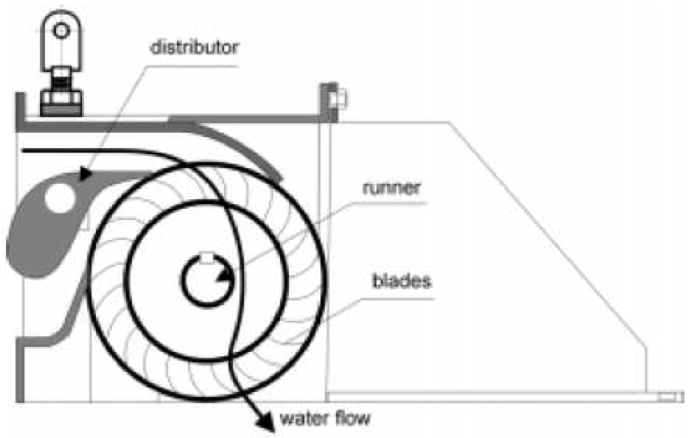

Figure 5.6 – A Crossflow Turbine [6]

5.1 Turbine Selection

The process of choosing the right turbine for a particular situation is a very important step. This process, though not as simple as it sounds, boils down to measuring the head and the flow rate of the water flow. Because impulse, reaction, and Crossflow turbines' particular power outputs and capacities vary greatly with differing heads and flow rates, it is very important that these measurements be as accurate as possible. Please refer to Section 2 for information on how we obtained these measurements for the site.

Since there arises a large difference in the efficiencies of impulse and reaction turbines with relatively small differences in the head, and since too large of a flow is not necessarily a limiting factor (since part of the flow can be diverted), the head measurement becomes the predominant factor in determining the type of turbine that is preferable. Impulse turbines generally require high pressures to create an efficient jet of water so they work best with high heads (≈30+ meters). They do not require a large flow, though if the flow is too large, some of it may have to be diverted. Reaction turbines, however, have practically no limit on the flow rate, but work better with lower heads (2 to 350 meters). Crossflow turbines work with a comparable head to reaction turbines (3 to 250 meters) but do not necessarily have the same generous flow capacity ceiling, especially with higher heads.

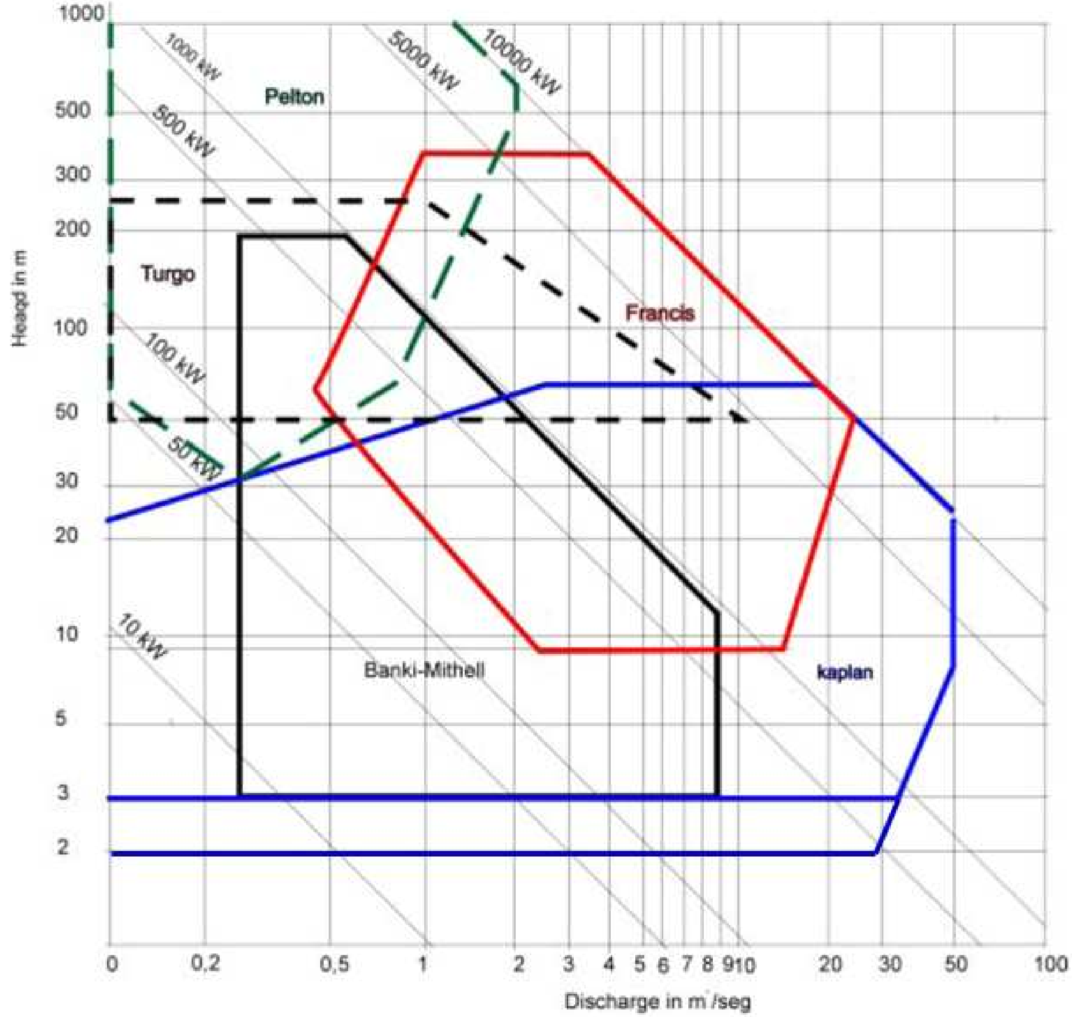

Figure 5.7 – Selection Chart for Micro-Hydro Turbines [6]

If we compare the calculated data from the site and from historical records with the Figure 5.7, we can narrow down the potential candidates for a suitable turbine. Taking our data (see Sections 2 and 3 for the complete data breakdown and analysis), we can see that our head, before any losses due to piping, trash racks, etc., will be approximately 3 meters. Our average expected flow is about 0.566m^3/sec, but will vary due to seasonal rain/drought. From a preliminary standpoint, we can see from Figure 5.7 that the two potential turbines that correlate to this data are the Banki-Michell, or Crossflow turbine, and the Kaplan reaction turbine. Impulse turbines (the Pelton and Turgo turbines) will not work with our site due to our low head. For the sake of completeness, we will also compare the positives and negatives of a standard propeller turbine, along with a classic water wheel.

5.2 Turbine Candidates

5.2.1 Kaplan

The Kaplan turbine (shown in Figure 5.8) was invented in 1913 by Austrian professor Viktor Kaplan. It is used in predominantly low-head, high-flow situations. [16] It is an axial-flow turbine, which means that the flow of water moves in the same direction as the axis of the rotating blades. It is one of the most widely used propeller-type turbines in the world, and is used in many larger hydro-power production plants. [16]

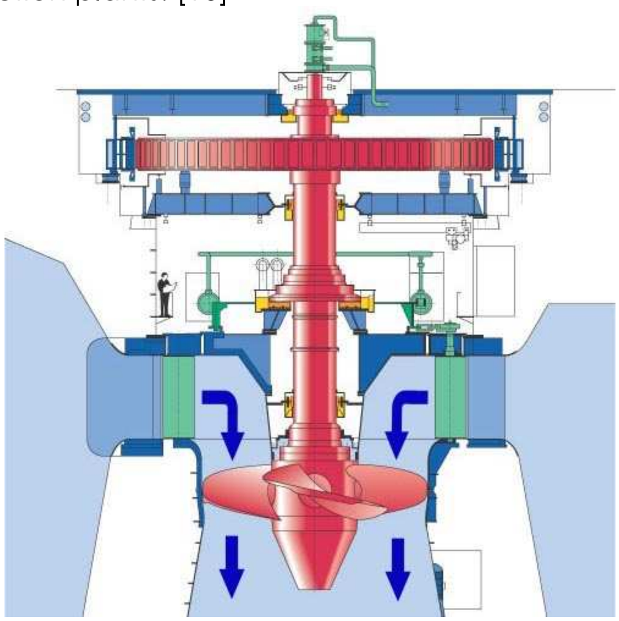

Figure 5.8 – A Vertically Oriented Kaplan Turbine [16]

The main innovation that the Kaplan turbine employs, however, is the use of adjustable blades. This allows it to remain optimally efficient for a wide range of flow rates, which is important in areas that have seasonal wet and dry conditions. The efficiency of Kaplan turbines is typically over 90%, but may be lower in low head applications. [16]Of course, the optimum efficiency of a Kaplan turbine depends on a number of factors, but the manufacturer will usually state an expected efficiency for a specific head within one or two percentage points.

Since the Kaplan is a reaction turbine, it makes power by "reacting" to the pressure of the water that is flowing past it. In a physical sense, the weight of the water pushes past the blades, which are shaped like airfoils, and causes them to turn the turbine. As the water moves through the turbine, its pressure is lowered, imparting kinetic energy to the rotating blades. Because this type of turbine relies on pressure to operate, the blades are contained in a tube and fully immersed in the water. The tube expands at the exit of the turbine to allow the water to slow down, thus imparting more kinetic energy onto the turbine. This *draft tube* also creates suction at the exit of the turbine, keeping the water flowing and increasing the efficiency. As long as the draft tube remains full of water, the turbine does not need to be located at the lowest point to maximize head. That is, head can still be measured from the difference of the surface heights between the inlet source and the outlet source.

Referring back to Figure 5.7, we see that the Kaplan turbine fits our criteria very well. Its minimum head is about two meters (but can go as low as two feet in some micro-hydro applications), where our head is just about 3 meters. Also, the flow rate range of a typical Kaplan micro-hydro turbine is 0 to 50m^3/sec, which encompasses the site's average flow rate of 0.24m^3/sec (usable).

The negative attribute of the Kaplan turbine is its cost. It can range anywhere from $10,000 to $50,000 for the turbine itself, depending upon the application. The reason for the high cost has to do with the variable blades of the turbine; i.e. the associated complexity and control features that are associated with this aspect of the device.

From a purely functional standpoint, negating the high cost, this may be the best possible turbine for the site.

5.2.2 Crossflow (or Banki-Michell/ Ossberger)

The Crossflow turbine was invented by an engineer named Michell, who obtained a patent for it in 1903. Around the same time, a Hungarian professor named Donat Banki unknowingly re-invented the same turbine at the University of Budapest. Since then, the turbine has been manufactured almost exclusively by a company called Ossberger in Bavaria, Germany. [14] Thus, the reason for its varied names.

The design is a very simple one in comparison to other hydro turbines. For this reason, they can be very cheap compared to Kaplan turbines (on the order of 10% of the cost, or less) and many micro-hydro users today even fabricate their own from easily obtainable materials. Its efficiency also remains constant over a wide range of flows and heads (o.3m^3/sec to 10m^3/sec, and less than 2 meters up to 200 meters respectively) at around 80%. [6] Its efficiency is much less than the Kaplan turbine, but its cost more than makes up for the shortcoming. Therefore, this type of turbine is very popular for enterprising and resourceful individuals who wish to generate electricity from water at the absolute lowest cost.

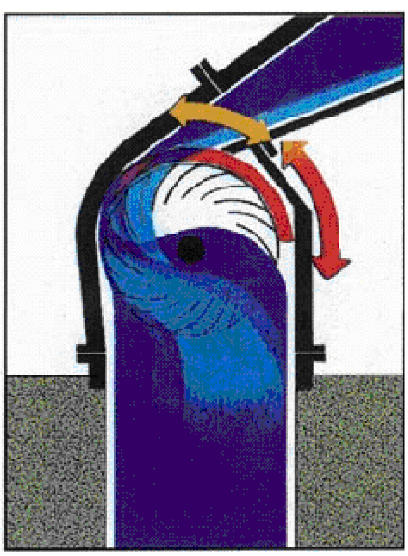

Figure 5.9 – A Crossflow Turbine in Action [15]

Many have this type of turbine classified as an impulse turbine, which is incorrect. It is actually *both* an impulse and reaction turbine, and can function as only one or the other in certain flow situations. At lower flow rates, the *gate*, or adjustable opening at the entrance of the turbine, can be moved to increase the pressure of the incoming stream, and thus cause the turbine to function more like an impulse turbine. When the flow is sufficient to fill the gaps between the blades, the gate can be opened to allow more water through and cause the unit to function more like a reaction turbine, with the water having a lower pressure at the exit than at the entrance of the turbine. [14]

The Crossflow turbine is well within our range of flow. However, the head that we have available at the site may be borderline for what is acceptable. Since this type of turbine is usually built to accommodate the site's characteristics, it is feasible though that this turbine could be made to work quite well. Though the efficiency is not as high as the Kaplan, the significantly lower cost could outweigh this factor.

If cost is the limiting factor in the decision, the Crossflow is the best candidate.

5.2.3 Propeller

Propeller turbines are essentially Kaplan turbines without adjustable blades. Much of the same design and science goes into this turbine as the Kaplan. They work with little to no head and large and small flow rates. Since the propeller turbine does not have adjustability, it does not have the same flexibility when it comes to variable flow conditions and it also has a much lower efficiency. However, these negatives can be outweighed by its lower cost and ease of installation in comparison with the Kaplan.

Figure 5.10 – A Tow-Behind Propeller Turbine [16]

Some variations of the propeller turbine are case-less; that is, they are not contained in a tube, nor do they have a draft tube. These variations are typically used in fast-flowing streams (called *Tyson* turbines) and on boats to produce power extra power, however due to their low efficiency; they cannot generate a large amount of power; generally on the order of hundreds of watts maximum. [16]

5.2.4 Water Wheel

Water wheels are the oldest methods for obtaining power from moving water. They have been in use from thousands of years ago, in Egypt and China, all the way to today. [17] They work on the basic conversion of water flow to mechanical work. Most of the recent use of water wheels has come from grist mills, which is, in fact, what our site once operated as. [16]

There are a few different configurations for water wheels, but they all work on the same principle: moving water is channeled into the side of a large wheel, which is fitted with numerous blades or buckets, and the force of the moving water causes the wheel to turn. Figure 5.11, below, shows the earliest version of the water wheel, called an *undershot water wheel*.

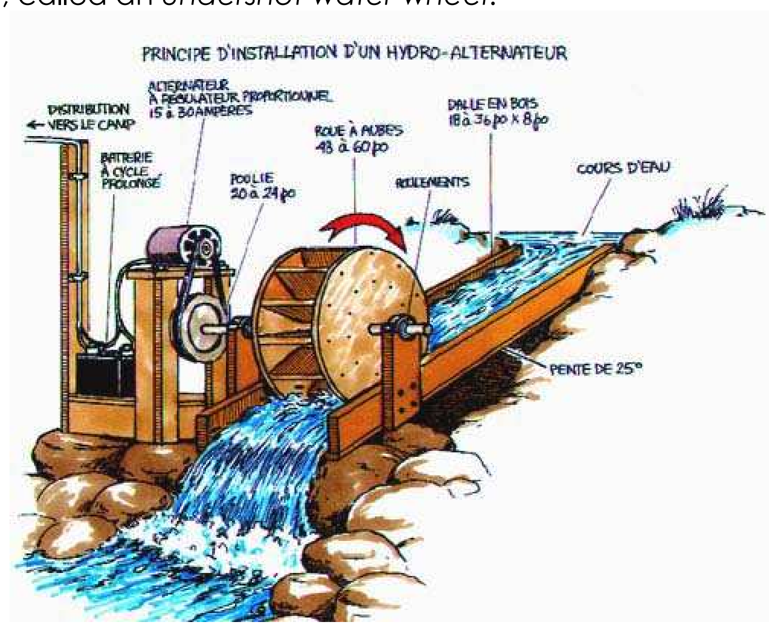

Figure 5.11 – An Undershot Water Wheel

The undershot water wheel directs the flow of water underneath the wheel, where it meets the wheel in one spot. This early type had very low efficiency and could not handle a very large flow rate. (Nor)

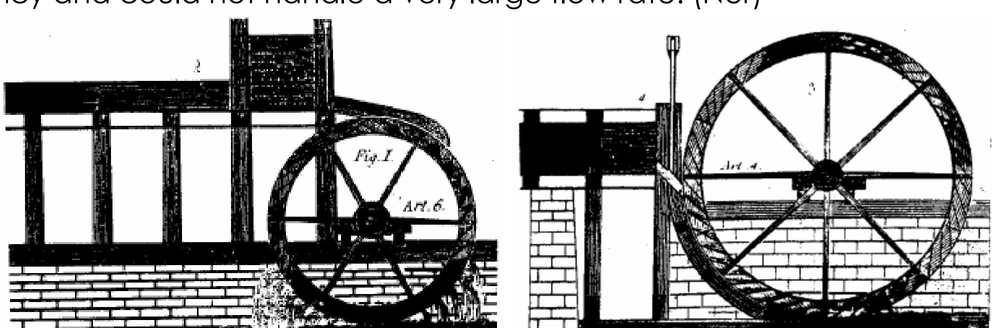

Figure 5.12 – An Overshot Water Wheel (Left) and Breast Water Wheel (Right) [17]

Figure 5.12 shows two advancements in the design of water wheels called *overshot water wheels* and *breast water wheels*. In the overshot design, water is directed over the wheel using a dam or elevated channel. For the breast design, water is directed into the midpoint of the total height of the wheel. These designs were able to extract much more energy from the water. Not only was the kinetic energy absorbed, but now the potential energy could be absorbed by collecting the water in the wheel and allowing gravity to pull it down. In the past, practically all water wheels were made of wood. Today, they are still constructed of wood, but some are also fabricated from steel and other metals and efficiencies of up to 85% can be obtained using these designs in an appropriate way. [17] The cost, however, may be a negative factor considering the size and material cost that would be necessary for such a large wheel.

6 Power Electronics

6.1 Generators

A generator is a machine that transforms mechanical energy created from a turbine into electrical energy. A generator is simply an electric motor that is being turned by some mechanical means rather than by electric current. This generates a voltage and can be thought of much like a turbine is a pump with water being forced through it. There are two main types of generators available today: Synchronous and asynchronous generators.

6.1.1 Synchronous Generators

In a synchronous generator, the stator typically has three windings each separated by 120 degrees. The rotor consists of either permanent or electromagnets. As the turbine drives the rotor, a magnetic flux is created. This flux produces a voltage drop across the stator windings, thus creating three-phase current. As the name implies, synchronous generators must rotate at the same frequency as the grid. The power grid typically runs at 60Hz, so a two pole synchronous generator would have to rotate at 60Hz or 3600rpm. Synchronous generators dominate large power plants due to their synchronizing torque which will keep several generators all at the same frequency. To maintain the constant rotation of one synchronous generator, expensive hydraulic controls or variable-speed constant-frequency systems are needed. Synchronous generators also require strong magnets that tend to be very expensive. Therefore, this type of generator is not typically used for smaller hydro sites.

6.1.2 Asynchronous Generators

An asynchronous generator, also known as an induction generator has a squirrel cage rotor that sits in the middle of the stator. This is what makes it different from the synchronous generator. The rotor (Fig. 6.1) is usually made up of aluminum rings connecting copper bars. When an alternating current is connected to the stator windings, a rotating magnetic field is produced. From the rotating field a very strong current is in turn induced through the bars (Fig. 6.2). Very little resistance is felt by the current, due to the short circuit created by the end rings. As a result, the rotor becomes magnetized.

Figure 6.1 - Squirrel Cage Rotor [13]

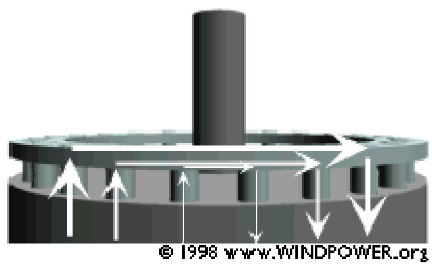

Figure 6.2 - Induced Magnetism [13]

The generator will function as an induction motor at this point and begin to turn just below the synchronous frequency of the power grid. This power from the grid is necessary to excite the generator before it can be used to create power itself. Figure 6.3 shows the torque created as a function of percent of synchronous speed. When turning at the synchronous frequency of the grid, the generator will produce no voltage. Once the load on the turbine causes the generator to spin faster than the grid frequency, a voltage drop will be made and current will be forced in the opposite direction. Because most electric motors are of this design, and can therefore be used as a generator, making the asynchronous generator much less expensive and more practical smaller power sites.

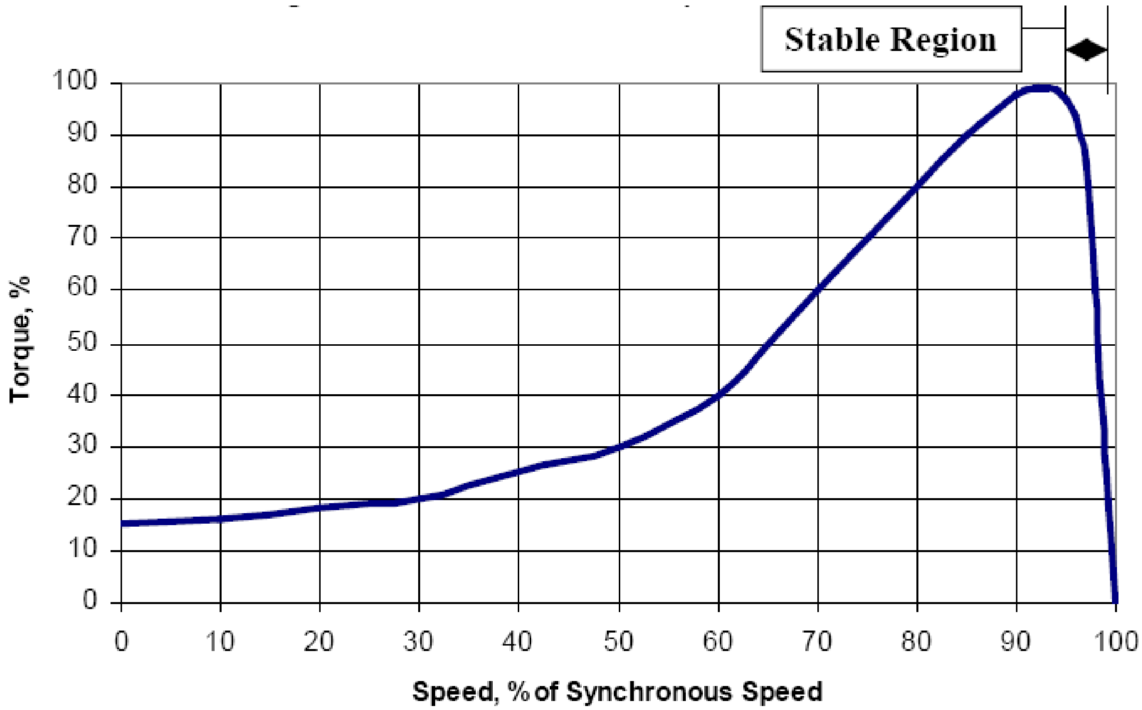

Figure 6.3 - Induction Motor Torque as a Function of Speed [10]

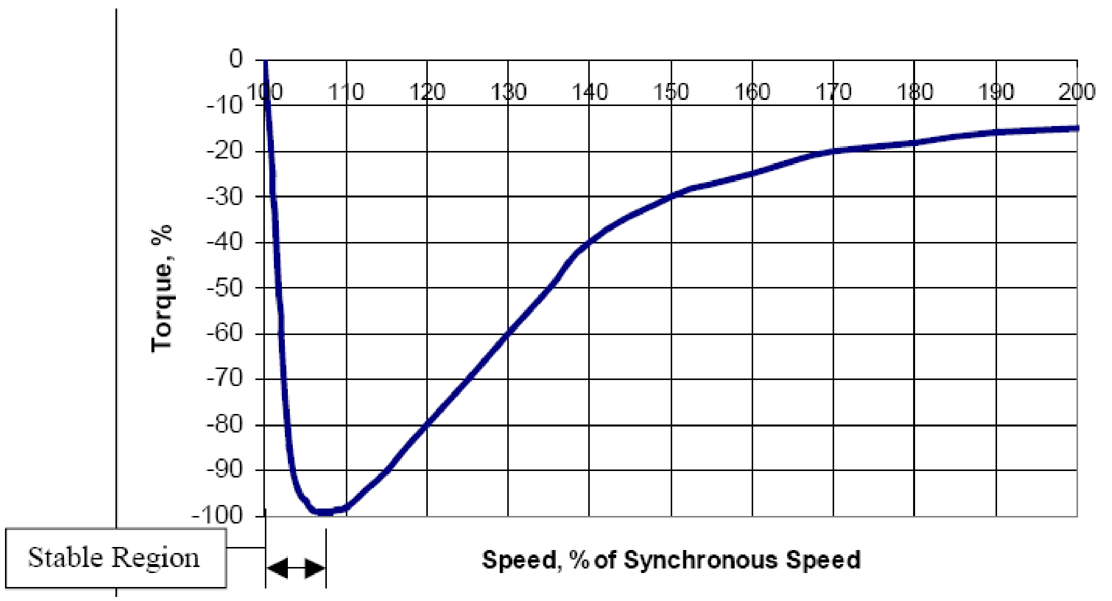

Figure 6.4 - Induction Generator Torque as a Function of Speed [10]

6.1.3 Generator Comparison

Each type of generator has benefits that make it ideal for a certain situation. As stated above, synchronous generators are typically used for larger power plants, where they are the main power source for the grid. There are several reasons for this. One reason for this is their ability to operate in standalone. It would not be practical to use an asynchronous generator for a large power plant because they cannot create their own reactive force. The synchronizing torque created by synchronous generators is another characteristic that benefits systems with many generators, but is has no effect when there is only one generator.

Asynchronous generators have a very small difference between the synchronous frequency and the frequency at maximum power. This creates less stress on the mechanical system, therefore making it very durable.

In general, as the power supplied to the grid become the dominating contributor, the synchronous generator is more feasible. A good rule of thumb for power plants is: 5000kVA and greater should use a synchronous generator. In the case of Minors Millpond, an asynchronous generator is the more practical choice because of the relatively low expected power, robust design and more a more economical price.

6.2 Drive System

It is important that the generator frequency is equal to that of the power grid (usually 60Hz ± 2Hz). If the turbine does not rotate at the required frequency, a drive system must be used to correct it. In the case where the turbine rotates at the frequency required, a direct drive can be used. This situation is ideal because there is less maintenance necessary, and virtually no losses. Unfortunately this is not usually the case. The speed required depends on the frequency of the grid and the number of poles in the generator.

$$\omega_{req} = \frac{2\omega_{grid}}{P}$$

P = number of poles in generator

ω_{grid}= 60Hz x 60s

Equation 6.1

From Equation 6.1, a two pole generator would need to have a speed of 3600rpm. For most turbine configurations, a speed that great is unrealistic. Therefore, most generators for hydro turbines have four poles, making the desired speed 1800rpm. Adding more poles can significantly lower the required speed of the turbine, but this also increases the size and cost of the generator. Achieving the desired speed can be done many ways. In most cases this is achieved by determining the necessary ratios of gear teeth (or pulley diameter) on the drive and driven shafts.

6.2.1 Belt Drive

Belts and pulleys are used frequently for machine transmission, making for very good part selection and price. V-belts can be operated at very high speeds and loads. Another trait of the v-belt is its low maintenance and ease of repair if maintenance is necessary. When properly aligned, there is negligible power loss. A drawback to this style is the possibility of creep or slippage.

Another type of belt drive is the toothed belt and sprocket (Fig. 6.1). This design is extremely efficient and used in many applications from car timing belts to motorcycle transmissions. Because the belt has teeth there is no slippage and can thus be used in systems where synchronism is a must. Toothed-belt systems tend to be more expensive than v-belts and are used primarily for turbine systems operating at less than 3kW.

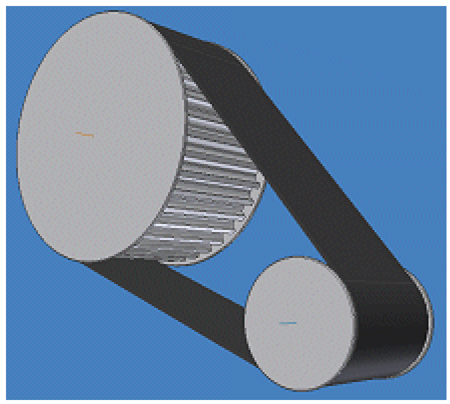

Figure 6.5 - Toothed Belt Drive [10]

6.2.2 Gearbox Drive

The gearbox is used in many applications, from industrial equipment to automotive transmissions. Gearboxes are efficient, durable, and precise. As long as the gears are kept properly lubricated, there should be no maintenance. Through the use of bevel gears, a gearbox also has the benefit of being able to change the axis of rotation. However, the design and construction of a proper gearbox can be very expensive, so they are generally only used for larger hydro turbines, where strength is imperative.

6.2.3 Drive System Comparison

Depending on the application, there will be a better choice for the drive system. Some decisions are more ambiguous than others. There is also the possibility of the need for a combination of two systems. However, given the calculated flow and measured head of Minors Millpond, a v-belt system will most likely be the best drive system because of cost and ease of maintenance.

7 Design Options

In the interest of bringing some practicality to the report, five of the top off-the-shelf options are being included for consideration. The head and flow rate at Minors Millpond puts it somewhere in the gap between micro and small hydro. This means that most of the micro-hydro off-the-shelf options are too small and too cheap to consider for a long term installation, and the head and flow are too small to be seriously considered by a large custom turbine manufacturer. Nevertheless, there are some promising options.

7.1 LH1000

The Low Head One Thousand is really at the bottom of the list in terms of aesthetics, quality and efficiency. It is included here because it is cheap and easy to install. The LH1000 can operate under a wide variety of flow conditions and has an output of 1000kW. This means that for the Minors Millpond site, it would be necessary to install no fewer than four.

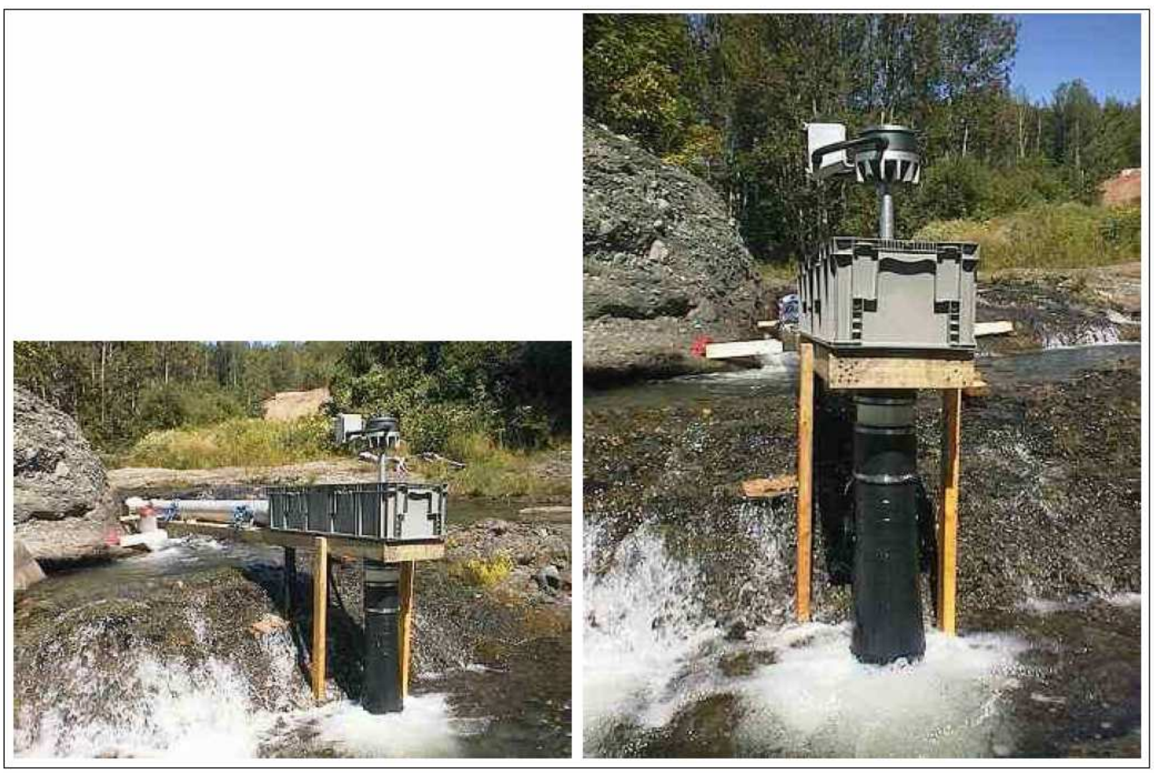

Figure 7.1 - Photographs the LH1000 in operation [Appendix C]

This option incorporates the generator, controller, turbine, and tailrace all in one small compact package. The runner in this turbine is a propeller type, so it would have good efficiency if it were optimized for our flow; which would be wishful thinking.

7.2 Voith Siemens Radial Axial Turbine

Voith Siemens was identified as a major manufacturer of turbines in the United States, having done a great job on some large projects with the Tennessee Valley Authority. Basically, these are the people you want to design your turbine. John Kinard in Chattanooga, TN is the area representative for Voith Siemens and he was contacted about this project. John suggested we look into propeller type Radial Axial turbines and he sent a brochure about their off-the-shelf small hydro options [Appendix C]. Like the low head 1000 this turbine has all the controllers and actuators and generators included. Unlike the Low Head 1000 the tubular axial turbine has a great efficiency which approaches the maximum possible efficiency of a turbine, and it has a much greater life expectancy around 50 years with good maintenance. Figure 7.3 shows the components of the tubular axial turbine.

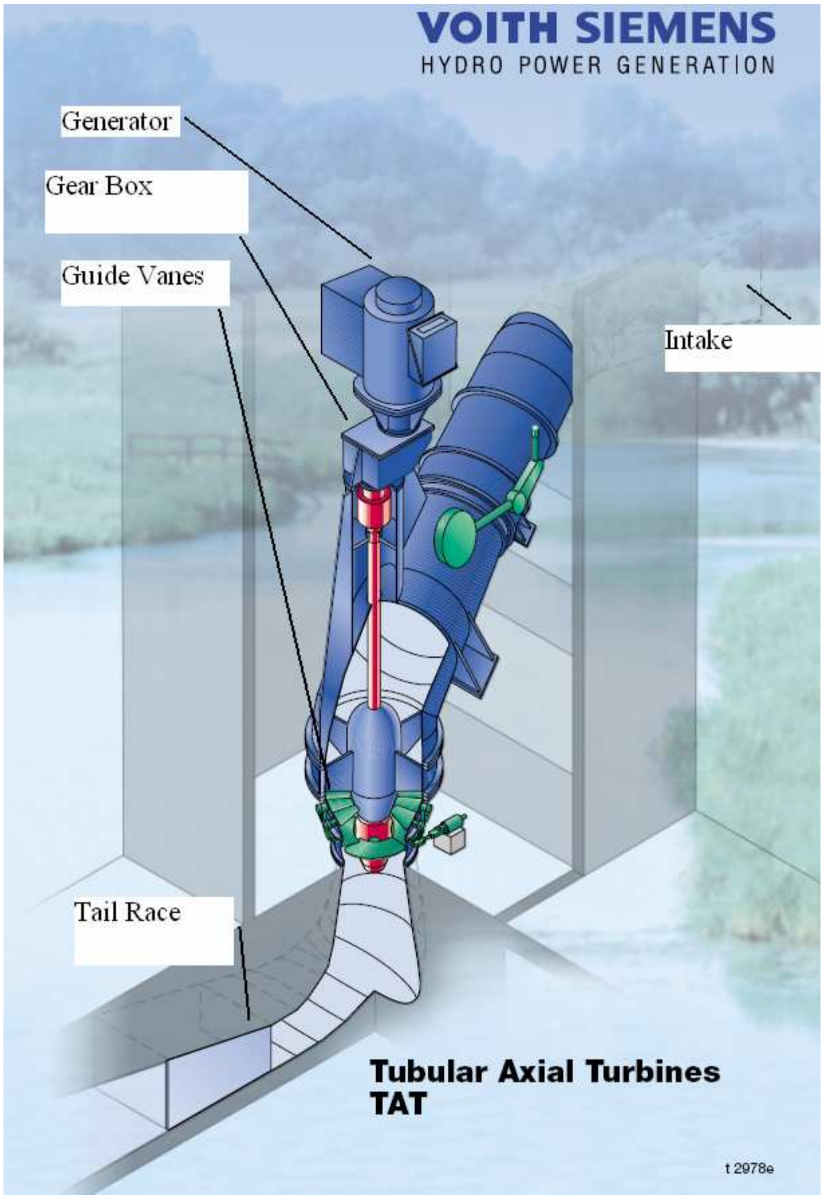

Figure 7.2 - Cutaway CAD of Voith Siemens Tubular Axial Turbine [12]

Referring to the Voith Siemens spec sheet [Appendix C] there are several options for the layout of the tubular axial turbine. It would be necessary to remove the timbers in front of spillway one and recast it with concrete so that the turbine could be built into the structure. This would require the design work of a structures specialist. Figure 7.4 shows the tubular axial turbine installed in a siphon setup as suggested in the hydraulic structures section.

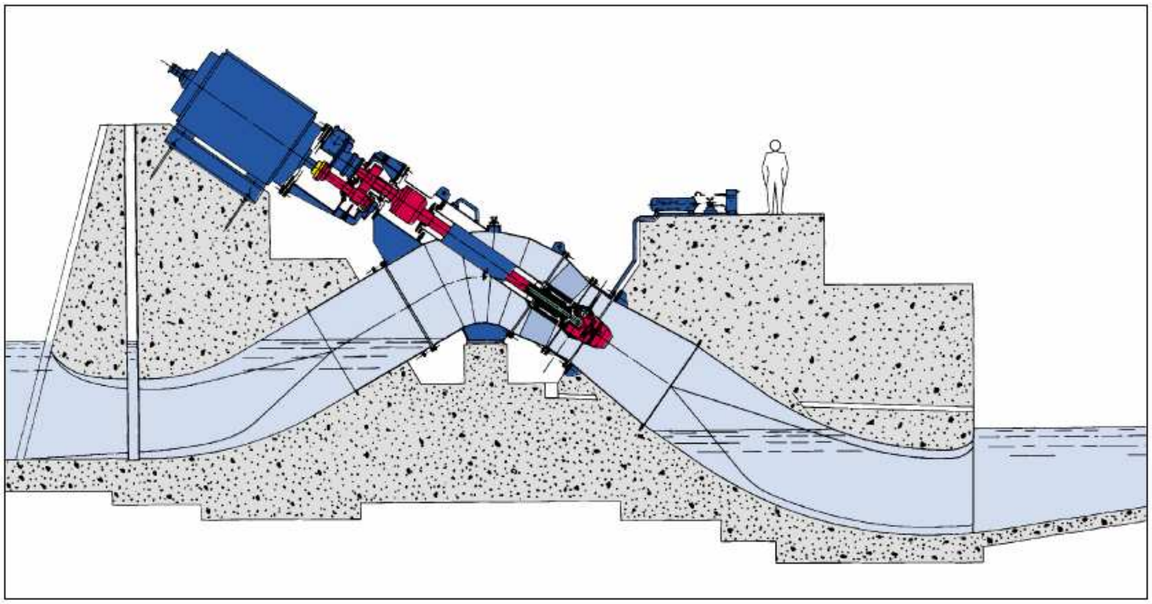

Figure 7.3 - Siphon Layout for Voith Siemens TAT [12]

The tubular axial turbine requires a minimum flow rate of 1.5 cubic meters per second. If we divert 2/3 of the average flow rate of panther creek and use it to run the turbine we would have 8.58 cubic feet per second which is 0.24 cubic meters per second. This is really not enough to run the tubular axial turbine in a constant flow scheme so if this were going to be used it would need to be in the intermittent scheme as discussed in the hydraulic structures section. In order to meet a minimum of 4 cubic meters per second and not drain the lake the turbine could only be allowed to run an average of 1.5 hours every day.

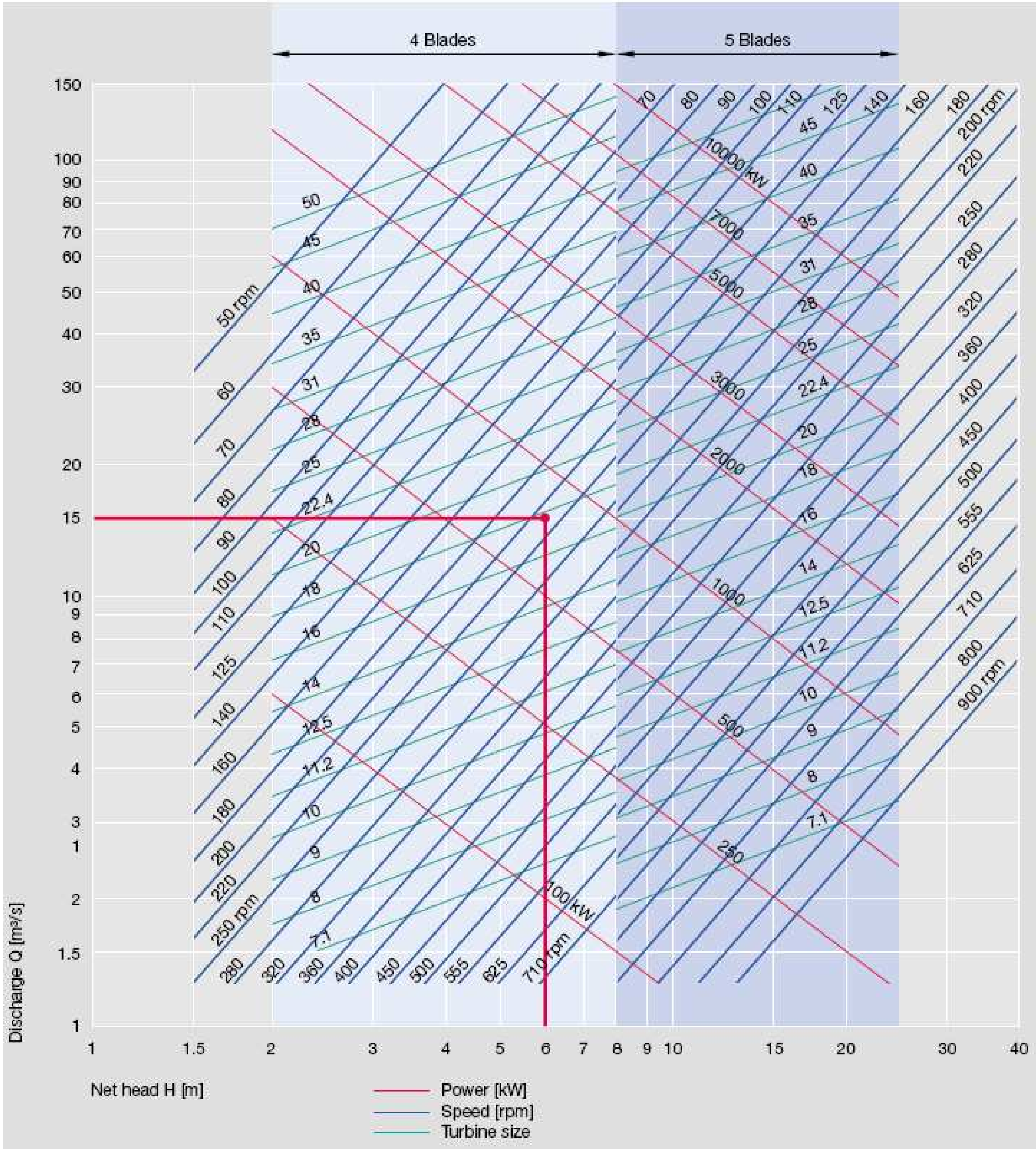

Figure 7.4 - Voith Siemens TAT Sizing Chart [12]

7.3 Water Wheel

Water wheels are the roots of hydropower, and the industrial revolution was built on their technology. They have a quaint appeal and if they are designed properly they can operate in the 85% efficiency range. There are three common setups.

Undershot Wheel: this type is simply set in a stream and the water hits the bottom to make it spin, these are the least efficient.

Breast Wheel: in this arrangement the water flows into the side of the wheel and causes the wheel to rotate clockwise if flow is right to left.

Overshot Wheel: this is the most efficient water wheel setup, the water flows over the top and is deposited at the top of the wheel causing it to rotate counter clockwise if flow is right to left.

7.3.1 Breast Wheel

A European manufacturer called Hydrowatt was discovered. These wheels are really beautiful pieces of workmanship that are also very functional

Figure 7.5 - Breast Wheel [Hydrowatt]

In a breast wheel configuration, the reservoir behind spillway one could be left as is and a wheel up to 20 feet in diameter could be installed. This would be a gorgeous addition to the old mill house at Minors Millpond especially if the house is to be restored to its former style.

Figure 7.6 - Breast Wheel in Action [App. C]

7.3.2 Overshot Wheel

The overshot wheel is the most efficient of the water wheels. Figure 7.7 shows an overshot wheel. The Water Wheel Factory is an American company that creates old fashioned functional water wheels. They have units across the nation, from Georgia to Idaho. This company could likely create any of the three types of wheels.

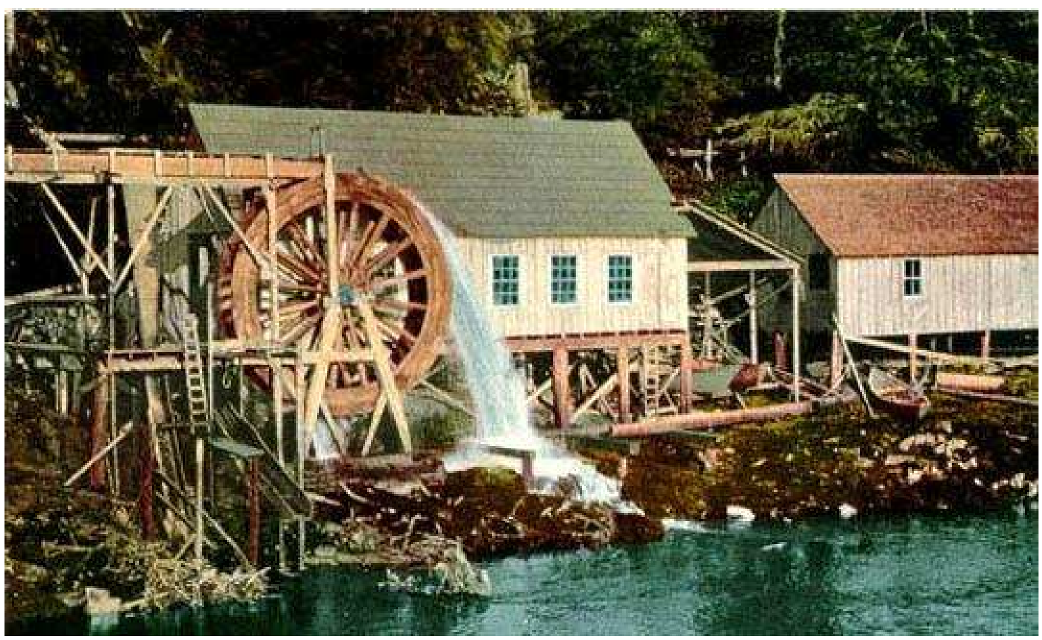

Figure 7.7 - Overshot Wheel

If an overshot wheel were installed at the Minors millpond it would be best left with a diameter less than 8 feet. That way, it could sit in the area under the flow and create power. Unfortunately, being set down like this would reduce the visibility of the wheel. If the wheel were not visible it would lose a lot of its appeal as a design option

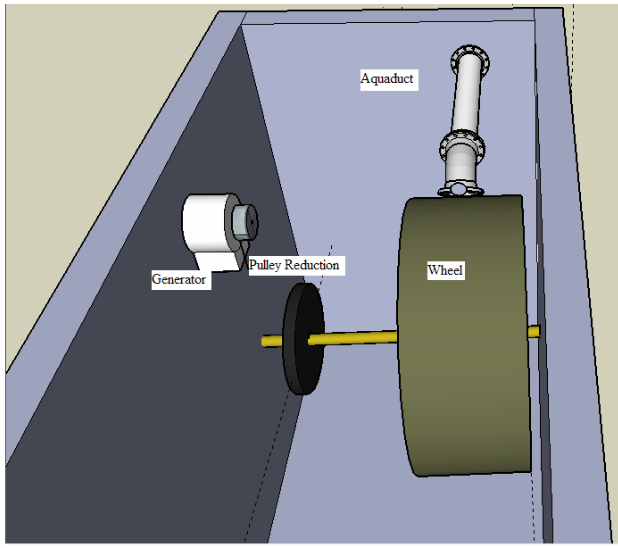

Figure 7.8 - Possible Layout For Overshot Wheel at Spillway One

7.4 Nautilus Turbine

The Nautilus turbine is a Francis-style reaction turbine manufactured by ABS Alaskan, Inc. There are two models of the Nautilus, one with a 8 inch runner and one with a 10 inch runner. The Minors Millpond site would likely benefit more from the 10 inch runner, due to the higher flow rate.

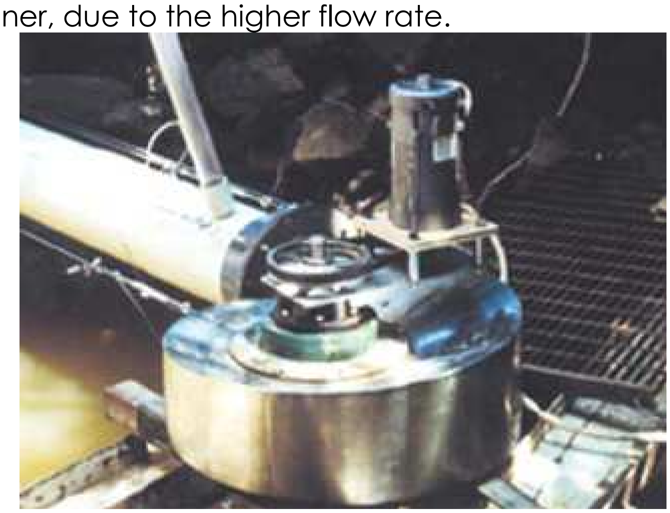

Figure 7.9 – Nautilus Turbine from ABS Alaskan, Inc.

The Nautilus incorporates both a penstock and a draft tube, increasing the suction in the turbine and thus creating more power and improving the efficiency. At a flow rate of 4.47 cfs, the Nautilus would produce 2510 W at an efficiency of 77%. Since this flow rate is about half of our calculated value, two Nautilus turbines would be required for the site.

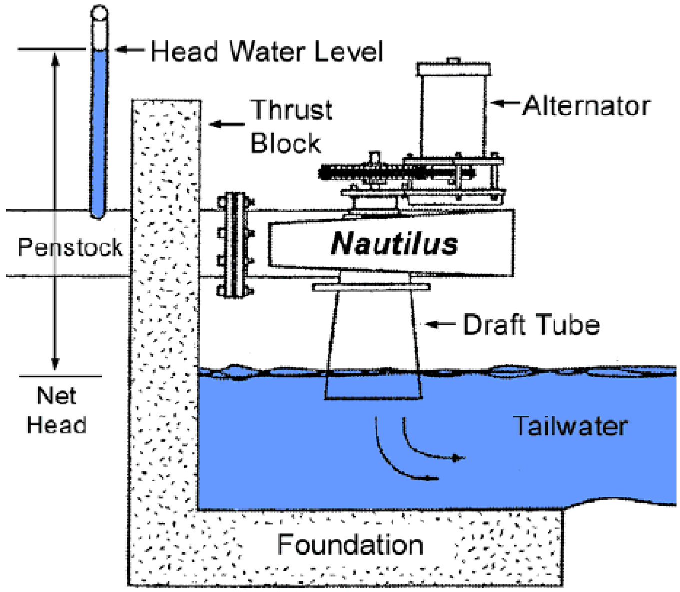

Figure 7.9 – Diagram of a Typical Nautilus Turbine Setup

The Nautilus' main shortcoming is its price: typically $11,000 each depending on the site specifics. Thus, the total cost of the two Nautilus turbines would be around $22,000.

7.5 Axial-Tubular Micro-Hydro Power Unit from U.C.M. Resita Research and Development

One last design is submitted, it is not strictly a product for sale, and it was discovered in the research and development page of U.C.M. Resita. This developmental turbine is of the tubular axial type just like the Voith Siemens. The difference between the Resita Turbine and the Voith Siemens turbine is the flow, where for the Voith Siemens turbine our flow is too small, with the Resita turbine the flow at Minors Millpond is too large and would need to be divided up between two units.

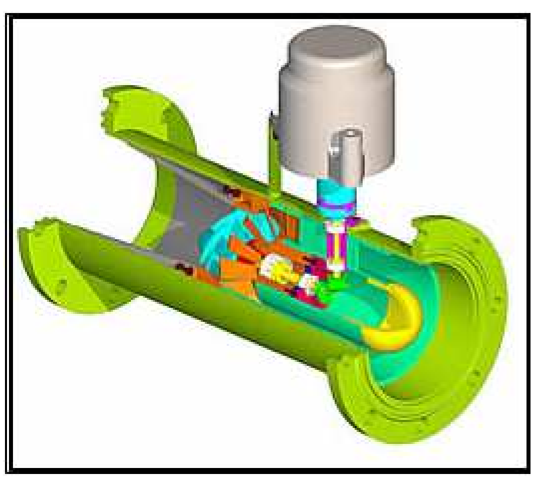

Figure 7.10 - U.C.M Resita Research Turbine

Installing the Resita turbine at Minors Millpond would be as simple as casting gates or valves into the bulkhead of spillway one and bolting on the UCM device.

8 Generation Type

8.1 System Types

When the appropriate turbine or water wheel has been selected the mechanical energy must be converted to electricity. There are several different systems and a variety of equipment to consider when connecting a renewable energy source to home or to a local utility. Battery based systems or "off the grid" systems allow for total independence from the utility and sends all electricity to a battery which can then be used for electricity needs. For this study it is clear that an "on the grid" system is desired because of the ability to send electricity back to the utility company and earn profit on an investment. The systems being analyzed are the grid connected battery operation system, grid connected system with out battery operation and Gridpoint ™ Connect Series a renewable energy appliance. (See Home Power Magazine, Mirco Hydro – Electric Systems Simplified, Appendix D)

8.1.1 Grid Connected Battery Operation

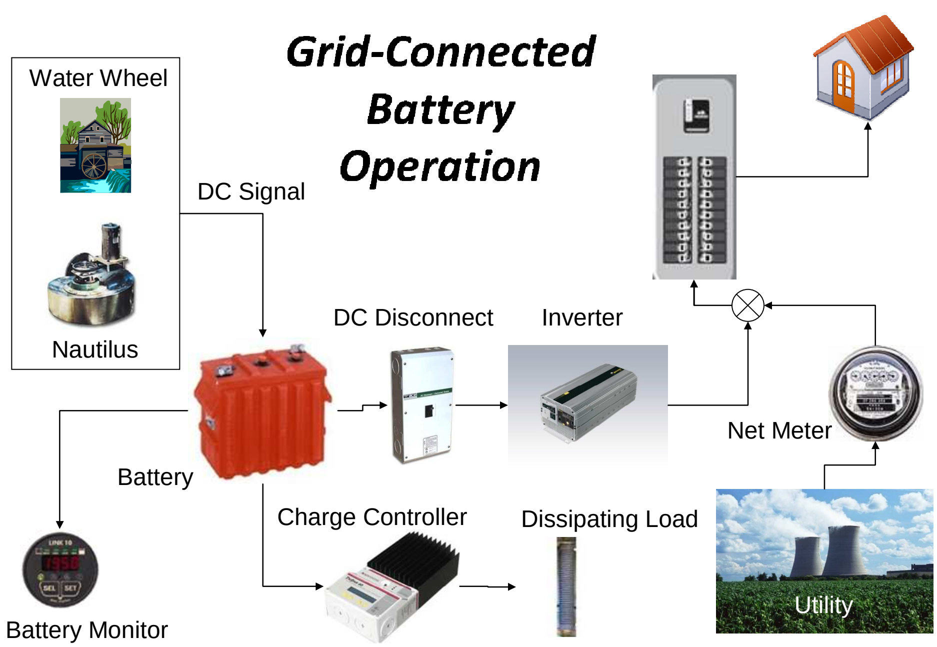

Figure 8.1

The system in Figure 8.1 shows connections required with a grid connected battery system. Whether coming from a water wheel or turbine a DC signal must be sent to the battery. For the water wheel this will require and alternator which has a built in rectifier to convert the generated AC signal to a DC signal. The specified turbines which convert mechanical energy into electrical energy use an alternator that outputs a DC signal. This eliminates an up front cost of an alternator for the turbine options but will be needed for the water wheel. The DC signal is then sent to the battery where, along with the batteries a monitor will be needed this way you can determine how much electricity the turbine is generating, the consumption of that energy and battery capacity. Now that the mechanical energy has been converted into electrical energy and stored the energy can be routed to the utility. Before that connection can be made several controls must be implemented in the connection for safety and circuit protection. A charge controller is connected with the battery operation to prevent overcharging of the batteries. In the event of a power outage excess electricity could be produced and the charge controller would absorb the excess energy to protect the batteries. The energy absorbed by the controller would be sent to a secondary dump load which is an electric resistance heater. Now the battery can be operated safely and the energy can be sent to the utility. In Figure 8.1 a DC disconnect and an inverter sit between the battery and the home/utility. The DC disconnect is there simply to disconnect the batteries and the inverter. The Inverter finally turns the DC signal to AC signal and sends that energy to the meter which is then sent to the home and/or back to the utility.

8.1.2 Grid connected system with no battery

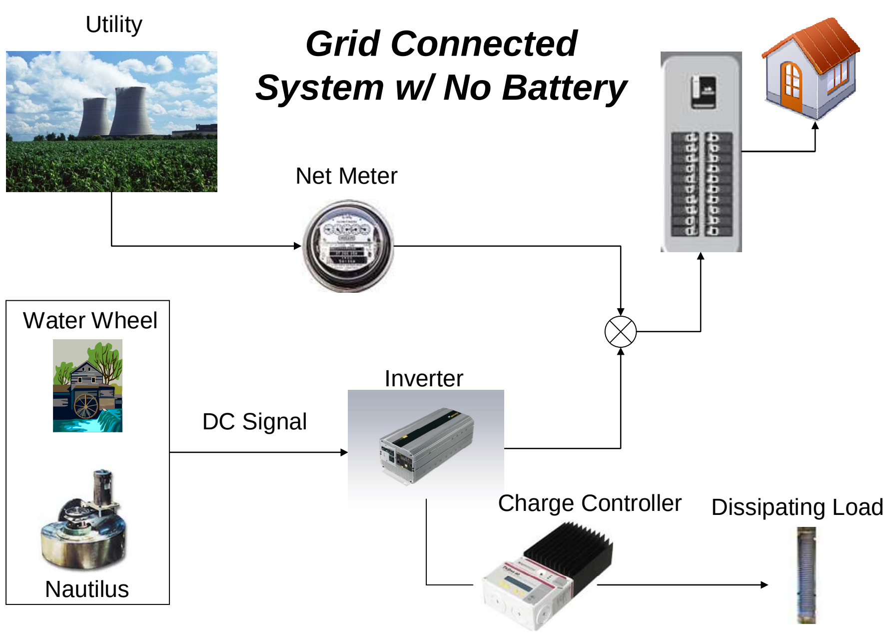

Figure 8.2

The grid connection with out the battery is somewhat simpler and cheaper because of the lack of batteries. Figure 8.2 shows the water wheel and the turbine output as a DC signal. As in the pervious setup an alternator would be required at the turbine. The DC signal is then inverted to AC and is sent to the home or to the utility. The Charge controller is still necessary in this setup up to protect the system in the event the grid shuts down. The system is simple and cheap, but has drawbacks and is less flexible which will be discussed in a later section.

8.1.3 GridPoint ™ Connect

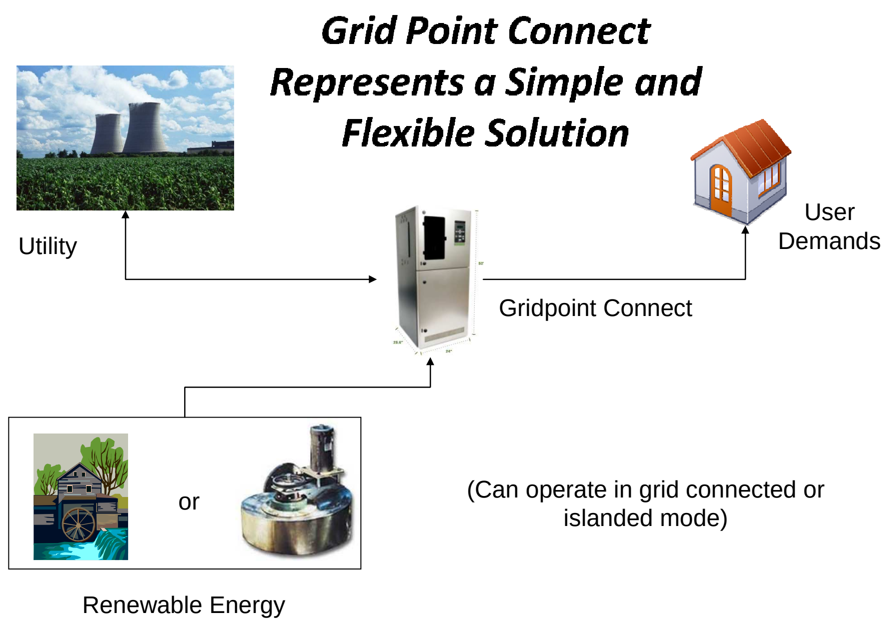

Figure 8.3

GridPoint ™ Connect represents a simple and flexible solution for all our connections. GridPoint ™ claims, "The GridPoint ™ Connect Series is the first appliance to easily integrate renewable energy sources, automatically increase energy efficiency and provide clean, instant, reliable backup power." This renewable energy appliance is an all in one system to integrate all your needs for renewable energy connections. It includes an integrated inverter so that it can accept a DC signal, power electronics, high-capacity batteries, and circuit protection. This system allows the user to control and monitor their energy consumption and production. Because the GridPoint ™ has batteries power outages are also eliminated. The main advantage of this system is that a, "plug and play" allowing simple and very efficient connection to the grid and to your home and it is only the size of a refrigerator. The GridPoint ™ Connect Series is currently available for photovoltaic systems but should be adaptable to hydro power because it requires a DC input make this a feasible solution for generating power. Figure 8.3 shows a simple connection that the pervious options had in several different components. (For more information on GridPoint ™ see Appendix C)

8.2 Cost analysis

The following charts show the estimated prices and quantities of each component for all of the represented generation types.

Grid Connected Battery Operation			
Item		Quantity	Cost($)
Alternator		1	2,100
Battery		2	2,540
Battery Monitor		1	250
Charge Controller		3	654
DC Disconnect		1	329
Dump Load		5	1,000
Inverter		4	1,600
Total			8,473

GridPoint Connect Series			
Item		Quantity	Cost($)
Alternator		1	2,100
GridPoint Connect		1	10,000
Total			12,100

Grid Connected No Battery			
Item		Quantity	Cost($)
Alternator		1	2,100
Charge Controller		3	654
Dump Load		5	1,000
Inverter		4	1,600
Total			5,354

See Appendix C for purchasing information.

8.3 System advantages and disadvantages

The standards for interconnecting distributed resources with electric power systems is specified by the Institute of Electrical and Electronics Engineers number 1547 (IEEE 1547). There are several stipulations and requirements in this standard which most contractors and engineers are familiar with and would be held accountable to these standards. This holds true for all system types. The installation challenges are evident from each diagram presented in the previous section. The GridPoint ™ Connect Series is the simplest setup and, of the three offers the best performance and monitoring. This of course comes at an extra cost. An on grid battery system offers an advantage over the battery-less system at a higher up front cost as well but at a lower price than the GridPoint ™. The advantage of the GridPoint ™ is its ease of installation and support from the GridPoint ™ Company. The system that connects only to the grid leaves the user with less flexibility with their renewable energy source. The largest disadvantage of a battery-less system is its dependence on the grid. If the grid were to go down so would your system because in the event of grid failure this type of system is designed to automatically shut down.

8.4 Energy Buy Back and Net Metering

The First legislation for renewable energy came from the Public Utility Regulatory Policies Act of 1978 (PURPA) which requires energy providers to purchase power from grid-connected renewable energy sources at a rate that was equivalent to the cost to the provider to generate that power [24]. Georgia also passed its own law in 2001, Official Code of Georgia (O.C.G.) § 46-3-50 (See Appendix D) setting down the ground work for relationships between small renewable energy sources and utilities [25] called "The Georgia Cogeneration and Distributed Generation Act of 2001." This act stipulated the requirements for small renewable energy source (residential no more than 10kW) and the means for distribution and pay back to the renewable energy source. Section § 46-3-55 measurement and payment of energy flow has the guide lines for net metering and pay back. The metering type can be either bidirectional metering, meaning one meter measures the flow of electricity in both directions or send the power directly to the grid from the source. Bidirectional metering is more desirable because you can consume the energy you generate before it is sent to the utility. The advantage of this is that the utility will only buy back power at an avoided cost. All the energy that you use will be charged to you at retail rate but the utility company only buys energy back at the whole sale rate or the rate that it would cost them to produce that same amount of energy. By using a bidirectional meter you can consume the energy you generate rather then pay retail price for the energy before you send it to the utility company. In this feasibility study the Minors Millpond will not make enough energy to send back to the utility, therefore a bidirectional meter will be necessary for all of the systems that are grid connected. For information on federal tax incentives for renewable energy see section 9.5 of this report.

9 Economics

In previous portions of this report options have been considered without regard to the economic feasibility. Disregard for economic feasibility lead to the consideration of the broadest range of possible options and from a technical position any of the options should be feasible, however from a economic point of view the project would only be successful if the chosen option is a smart investment. Several tools are presented here to determine if a particular option is a smart investment.

9.1 Time Value of Money

One dollar today is not worth the same thing as one dollar tomorrow. In fact one dollar today is worth more than a dollar tomorrow, that's because if one had control over that same dollar today then they could invest it somehow and earn some return on the investment. The time value of money makes it difficult to compare options that money through time. For example a turbine that is installed at a site and begins earning savings while at the same time incurring maintenance costs. You cannot simply weigh the upfront cost of the turbine installation and the future maintenance against the future value of the avoided electric costs. These avoided electric costs are less valuable to us than the upfront cost.

A common problem found in the evaluation of time values of money is the present value of a growing annuity. Take for example a hydro turbine that is installed and begins saving the owner money this savings is equal to the product of the power produced by the turbine/wheel, the cost of energy and the time in the period of one year, an example of this is shown in Equation 9.1 for the LH 1000 Turbine.

$$\mathrm{lh}_{\mathrm{yearlySavings}} := 3450\mathrm{W} \cdot .11 \frac{\$}{\mathrm{kW} \cdot \mathrm{hr}} \cdot 365\mathrm{day}$$

Equation 9.1

This is representative of the money saved the year that the turbine becomes operational, but it would be inappropriate to assume that this is the value of the savings over the life of the whole turbine. Once the avoided electric cost value has been adjusted for the time value of money the present value of the avoided electric cost would be the sum defined by Equation 9.2. Where A is the yearly savings, r is the current prevailing interest rate, and n is the number of years that the sum will be evaluated (life of the turbine.)

$$PVA = A + \frac{A}{(1+r)} + \frac{A}{(1+r)^2} + \ldots + \frac{A}{(1+r)^n}$$

Equation 9.2

This is a pretty good way to adjust for the time value of money, and it is the way the maintenance costs are computed. Equation 9.2 is deficient in that it is incapable of adjusting for a yearly savings that will grow. Taking Equation 9.2 and writing A as a growing value yields Equation 9.3 where A, r, and n are the same as before and g is the rate of growth of energy cost.

$$PVA = A + \frac{A*(1+g)}{(1+r)} + \frac{A*(1+g)^2}{(1+r)^2} + \ldots + \frac{A*(1+g)^n}{(1+r)^n}$$

Equation 9.3

Equation 9.3 can be simplified to the expression in Equation 9.4 the details can be found in app. F.

$$PVA = \frac{A}{(r-g)} * \left[1 - \left(\frac{1+g}{1+r} \right)^n \right]$$

Equation 9.4

9.2 Cash Flow Diagrams

The Cast flow diagram presents a graphical view of money spent or earned over a period of time. This is particularly helpful for our analysis. Consider the cash flow diagram Figure 9.2 for the LH 1000 in this diagram the upfront cost is represented as the blue bar reaching down to negative $40,000.00 this cost is the estimated present value of the installation, dam redesign, and grid connection. Following the upfront cost there are green bars that grow exponentially for each year, these green bars represent the future value of the avoided electric costs, they are growing because we assume that the cost of energy grows at a rate of 3%. Finally the red bars that occur on three year intervals are the expected maintenance cost estimated by the cost of replacing two turbines. This tool is good for visualizing the costs through the life of the turbine/wheel, but the total present value must be determined by using the concept of the time value of money explained in section 9.1.

9.3 Payback Period Charts

The payback period is the time in years it takes for the avoided electric costs to equal the upfront costs all in the present value. A Payback Period Chart is the name coined by the group for the graphical representation of the payback period as a function of the upfront expenditure. This payback period is a function of the current prevailing interest rates and the power generation option, therefore there is a diagram for each of the options as well as separate lines on each diagram for the different interest rates. The lines have a stair step Characteristics by virtue of the code (Appendix B) used to generate the plot only checking the payback condition at the end of each year. One interesting result of the present value of money equation is the possibility of investments that will never pay themselves off. Such investments have an infinite payback period this is represented by the line terminating midway through the plot (purple line in Figure 9.1) this represents the fact that any upfront costs greater than $30,000 will never pay for themselves, the future value of the avoided electric costs is simply not great enough to offset the maintenance and pay for the initial investment.

9.3.1 How To Use the Payback Period Chart

The advantage of the payback period chart is in its flexibility with respect to unknowns. For example the group is unaware of the costs associated with redesigning the dam. This redesign cost could be very extensive if the whole dam is torn down and a new dam is designed by an engineering firm. This cost could also be a very small expenditure if all that is desired is to replace the timbers in the spillways. Ultimately this decision will be made by Leo. These uncertainties drove the decision to plot the payback period as a function of upfront expenditure in hopes that Leo and his business partners can make the most informed decision.

The overshot waterwheel option will be used as an example of how to use the chart. Table 9.1 shows some of the costs and credits associated with installing the waterwheel at the site to determine the payback period for this configuration. Notice that the total upfront cost is located on the x axis in Figure 9.1 then a line is drawn up to the line corresponding to the appropriate interest rate, from here a horizontal line is made to extend over to the y axis were the payback period is read off. So for the installation parameters in Table 9.1 it would take four years for the avoided costs plus the tax credits to equal the installation costs.

Table 9.1

Cost	Present Value
1 water wheel $12 000.00	$12 000.00
Redesign Dam	$20 000.00
Grid connection	$15 000.00
Government Tax Credit	$-3 180.00
Total upfront cost	$43 900.00

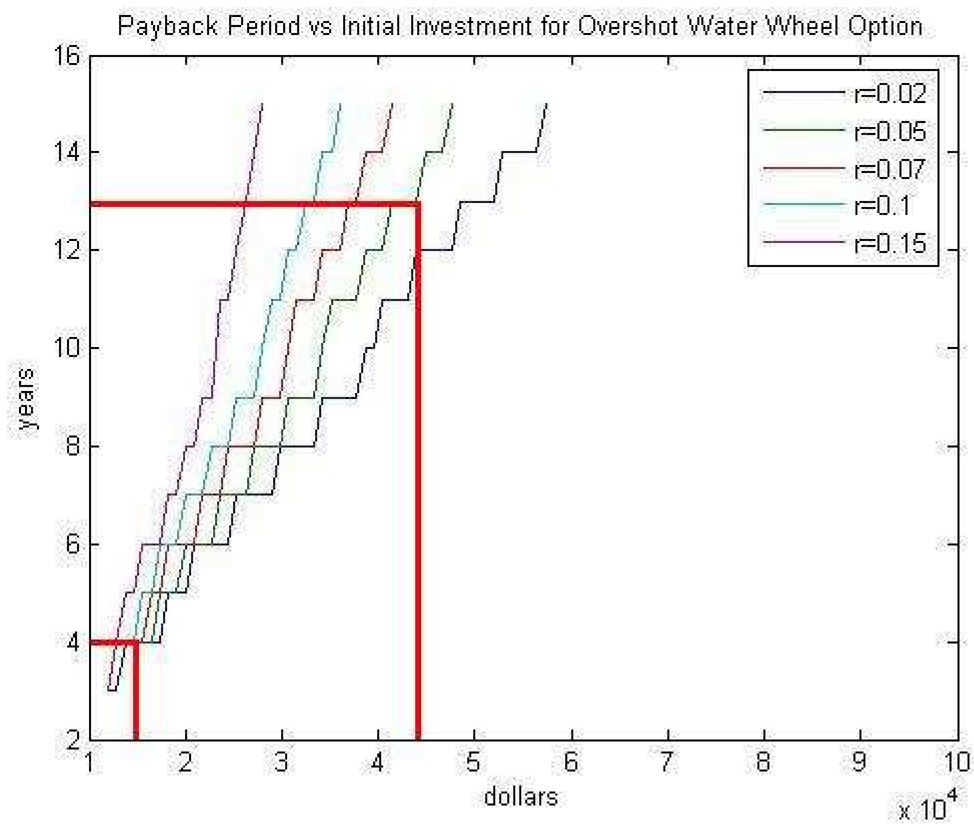

Figure 9.1 – Using the Payback period Diagram
The upfront cost for this option refers to a 13 year payback period

9.4 Options

The following design options have been analyzed with the following assumptions

Prevailing Interest rate at 5% (cash flow diagrams only)
Energy cost grows at a rate of 3% above inflation
Price of energy at Minors Millpond is 0.11 $\frac{\$}{kW * Hr}$ [app. F],[19]

9.4.1 Voith Siemens

After Talking to the Voith Siemens Representative in Chattanooga TN it was determined that the cost of installing a Voith Siemens turbine would be one million dollars this is not economically feasible so it has been left out of the economic analysis.

9.4.2 U.C.M. Resita

The Resita experimental turbine demonstrates that the small scale low flow, low head hydro site is becoming economically feasible; however this turbine is not yet available. As this turbine is not yet available we will not do an economic feasibility study which includes this turbine.

9.4.3 LH 1000

This option has the advantage of being able to split up the turbines between the two spillways thus utilizing 100 percent of the flow without causing any problem to the flow through the second spillway. One severe problem is that the LH1000 is perceived by our group to be very low quality. Thus it has a very small lifespan. We will evaluate 15 years worth of operation and assume that we replace two turbines every three years we will

Table 9.2

Cost	Present Value
4 LH1000s @ $2 625.00	$10 500.00
Redesign Dam	$15 000.00
Grid connection	$15 000.00
Replacing two every 3 years for 15 years	$23 190.00
Total Present Value of avoided Electric costs	$41 650.00

The model case shown above has a 13 year payback period. With cash flow as pictured in.

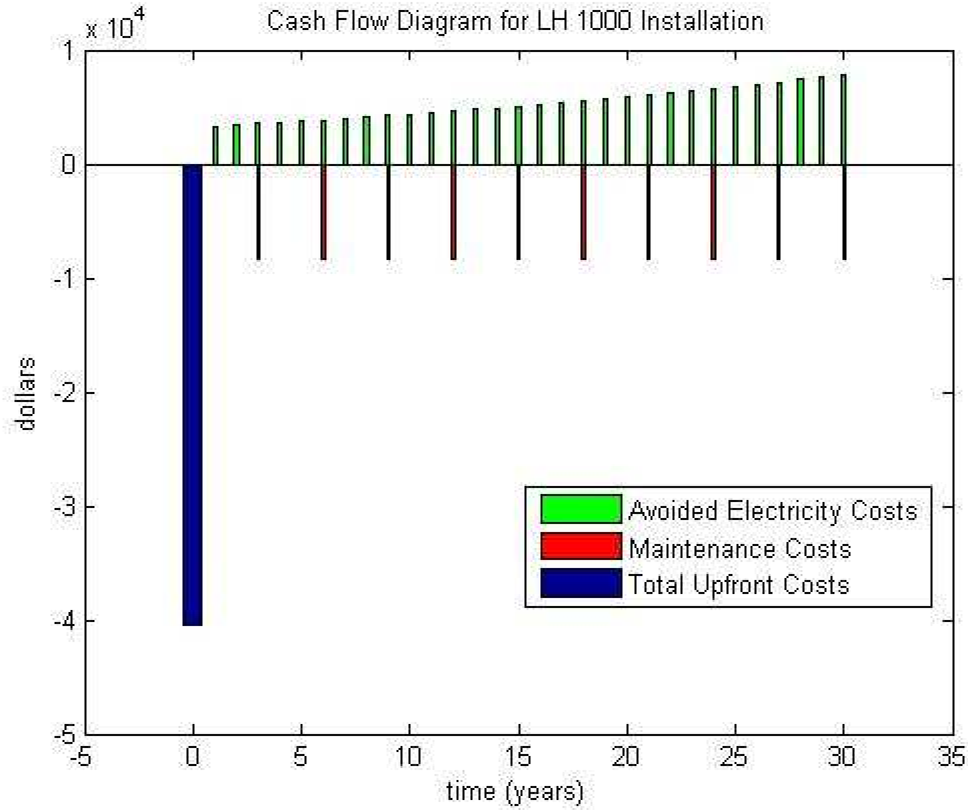

Figure 9.2 – Cash Flow for LH 1000 Installation

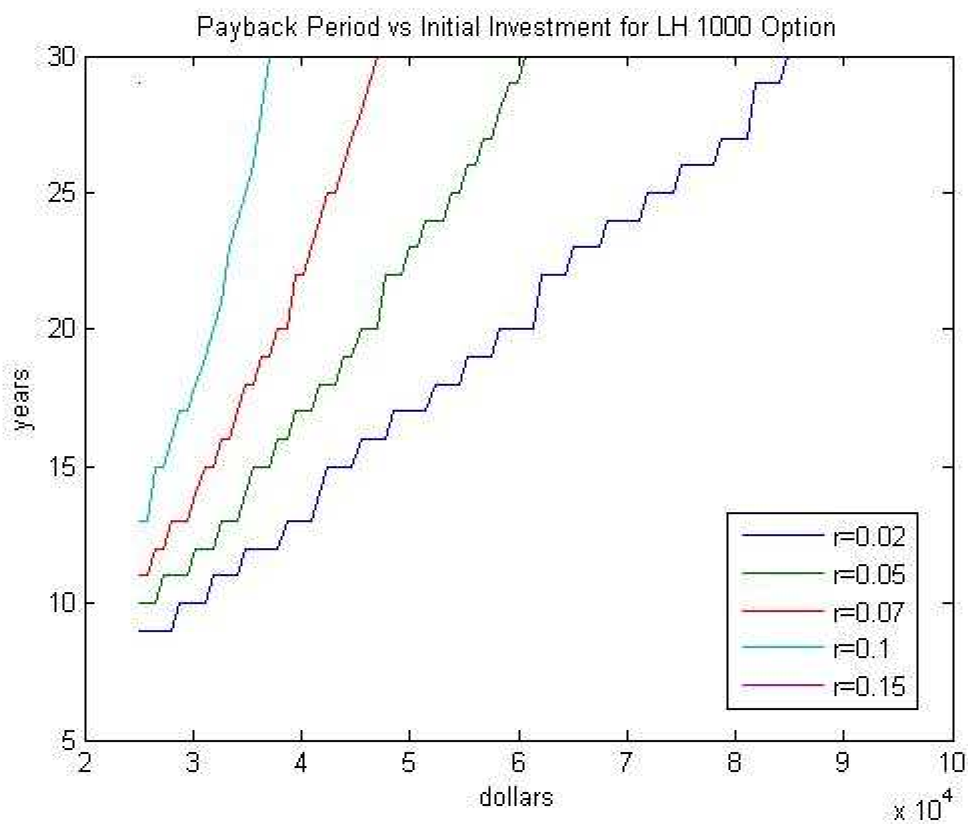

Figure 9.3 – LH 1000 Payback Period Chart

Clearly comparing the present value of avoided energy cost to the installation costs this option is really not very good.

9.4.4 Nautilus

The Nautilus is perceived to be a higher quality turbine than the LH 1000 this turbine is naturally a little more expensive as well, however with a greater flow rate capacity of

Table 9.3

Cost	Present Value
2 Nautilus @ $12 000.00	$24 000.00
Redesign Dam	$15 000.00
Grid connection	$15 000.00
Maintenance Cost over 50 years	$12 000.00
Total Present Value Cost	$66 000.00
Total Present Value of Electric	$113 000.00

The present value of Electricity costs avoided is not great when compared to the costs of installation, this option would pay for itself in 22 years. See Figure 9.4 for the cash flow diagram of the proposed installation.

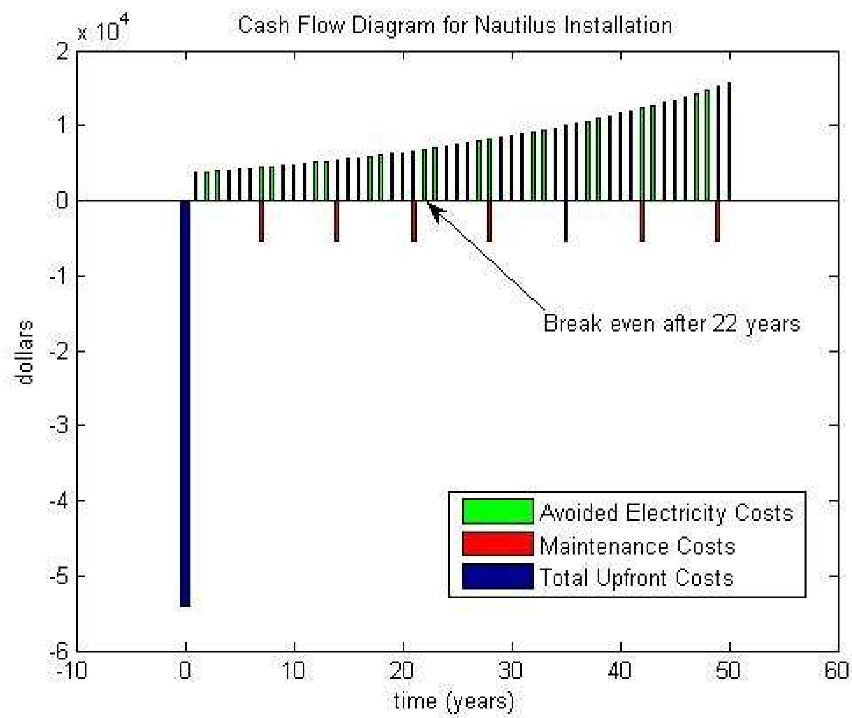

Figure 9.4 – Cash Flow Diagram for Nautilus Installation

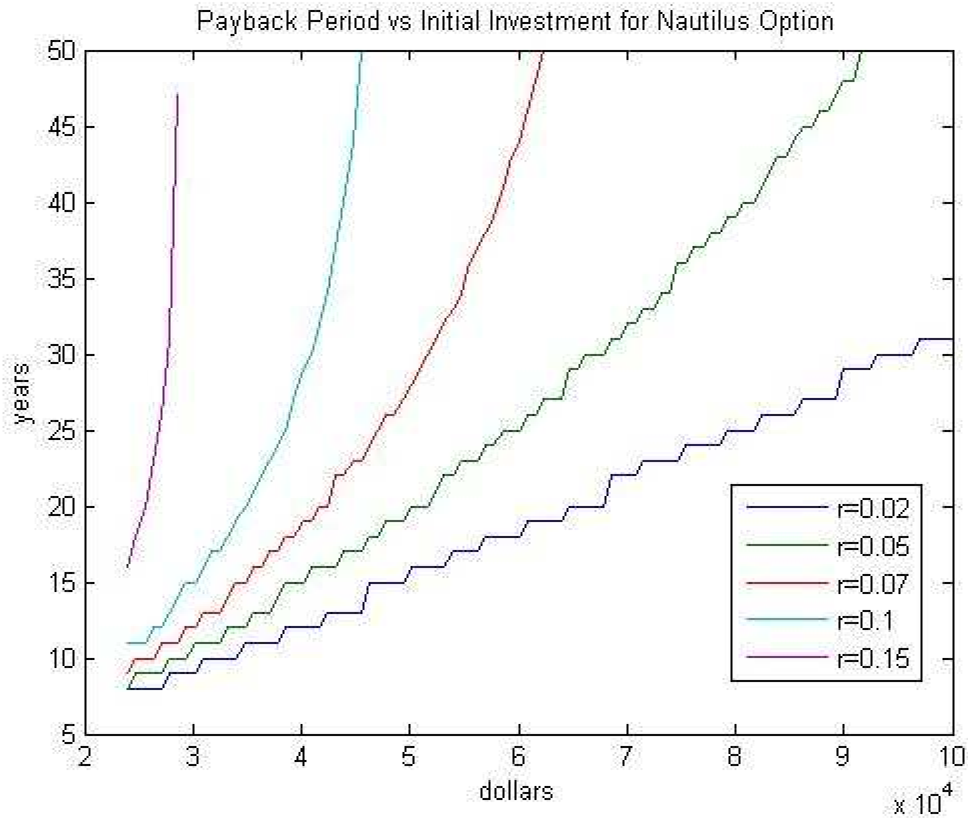

Figure 9.5 Payback Period Diagram for Nautilus Option.

9.4.5 Overshot Water Wheel

By nature water wheels should be less efficient than turbines, what the research has shown is that for these very low head and low flow situations such as at minors millpond the turbines have not been optimized therefore the waterwheel actually ends up being a more efficient option. The life of new water wheel is approximately 14 years. There would be a slightly greater cost associated with redesigning the dam for a water wheel than for a turbine like the ones we have been looking at. For the economic analysis we assume maintenance every five years at roughly 10% the upfront cost of the installation.

Table 9.4

Cost	Present Value
1 water wheel $12 000.00	$12 000.00
Redesign Dam	$20 000.00
Grid connection	$15 000.00
Maintenance Cost over 14 years	$6 500.00
Total Present Value Cost	$53 500.00
Total Present Value of Electric	$53 600.00

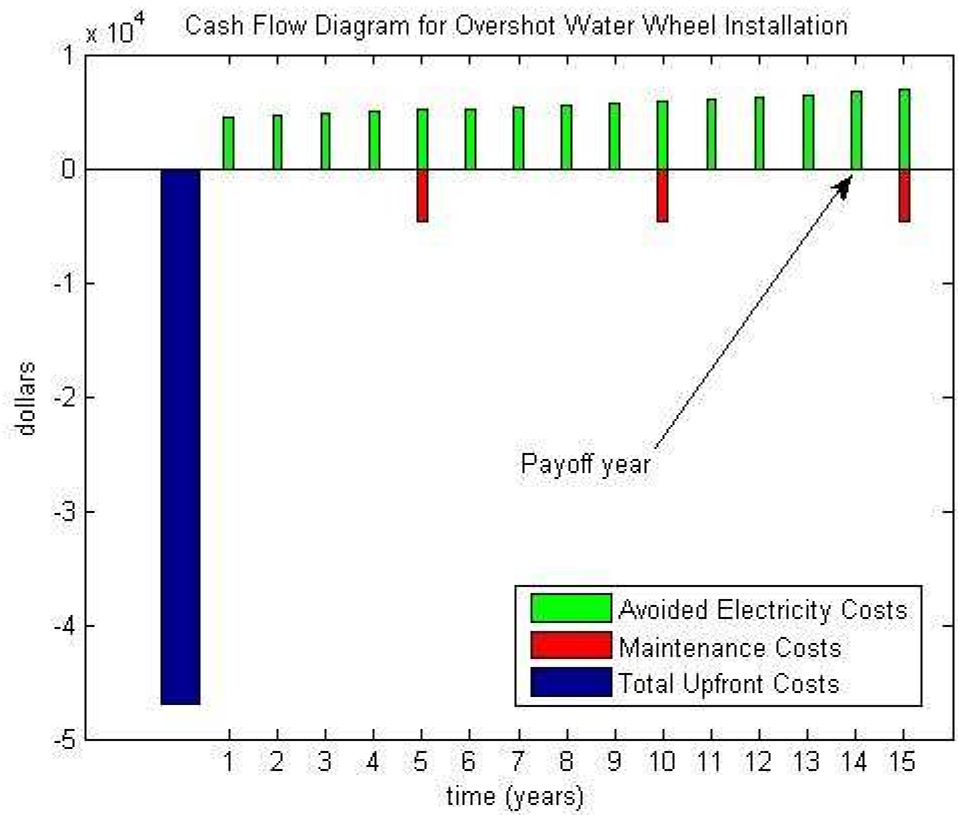

Figure 9.6 – Cash Flow Diagram for Overshot Wheel Installation

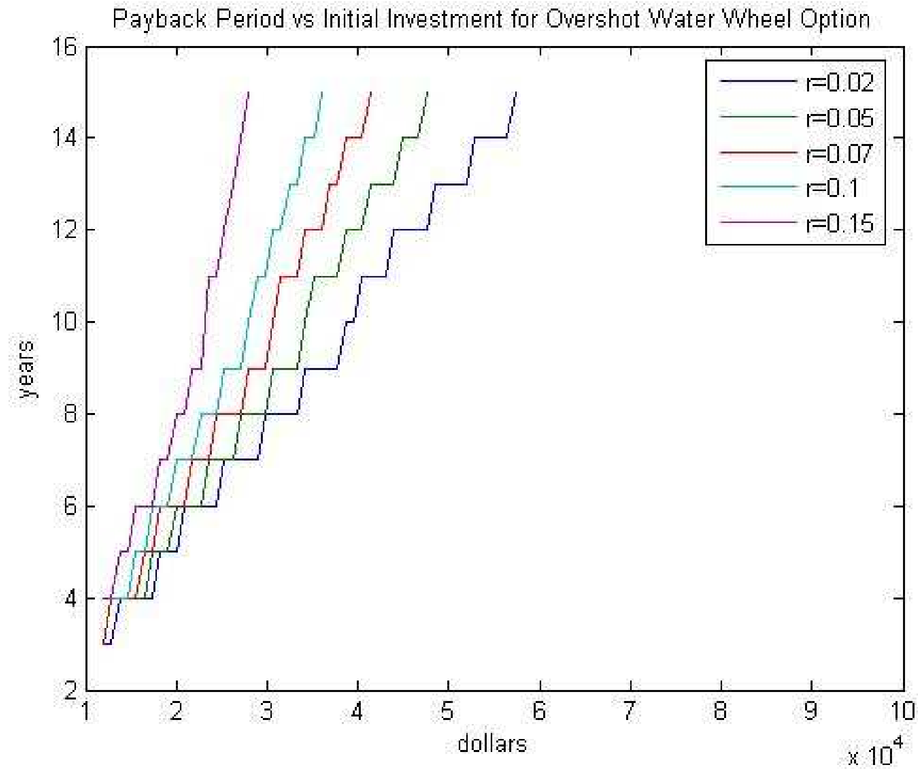

Figure 9.7 – Payback Period Diagram for Overshot Wheel Design

9.4.6 Breast Water Wheel

The breast water wheel is a larger wheel and this is good because that makes it visible from across the pond and it will therefore be more attractive to buyers. Unfortunately the aesthetics come at a price, the breast water wheel is also slightly less efficient then an overshot wheel and this slight change in efficiency coupled with greater upfront costs due to the increased size ends up making the breast wheel a very different type of investment.

Table 9.5

Cost	Present Value
1 breast water wheel	$20 000.00
Redesign Dam	$20 000.00
Grid connection	$15 000.00
Maintenance Cost over 30 years	$14 000.00
Replacing Wheel at 15 years	$9 620.00
Total Present Value Cost	$78 600.00
Total Present Value of Electric	$93 200.00

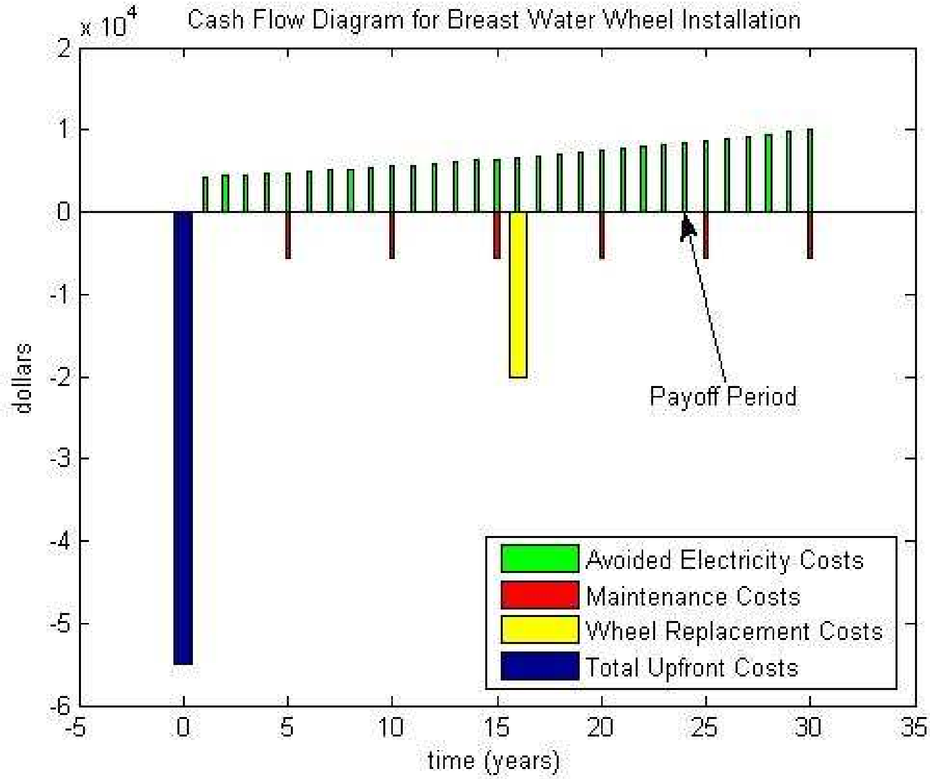

Figure 9.8 Cash Flow Diagram for Breast Wheel Installation

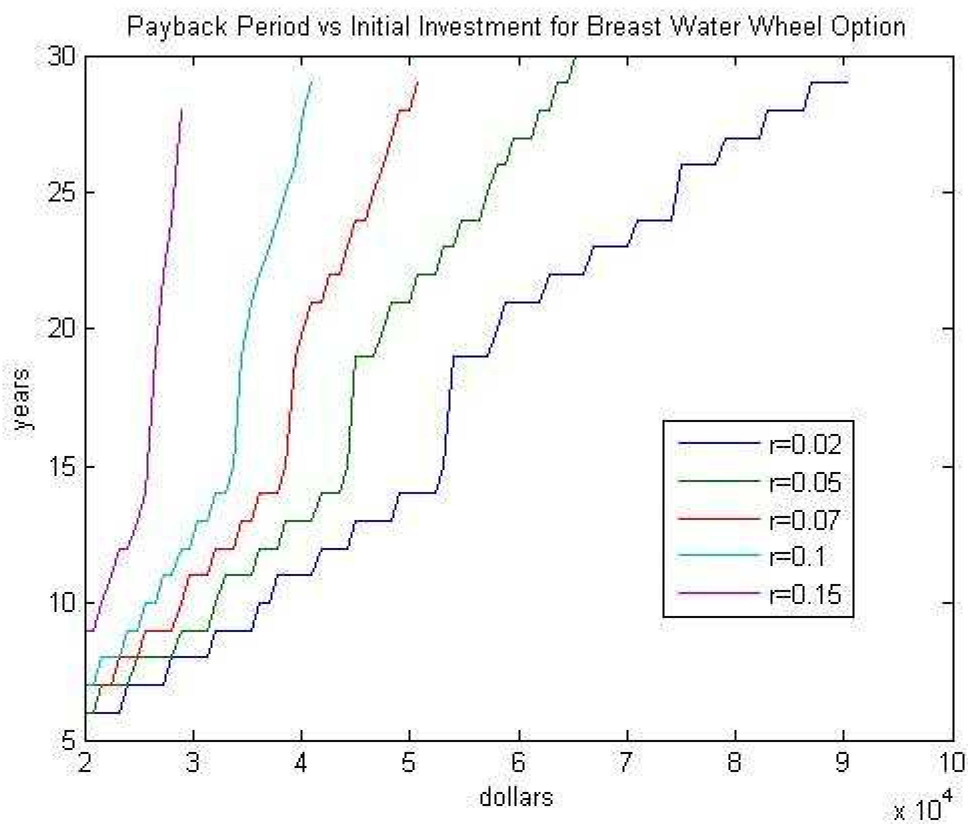

Figure 9.9 –Breast Wheel Payback Period Diagram

9.4.7 Breast Water Wheel + Nautilus

The water wheel plus Nautilus option is an attempt to utilize 100% of the flow that we could possibly utilize and make sure that we don't have any adverse effects on the ecosystem. The stream flow behind spillway one is a big concern because it has been reported that there is an abundance of fish behind this spillway. There is several ways around this problem, one is to design the wheel/dam at spillway one to utilize a fraction of the total flow, the second way would be to put a wheel/dam at spillway two. This would allow the flow at spillway two to go towards power generation as well as allowing the flow to go unchanged. Unfortunately this method requires a lot of extra work to go into Dam redesign; furthermore it would require an increase in material for connecting both wheel and turbine together, and also to the grid.

Table 9.6

Cost	Present Value
Water Wheel (smaller)	$10 000.00
Wheel Maintenance over 50 years	$2 390.00
3 replacement waterwheels	$8 240.00
Nautilus Turbine	$12 000.00
Nautilus Maintenance over 50 years	$2 680.00
Redesign Dam	$25 000.00
Grid connection	$20 000.00
Total Present Value Cost	$80 300.00
Total Present Value of Avoided Electric cost	$142 000.00

Given these values there is a 27 year payoff period.

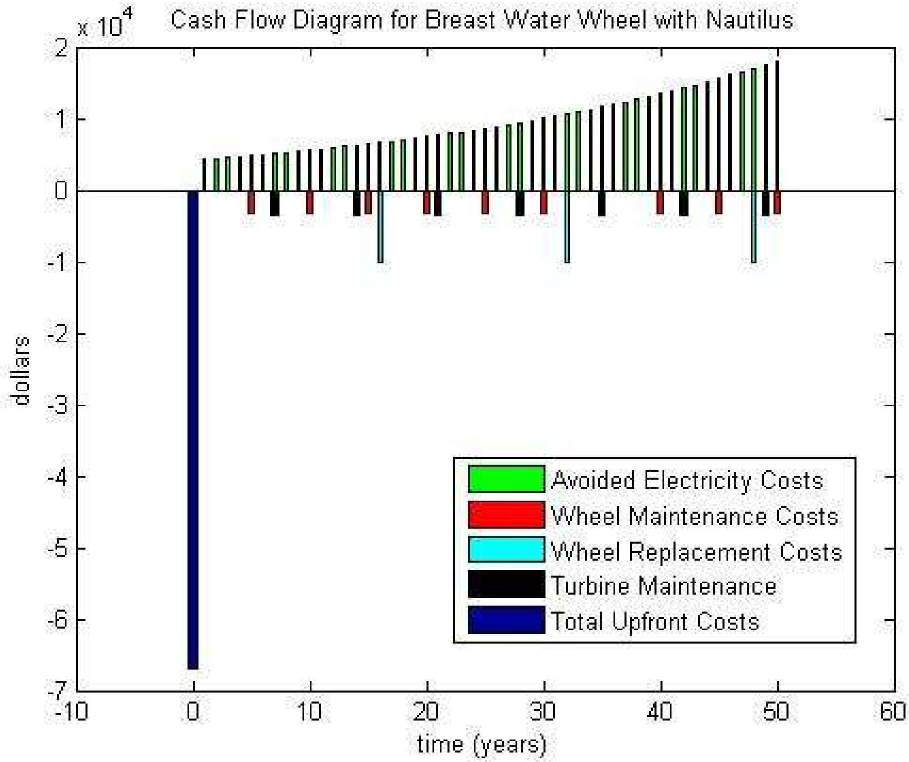

Figure 9.10 – Breast Wheel + Nautilus Cash Flow Diagram

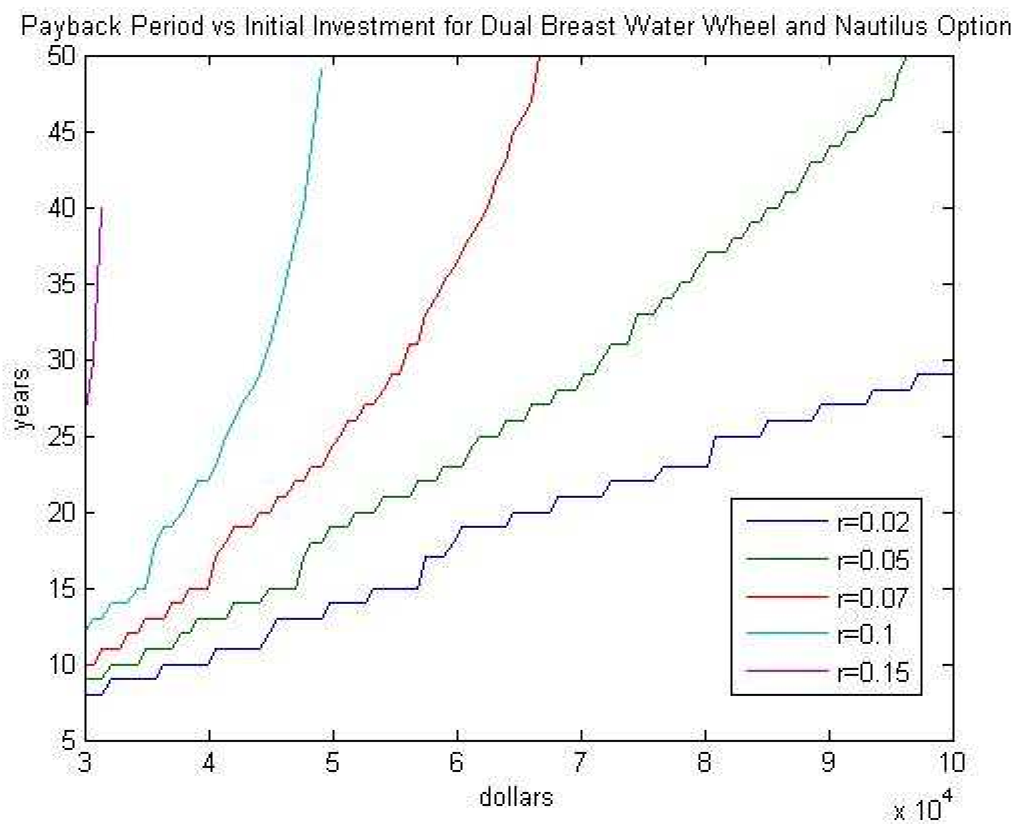

Figure 9.11 – Breast Wheel + Nautilus Payback Period Diagram

9.4.8 Breast Wheel + Overshot Wheel

Given the excellent efficiency of the wheels as compared to the turbines it is worth considering an installation with two wheels.

Table 9.7

Cost	Present Value
Overshot Water Wheel (smaller)	$10 000.00
Breast Water Wheel	$18 000.00
6 replacement waterwheels	$23 060.00
Wheel Maintenance over 50 years	$18 280.00
Redesign Dam	$27 000.00
Grid connection	$20 000.00
Total Present Value Cost	$114 340.00
Total Present Value of Avoided Electric cost	$142 000.00

This option has a 37 year payback period.

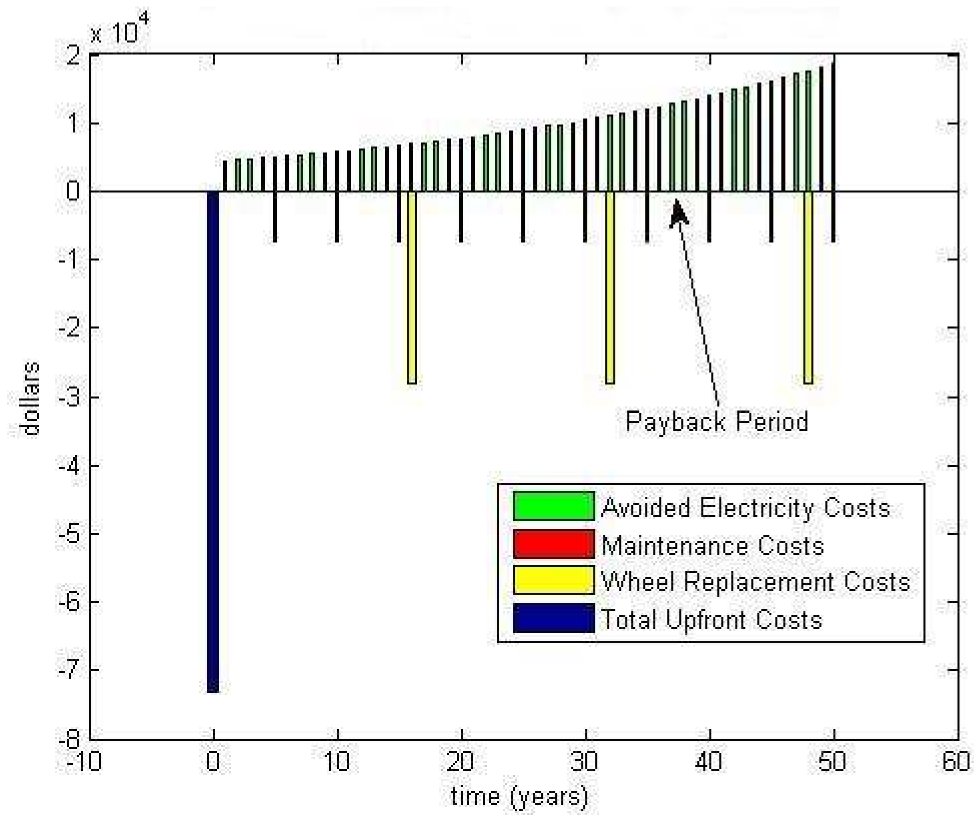

Figure 9.12 – Dual Water Wheel Cash Flow Diagram

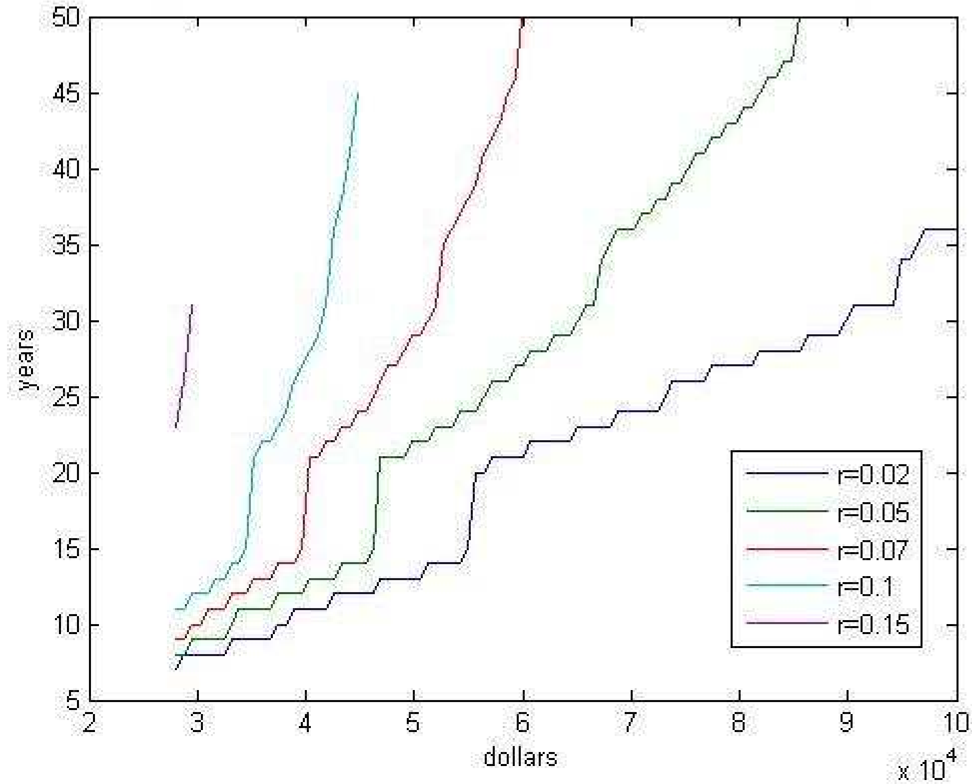

Figure 9.13 – Dual Water Wheel Option Payback Period Diagram

9.5 Final Crosswise Comparison

Figure 9.14 is meant to take into account all the different parameters and give our best educated guess for the payback period of the different options.

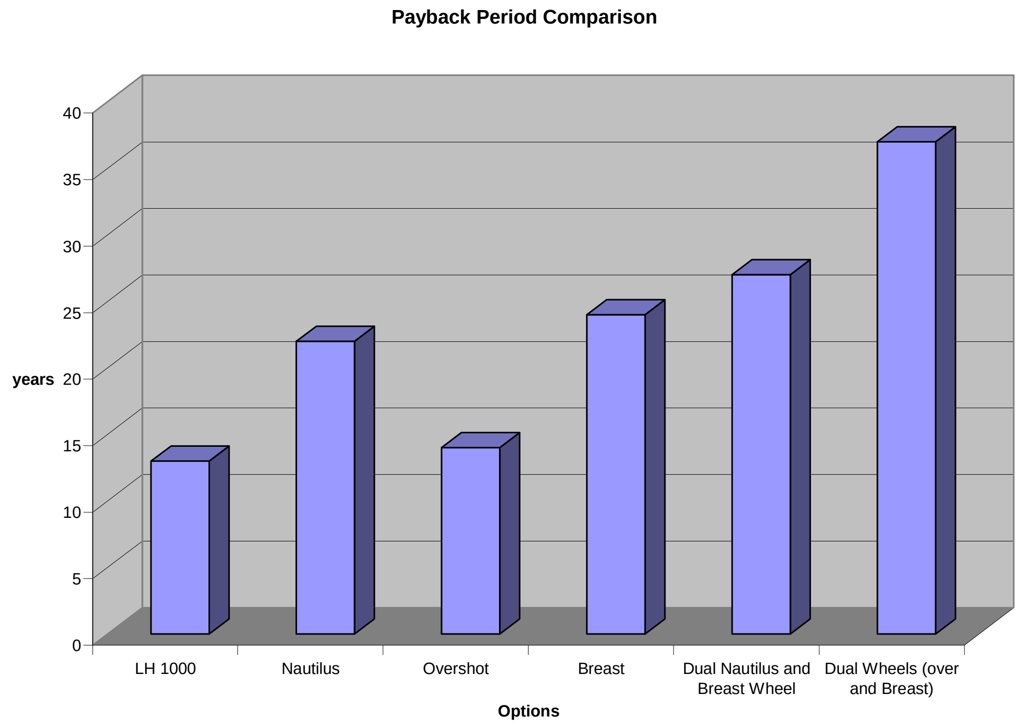

Figure 9.14 – Economic Analysis of Across All Options

Given the final chart it appears that the LH 1000 and the stand alone Overshot wheel are the best economic options.

9.6 Federal Tax Credit

In the example option above there is a table entry for federal tax credit this is based on a tax credit located using the DSIRE web site [18] Appendix(F). This tax credit is a credit that businesses can apply for using Form 8835 and Form 3800. the credit applies to the following renewables:

wind
closed-loop biomass
open-loop biomass
geothermal energy
small irrigation power (150 kW - 5 MW)
municipal solid waste
landfill gas
refined coal
hydropower
Indian coal

The credit yields $0.01 per kilowatt hour (for hydroelectric) which can be applied for every year for ten years starting the year the resource is installed. The present value of this tax credit is displayed in Table 9.8 for all the options.

Table 9.8

LH 1000	2333.66
Nautilus	2570.41
Overshot Wheel	3184.86
Breast Wheel	2986.20
Breast + Nautilus	2776.31
Overshot + Nautilus	2876.69
Breast + Overshot	3085.18

9.7 Hybrid Automobile Economic Analysis

The same economic analysis that is used to determine the economic feasibility of developing a micro hydro site can be applied to the question of whether or not there is a savings for the owner of a hybrid car over the lifetime of the vehicle. The details of this analysis can be found in Appendix F and the resources are from [20],[21].

The analysis is comparing the Honda Civc DX automatic to the Honda civic hybrid.

9.7.1 Data

Table 9.9

Variable	Present Value
Yearly milage	15 000 mi
Fuel Cost	$2.402

Table 9.10

Car	Efficiency (mpg)	Upfront cost(dollars)	Yearly maintenance (dollars)	Yearly Gas (dollars)
Civic Hybrid	49	22 600.00	565.85	735.31
Normal Civic	30	15 865.00	362.77	201.00

Table 9.11

Cost	Civic Hybrid	Normal Civic DX
Upfront cost(dollars)	22 600	15 865
Present Value 15 years of gas (dollars)	9 213	15 050
Present Value of 15 years worth of maintenance (dollars)	5 873	3 765
Total (dollars)	37 690	34 680

It is apparent from this table that it is not a good investment to buy a civic hybrid as opposed to the regular civic in fact it is a particularly bad investment if the consumer is not planning to keep the car for longer than 15 years. Even if the consumer does keep the car for 15 years there will be a $3 000 deficit in the consumer's wallet. The government does offer a $2 100 incentive for the purchase of this particular vehicle, but this still leaves a $900 deficit. This analysis assumes that the maintenance costs are fixed; the consumer should bear in mind that if the current hybrid technology falls out of use than the cost of maintenance over 15 years is likely to be very high.

10 Environmental Impacts

10.1 Greenhouse Gas Emission

Hydro power has been considered a clean source of energy due to the fact that it does not directly produce any greenhouse gases. Ultimately hydro power can be traced back to the sun, and is thus an indirect source of solar power. The sun's energy evaporates water into the atmosphere. As the water condenses and rains back down to the earth, the energy created from the water traveling from higher elevations to lower elevations can then be converted into electrical energy. It only seems logical to use the power created from the natural water cycle.

The major concern of environmentalists is the emission of greenhouse gases. There are three primary gases created from the burning of fossil fuels at power plants: nitrogen oxides, sulfur dioxide, and carbon dioxide.

Nitrogen oxides (NO_x) have many undesirable characteristics. Breathing conditions such as asthma can be worsened if NO_x is inhaled. When NO_x reacts with oxygen, the result is ozone which can eventually turn into nitric acid if dissolved in water. When nitric acid is formed in rain, it is more commonly referred to as acid rain, which can have negative effects on entire ecosystems. Smog, which can be seen as brown clouds, is the result of NO_x being released into the atmosphere.

Sulfur dioxide (SO_2) has many of the same effects as NO_x but is more prevalent. Like NO_x, SO_2 turns into sulfuric acid when reacted with moisture to create acid rain. Apart from environmental damage, acid rain is also responsible for the discoloration of statues and buildings.

The majority of greenhouse gas is made up of carbon dioxide (CO_2). The ever increasing amount of CO_2 is thought to be responsible for a global climate change also know as Global Warming due to the Greenhouse Effect. The Greenhouse Effect is the result of short wavelength radiation from the sun passing through the ozone layer and heating up the Earth. The longer wavelength radiation that the Earth then transmits back out cannot pass through the ozone layer and is reflected back to the Earth, thus increasing the temperature even more.

Figure 10.1 Greenhouse Effect [22]

For the Minors Millpond site in particular, the amount of greenhouse gases produced can be determined from the amount produced from the plant that would be supplying power. Using the average emission rates for Georgia,

10.2 Oil Shortages

Whether or not global warming is in fact happening from greenhouse gas emission, it is undeniable that there is a limited supply of oil. This is yet another reason why hydropower should be pursued. With the end of the oil supply becoming ever more near, it is important to become less dependant on oil. Hydropower is one of many ways to decrease the amount of oil used for power. As shown in Equation 10.1, the amount of energy associated with one barrel of oil can be equated to energy produced by hydropower. Assuming a power produced of 4kW over the course of a year is equivalent to over 20 barrels of oil saved.

$$\text{Barrel} := 6.1178632 \cdot 10^{9}\,\text{J}$$

$$4\text{kW} \cdot \text{yr} = 20.633\,\text{Barrel}$$

Equation 10.1

Although 20 barrels is very small compared to the billions of barrels used yearly by the United States, it is still a step toward being independent of oil altogether. As household appliances and automobiles become more energy efficient and renewable energy more prevalent, the demand for oil will decrease.

10.3 Local Habitat

With then installation of hydro power at a site, the amount of construction needed to be done to begin making power can be rather extensive. This construction often includes changes before and after the actual site that can be devastating to the local ecosystem if proper steps are not taken.

As the flow is dammed to divert the flow to make power, a reservoir is often created. This results in flooding of the land in front of the dam. In large scale extreme circumstances, homes and even entire villages can be displaced from the flooding. In smaller scale hydro sites, plant life and wildlife habitat is flooded. As the plant life dies and begins decaying, methane gas is released into the atmosphere. In some circumstances the amount of methane released is considered equivalent to the amount of other greenhouse gases prevented from the hydro power.

A hydroelectric site can have many effects on the fish habitat. With intermittent flow of the river, the river bed down stream of the dam can cause erosion and can leave fish stranded in pools. If the flow is completely blocked off, leaving there no passage down stream, the migration of fish up and downstream will be prevented, possibly causing decline in the fish population. To prevent this from happening, a device called a fishway, also known as fish ladder, has been developed to allow passage. A fishway is simply a series of steps the migrating fish can jump up. On the right hand side of Figure 10.2 is an example of a fishway.

Figure 10.2 Fishway [23]

The disruption or altering of the flow in a river will have an impact on the sediment collected along the stream. With too little flow or with no flow at all, sediment can buildup on the river bed. In many cases there is waste that has collected in the sediment which will then decrease the local fish population.

Oxygen levels in streams are often affected depending on how the flow is released. With flow being released from the bottom of a reservoir, oxygen levels will be lower than usual, however a supersaturation of oxygen can result from plunging water over the top of a reservoir that can be just as deadly to deadly to the local fish. Also associated with the release from the top or bottom of a reservoir is a change in river temperature, affecting the growth and survival of fish.

10.3.1 Minors Millpond Habitat

In the case of Minors Millpond, the effects of installing a hydroelectric site will be minimal. With the initial installation of the mill, much of the required construction and alteration for a hydroelectric installation has already taken place. It has already been observed that the local habitat has made the necessary adjustments to survive with the changes made to Panther Creek and Minors Millpond.

Although the fish life has still flourished, the installation of a fishway would require little construction in comparison to the entire hydroelectric installation. This would allow fish to migrate up and down stream, and likely increase the amount of species and total fish population. The effects of raising the head one and a half feet should have a small impact on the local habitat. The site visit confirmed the expectations based off of a topographical map (Figure 10.3) that raising the water level would flood very little land.

Figure 10.3 Topographical Map

The biggest impact from hydropower at Minors Millpond would come from complete diversion of the flow to one of the spillways. With complete diversion, the flow from the other spillway would become stagnant, resulting in loss of aeration and greater temperature changes in the stream. This impact will still be minimized due to the flow that each setup was design for. Any excess flow over the design flow will be sent to the vacant spillway. There should flow to the other spillway based off of the Flow Duration Curve (Figure 3.10), 95 percent of the time.

Figure 10.4 Spillway 1

Figure 10.5 Spillway 2

11 Final Conclusions and Recommendations

The Final recommendation is based on the following criteria: aesthetics, economics, life expectancy, maintenance, integration with current dam, the percent of utilized flow, and the environmental impacts. For each criterion, a weight was given based on the overall importance to the project.

11.1 Aesthetics

Given that the purpose of this design is to attract people to build at the development aesthetics is given a very high weight in our design considerations. The breast water wheel is given the highest rating here followed closely by the overshot wheel. The Breast wheel is given the highest rating because it will be more eye-catching since it is still visible from across the pond. The waterwheel options have the appeal of keeping the original idea of the millhouse, while performing a more modern function. The turbine options are then rated based on the quality of each turbine. Four LH1000's are required for the design flow, and are therefore rated the lowest based on the cluttered appearance that setup would have.

11.2 Economics

The cost analysis component is made up of two components, namely upfront costs and payback period with weightings of these two components being 66% and 34% respectively. The economic scores for the options is shown in Figure 11.1.

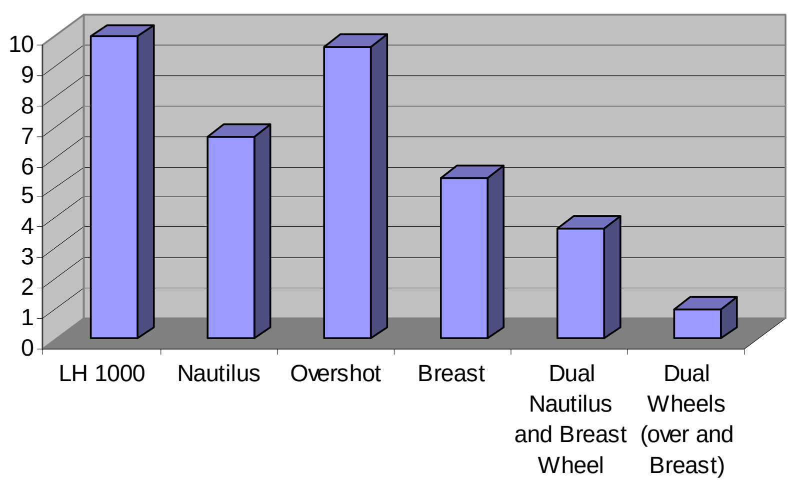

Figure 11.1 – Economic Scores

11.3 Life Expectancy

Since the primary focus of the project is to save money by making power, the life expectancy is given a lower weight. It is hard to predict how long a particular option due to different site conditions, therefore it would not be logical to give a high weighting base on speculation.

11.4 Maintenance

The lowest weighting is given to maintenance for similar reasons that the life expectancy received a low weight. This category deals with how often a particular option will need routine maintenance since cost of maintenance has already been accounted for in the economic analysis.

11.5 Integration with Current Dam

Integration with current dam was also given a low weighting. There is already construction and maintenance that needs to be done to each spillway. Including the installation and construction of a hydropower option would therefore be easy if include with the refurbishing of each spillway.

11.6 Percent of utilized flow

The amount of flow utilized is important to the projects because it is directly tied to money saved. Any flow that is not used to make power can be thought of as lost power and money. For this particular site, there is a fairly large amount of flow and a relatively low amount of head. Currently turbines are not being designed for these types of conditions so it is hard to utilize all of the flow with a turbine. Waterwheels received the highest scores because they can be designed to take full advantage of a given flow.

11.7 Environmental Impacts

The final major component in the decision is the Environmental impact and given that this impact is largely determined by how much flow is diverted this factor is weighted toward options that can be divided between the two spillways.

Table 11.1

	Weight	**Overshot Water Wheel**	**Breast Water Wheel**	**Nautilus**	**LH 1000**	**Overshot Water Wheel and Nautilus**	**Breast Water Wheel and Nautilus**	**Dual Overshot and Breast Wheels**
Economics	25%	9.7	5.3	6.7	10.0	3.7	3.7	1.0
Life Expectancy (Years)	10%	3.0	3.0	10.0	0.4	6.5	6.5	3.0
Maintenance (Years)	6%	5.0	5.0	7.0	1.0	1.0	1.0	5.0
Integration w/current dam	10%	8.0	8.0	10.0	7.0	7.0	7.0	8.0
Aesthetics	25%	8.0	10.0	3.0	2.0	7.0	8.0	10.0
Percent Utilized	24%	7	7	10	10	10	10	10
Total	100%	**7.5**	6.9	7.2	6.2	6.5	6.7	6.6

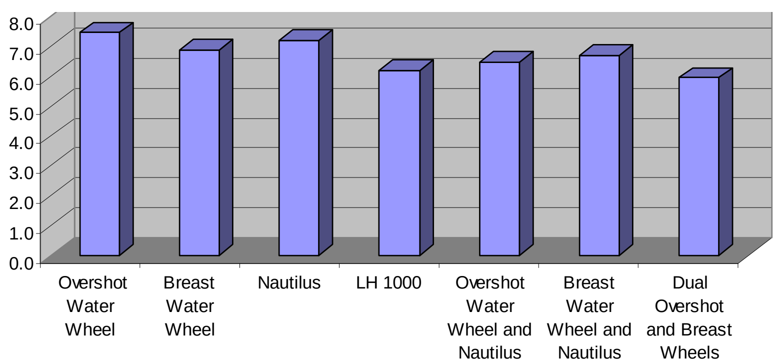

Figure 11.2 – Decision Matrix Scores

11.8 Recommendations

Our final recommendation is that Bob Natalie [26] of the waterwheel factory be contracted to design an overshot water wheel for the site, we recommend that both spillways be renovated with the idea of lasting for 15 years minimum, and for a head increase of 1.5 feet this renovation also needs to take into account the addition of a trash rack to keep large debris from flowing over the water wheel. We also recommend that Peter Landauer [27] of Gridpoint be contacted about installing a Gridpoint Connect on sight for managing the electrical loads. For flow control we recommend a gate at spillway one (Appendix C) and a flow meter at spillway two. This arrangement would allow for control of the flow with a minimum of components.

12 Glossary

Run-of-River: Scheme For power generation that is characterized by running generator with less than the full river's discharge.

Weir: Hydraulic structure used in a run-of-river scheme to divert river discharge.

Intake Structure: Hydraulic structure used to divert water from a natural course into an open channel or pipe for conveyance.

Power Intake: Opening of the penstock that further filters water for flow through the turbine.

Penstock: Pipe to convey water from the power intake to the turbine

K Losses: Losses associated with rapidly changing the direction or velocity of flowing fluid

K: Coefficient used to determine the pressure losses associated with a particular component.

Vortex: Turbulent and often spinning fluid flow about an axis.

Grist Mill: A building where grain is ground into flour – also known as a flour mill.

Stator: The stationary part of a generator in which the rotor turns

Rotor: The rotating part of a generator

Excite: To supply with electricity for producing electric activity or a magnetic field.

Pole: Either of the two regions or parts of an electric battery, magnet, or the like, that exhibits electrical or magnetic polarity.

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[26] Bob Natalie of The Water Wheel Factory. Email: waterwheel@dnet.net

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Appendix A: Site Survey

Appendix B: Flow Data and Calculations

Appendix C: Products

Appendix D: General References

Appendix E: Site Pictures and Maps

Appendix F: Economics