OREGON STATE UNIVERSITY
ME 406: INDEPENDENT PROJECTS
RESEARCH FELLOW TRANSCRIPT NOTATION

Micro Hydro Penstock Design

Quantitative analysis of re-routing a high-head, low-flow, run-of-the-river, under-100 kW hydroelectric power plant penstock and comparison with the original route for purposes of head loss estimation and available hydraulic power prediction

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Abstract

Part of the infrastructure of a disused mill in Dee, Oregon is being converted into a hydroelectric power station. A turbine and generator combination must be selected to match the flow and pressure at the bottom of the penstock. One old penstock route is being abandoned and replaced with a new route. Inaccurate flow versus pressure measurements exist for the old penstock route. In order to estimate the available hydraulic power which can be expected from the new penstock route, both routes were mapped with special attention paid to elevation changes. Total head was found to be 473 feet over a distance of roughly 3.8 miles. The effects of fittings and pipe dimensions, materials and ages on pressure dissipation were accounted for via minor loss correlations and both Darcy-Weisbach and Hazen-Williams equations. For each penstock route, total head loss was calculated at various flow rates from which total hydraulic power could be estimated. The head loss calculated in the old route was compared with the existing measurements. At the permitted water right flow rate of 2.5 cubic feet per second, hydraulic power is predicted to be 93 kilo Watts using the new route and a Pelton turbine is recommended. While the original measurements corroborate this finding, corrections made to the measurements suggest that 80 kilo Watts is a more reasonable power estimate. It is recommended that new flow versus pressure measurements be taken before a final turbine selection is made.

Acknowledgements

Technical assistance and research materials were donated by Dr Kendra Sharp and her graduate student, Nathan Germann. Also, another graduate student named Marc Whitehead helped with determining the pipe inner-wall roughness and recommended the Hazen-Williams method for calculating head loss. Thank you.

Project Overview

The infrastructure of a destroyed saw mill is being re-engineered. One project involves installing a micro hydroelectric power station at the end of an existing pipeline. The hydraulic power available to the generator is estimated in this report. Much construction and engineering work has gone into the design and partial build of the power station, including the repair of an old section of pipeline, re-routing the lower pipeline section, and building a bridge. This report focuses on the pipeline that brings water to the power station.

When supplying water to a power station, a pipeline is sometimes called a penstock. In this case, the penstock travels 4 miles underground to bring water from a creek to the power station. There are two possible penstock routes: the old route which comes straight from the creek to the burned mill complex where it zigzags below the ruins through many fittings and rusty sections of pipe before reaching the turbine house; and the new route which splices into the old pipeline just before the mill complex and takes a direct path over a bridge to the turbine house. At this point, both pipeline routes are nearly operational. The paths of each pipeline were accurately mapped. To assist with turbine and generator selection, an estimate for available hydraulic power was made. Figure 1 is a fairly accurate representation of the general penstock layout.

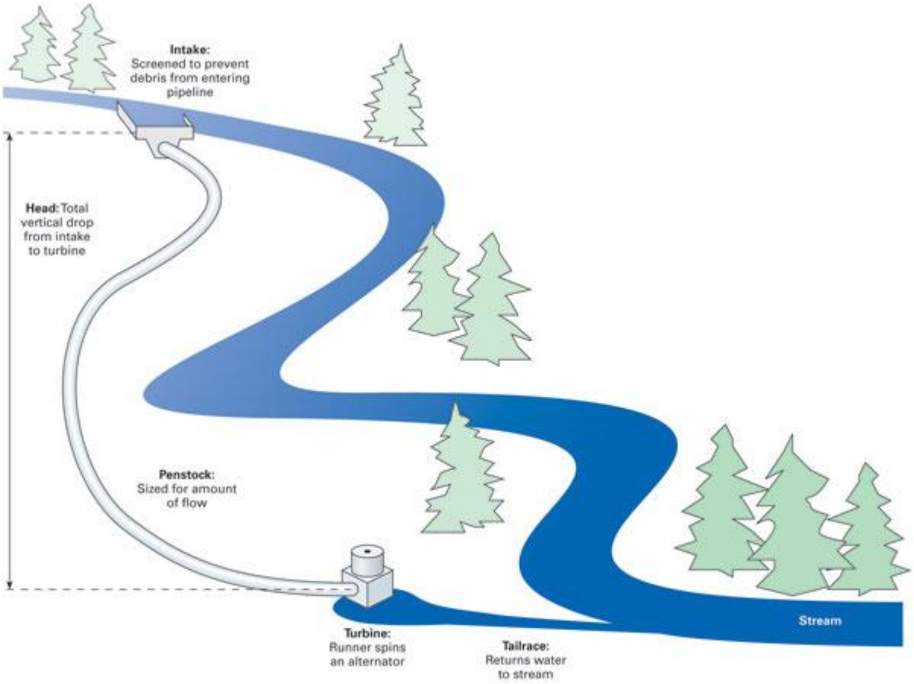

Figure 1. The general layout of the hydroelectric infrastructure

Estimating hydraulic power involves calculating the theoretical maximum power available from the water flowing through a perfect penstock, then subtracting the power lost due to friction, pipeline geometry, and fittings. This was done for several different theoretical flow rates. The annual flow variations in the head source creek were also accounted for to ascertain whether sufficient power would be available during the dry fall months. Local protected fish species and their susceptibility to injury by the power station were noted. The 2001 flow measurements were used as a rough reference.

Pipeline mapping was done using archival maps, GPS, Google, a skydiving altimeter, and static penstock pressure readings. Fittings were counted – with assistance from the map archive – by re-tracing the penstock route from above ground and counting the protruding structures. Several old timers, who worked on the pipeline back in the day and still live in the area, were solicited for help during this stage. Pipe material and dimensions was accounted for in much the same way.

Head loss and available power predictions at several flow rates were calculated via two methods: Darcy-Weisbach and Hazen-Williams. Discrepancies between the two methods were noted and discussed. The final results were compared to the corrected 2001 flow measurements and a preliminary turbine selection was made; an 80 kW Pelton. However, two or three smaller turbines in parallel may be a wise choice. Future testing is suggested before final turbine selection.

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Introduction

Dee Mill is an enormous old lumber mill complex dating from the original Mount Hood area logging operations in 1906. During the heyday of the mill, there was a veritable town of 250 lumberjacks and their families built up in the surroundings. A rail line brought supplies up from nearby Hood River. Cut lumber was floated down in an aqueduct which was filled by a river-blockading dam.

Today, Dee Flat, as the unincorporated community is known, hosts only a handful of orchardists and however many seasonal laborers happen to be in town. The mill burned down in the winter of 1996 after a heavy snow and ice storm collapsed a large building, igniting a sawdust fire and incapacitating the fire sprinkler system. The sprinkler system was fed by a large water tower which was in turn replenished by the eponymous 4 mile pipeline of this report. Being safely under several feet of earth and concrete, the pipeline suffered only minor damages during the otherwise disastrous fire.

The head source at the top of the pipeline is known as Tony Creek. Besides the mill, Tony Creek also supplies water to a beverage bottling company and to several hundred acres of orchard. Since the pipeline has been in place for at least 60 years, it has grandfathered water rights, allowing priority to take 2.5 cubic feet per second so long as 1 cubic foot per second remains, before any but the oldest orchards.

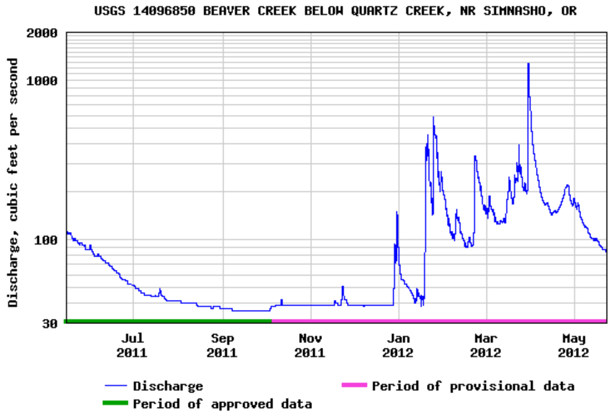


Figure 2. Beaver Creek annual flow fluctuations

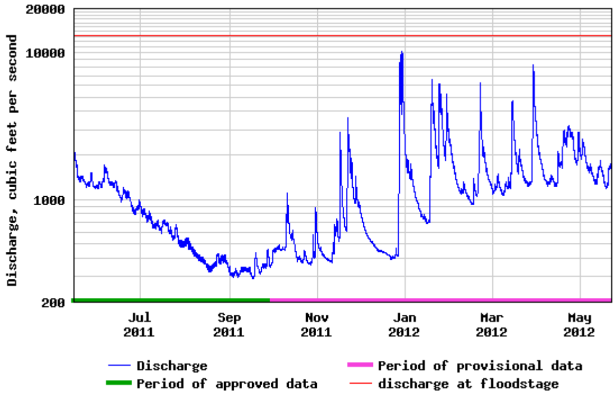


Figure 3. Hood River annual flow fluctuations

Inexpert analysis of flow records posits that only at the end of the driest of dry summers following an unreasonable snowless winter would Tony Creek have insufficient flow to feed the pipeline a consistent full water right. Figure 2 and Figure 3 show the annual flow fluctuations of Beaver Creek, a similarly sized nearby creek in the same watershed as Tony creek, and of the Hood River, for which Tony Creek is a tributary. Judging from the plots and assuming that Tony Creek will likely mirror the behavior of both Beaver Creek and the Hood River, flow fluctuates considerably – high flow may be three thousand percent as great as low flow – but will maintain a minimum capable of meeting the oldest water rights. To compensate for the wild fluctuations in flow, several smaller turbines installed in parallel with the capability of shutting down one or two if the head source flow rate temporarily drops too low. This plan would also allow for the activation of more turbines during especially high flow.

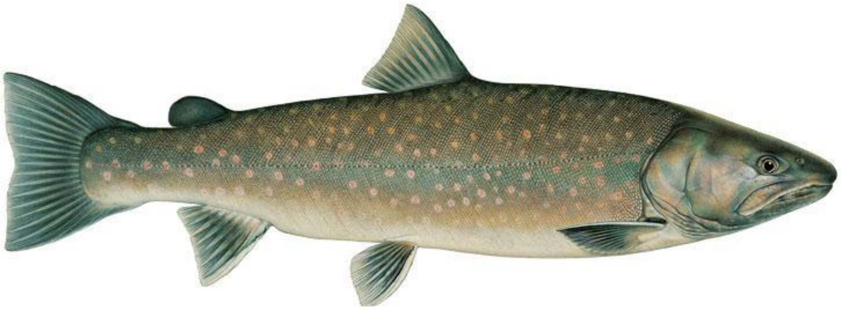


Figure 4. Adult Bull Trout

At the entrance to the pipeline sits a screen diversion. A slight concrete wall channels part of Tony Creek through a large-debris grate and into a screen house. In the screen house, water flows through a channel with a very fine screen along one wall. Some water seeps through the wall screen and the unused water is gently returned to Tony Creek. This screen system has never been known to foul. While the peaks that can be seen in Figures 2 and 3 suggest dangerous flood activity, likely due to local clear cutting, the head source diversion facility has never been severely damaged.

There are two active species of threatened fish in Tony Creek: steelhead and bull trout, seen in Figure 4. Neither fish should consider the head source diversion nor screen house a threat since the water flows so gently through the screen house trough and since the wall screen is far too fine even for juvenile species to pass through.

At the bottom of the penstock, after passing through the turbine, the tail race feeds a pond. Used water is left to mellow in the pond before being fed into the Hood River. The environmental impact of the penstock is negligible. And besides, it has been installed for nearly three quarters of a century and its presence has long since been integrated into the local biosphere. Additionally, electricity generated hydroelectrically is considered “green” and beneficial for the environment. Pacific Power, the local utility, has a painless net metering scheme.

Old Route

Built in the 1940's to supply water to the mill, the old pipeline route runs approximately three and a half miles from the head source diversion to the banks of the Hood River where a newly installed splice sends the water either to the ruined mill complex or down the new penstock route. This long section from the head source must pass only eight known fittings: a twisty bridge of six fittings crossing Tony Creek immediately after the head source screen house, a water tap at a renaissance fairground, and another tap at a beehive storage lot. If routed down the old section, towards the mill, the water must squeeze through a decrepit Cla Val pressure reducing unit before crossing a rotten bridge over the Hood River. Once on the other side of the river, the route winds its way under half a mile of zigzagging, fitting-riddled mill yard before reaching the workshop cum turbine house.

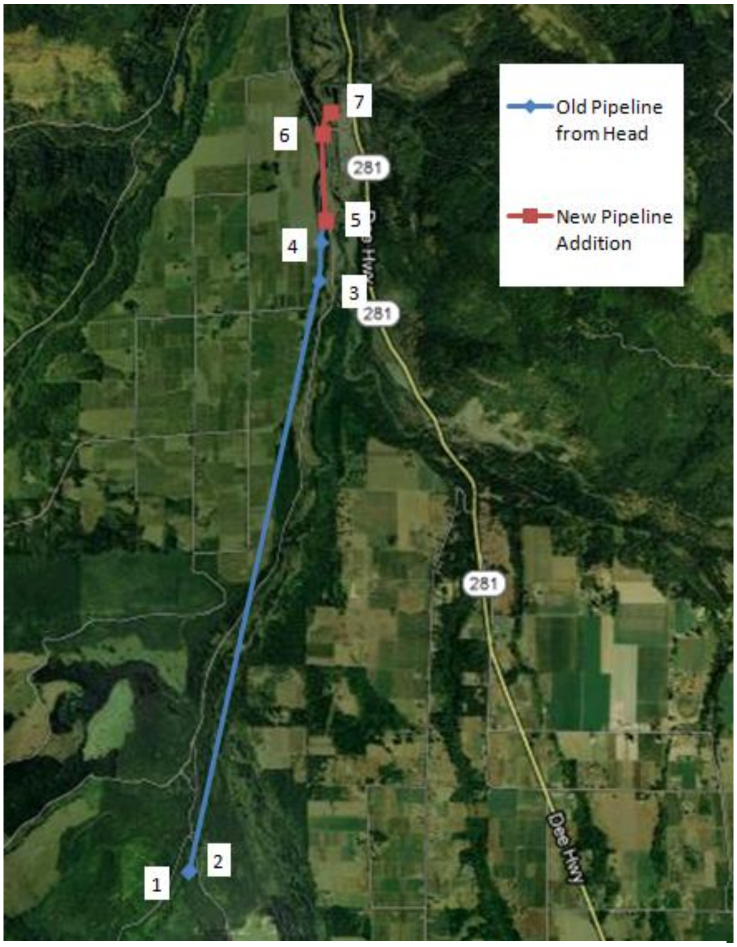


Figure 5. Map of the new pipeline route where point 1 corresponds to the Tony Creek screen house (and penstock head), point 2 the Tony creek bridge, point 3 the fairgrounds campsite, point 4 the beehive storage lot, point 5 the splice into the old pipeline, point 6 the west side of the new bridge, and point 7 the turbine house. Map was created by overlaying GPS measured coordinates onto a satellite image.

Although prone to regular blow-outs and constant minor leakage, this old route was operable until 2003. That year, a group of meth fiends scouring the mill complex for bits of copper to scrap decided to dig up several gate valves and dissect them. After a twenty five thousand dollar repair, the old route is believed to be again operable. However, the problems of leakage and regular failure still exist. To complicate matters, a large section of the mill complex under which the pipeline snakes now belongs to an unaffiliated third party. Abandoning the old pipeline as soon as possible, while perhaps retaining its operability as an emergency option, would be a good idea.

New Route

The freshly laid new penstock route splices into the old route right at the end of the long, straight, fitting-less section coming from the head source. Built of new, 16 inch cast iron sections that are jointed together rather than welded, the new route follows the west bank of the Hood River until parallel with the turbine house. The water is then routed across the river where it joins the old route for the last 500 feet to the turbine.

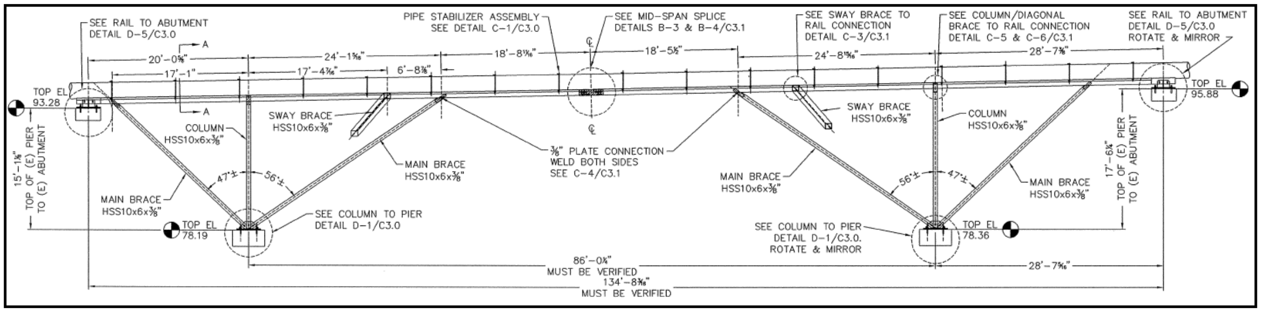


Figure 6. An expensive drawing of the bridge design

To cross the Hood River, a bridge had to be built for the new penstock route. Despite being of a simple design, the bridge has caused to end of red-tape headaches. As of writing, permission had finally been granted to install the two pre-welded sections meant to span the 130 foot wide river canyon. To solicit the endorsement of the local building inspector, a professional civil engineering firm had to be hired to re-draw the bridge design and apply their stamp of approval.

Notwithstanding the inconvenient formalities associated with constructing the bridge, the new route provides a much more efficient route to the turbine, as demonstrated in head loss comparison charts in the following sections. The primary objective of this report is to compare the head loss – and by inference the available hydraulic power – associated with the new route in comparison to the old route at a variety of flow rates. Corrected 2001 measurement data is used to corroborate the comparison.

Project Objectives

This report will cover the completion of three primary objectives:

1. Accurately map the old and new penstock routes along with all fittings, elbows, T-joints, and valves. Estimate the pipe inner wall roughness.

2. Estimate the head loss and hydro power available from either penstock route based on the mapping. Recommend a turbine.

3. Re-work the original flow measurements to account for discrepancies in the experimental set-up.

Timeline

1996	Saw mill burns down
2000	Hydroelectric project initiated, basic design outlaid
2001	Flow measurements taken via old route
2003	Pipeline vandalized by copper thieves
2008	New pipeline route outlaid
2009	New pipeline route specifics designed, earth moving begins
2010	Pipeline bridge designed, pipe laying begins, tailrace ponds landscaped
2011	Out route damage partially repaired, bridge design approved, bridge construction begins
2012	Pipeline construction continues against tide of red-tape, *scope of this project begins*

Scope of Penstock Design Analysis Project [Spring Term, 2012]

Week 1	Project proposal submitted and accepted
Week 3	Documentation gathered to facilitate a mapping field trip
Week 5	Old and new penstock routes mapped with multiple instruments
	Fittings counted and designs noted, pipe dimensions and materials noted
	Mapping data compared to archived maps
	Technical bridge design retrieved from engineering firm
	Site of 2001 flow measurements examined
Week 6	Head source annual flow variations noted
Week 7	Head loss and available hydraulic power predictions made
	Turbine design recommended
Week 9	Project presentation made at CUE Expo
Week 10	Project presentation made to ME 499 lecture
	Technical write-up submitted to faculty advisor

Future	Construct an improved flow testing apparatus
	Make new flow measurements at multiple locations along both penstock routes.
	Use the new flow measurements to verify head loss and power predictions.

Mapping Overview

Mapping of both penstock routes was aided by several old maps found in county archives, additionally annotated by a couple of old men who had spend their careers working at the mill. The length of each section of pipeline was noted in the archive maps. A simple automobile GPS unit was used to locate the head source diversion and the turbine house, globally. Several prominent fittings along the new route were also located by GPS. The straight-line distance between each global point was calculated using trigonometry.

Google distributes a well known online database of satellite imagery which was used to find the head source diversion and turbine house by inspection. Then Google generated walking directions from the head source to the turbine house which followed logging roads. Google warns that walking directions "are in beta." As such, the most accurate data for penstock route distance is considered to be the archival maps.

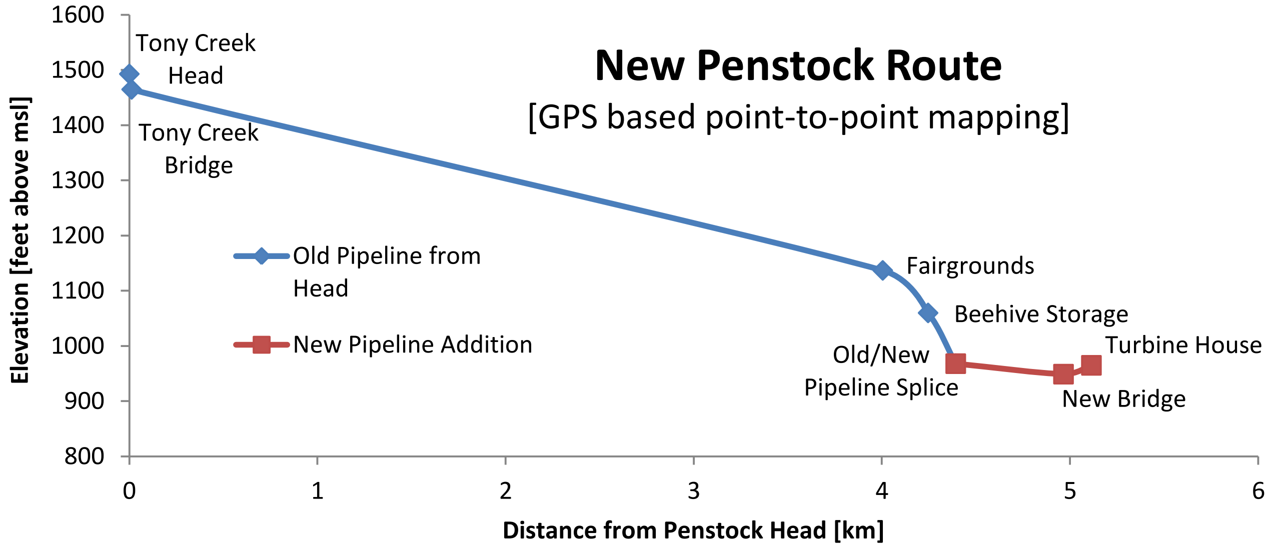


Figure 7. Elevation change as a function of distance from the penstock head (Tony Creek water intact).

The GPS device used was able to generate altitude readings as well, presumably from satellite triangulation. The GPS altitude numbers are suspected of being highly inaccurate, as is apparent from the discrepancy between the high and low estimates, seen on page 12. Altitude was additionally measured at each GPS location by a 40 year old skydiving altimeter with a resolution in the hundreds of feet. The most accurate altitude estimate was made by filling the old penstock route to the top with water. Static pressure at the tail of the penstock was then measured by a purpose-built water pressure gauge at zero flow. This static hydraulic pressure can be used to calculate total head, assuming incompressible water, and is considered the most accurate measurement.

Mapping Data

TOTAL HEAD

The total head of the penstock as measured by different equipment:

- GPS high estimate – 528 ft
- GPS low estimate – 499 ft
- Skydiver Altimeter – 500 ft
- Statically Charged Head Pressure (205 psi) – 473.1 ft [BEST]

TOTAL PIPELINE DISTANCE

The total distance traversed by the pipeline as measured by different means:

- Google Maps – 3.4 miles
- GPS point-to-point – 3.18 miles
- Map Archive – 3.8 miles [BEST]

Calculations

ASSUME

Assumptions made in calculations:

- Incompressible
- Steady state (penstock is not emptying)
- Constant temperatures (everything equals about T = 20°C)
- Constant Moody Friction Factor per pipe section
- Constant material and liquid properties in each section
- Nozzle Coefficient of 1 at penstock tail
- Measurements consider pressure drop beginning immediately after screen house

CORRELATIONS USED

Entry Length

[considered only at head source]

$$L_e \approx 10\,d$$

Reynolds Number

[flow is everywhere turbulent, $Re > 2300$]

$$\mathrm{Re} = \frac{\rho \mathrm{v} D_H}{\mu} = \frac{\mathrm{v} D_H}{\nu} = \frac{\mathrm{Q} D_H}{\nu A}$$

Relative Roughness

$$\frac{\epsilon}{d}$$

Moody Friction Factor

$$f = fnct(Re_d, \varepsilon/d)$$

<u>Friction Head Loss</u>

Hazen-Williams Method

$$h_f = \frac{10.67 \quad L \quad Q^{1.85}}{C^{1.85} \quad d^{4.87}}$$

Darcy-Weisbach Method

$$h_f = f \frac{l}{d} \frac{V^2}{2g};$$

Minor-Loss

$$h_L = K_L V_{avg}^2 / 2g$$

Pressure Drop

$$\Delta P = \rho\, g\, h_f$$

Power Available

$$W = Q\, \rho\, g\, h$$

Friction Losses

The Darcy-Weisbach method is the familiar correlation used for calculating friction head loss in any sort of duct, for any sort of fluid. Simple and easy to use, it is derived from dimensional analysis. However, the head loss is directly proportional to the Moody Friction Factor, which can be difficult to estimate, and is a function of Reynolds number. The Moody Friction Factor thus changes with velocity.

Alternatively, the Hazen-Williams method is specifically designed for use in water-filled pipe systems. The roughness coefficient, *C*, is not a function of Reynolds number, and is considered more accurate, but is only valid for water. Also, the Hazen-Williams correlation cannot account for changes in viscosity or temperature, of which there are practically none in the penstock under consideration.

All of the friction coefficients and friction factors used in the head loss calculations were looked up in tables. Besides the pipe material, age and life history (maintained full versus maintained empty) are taken into account in certain tables. But the bottom line is that choosing a friction coefficient is largely guesswork, since cutting the pipeline open is scanning its surface with an electron microscope was unfeasible. The following tables list the choices of friction factor and friction coefficient used.

Head Source to Splice

Pipe Section	Length [ft]	Roughness Coefficient	Moody Friction Factor	Diameter [inches]
16" entry length	14	64	0.027	16
16" 60yr old cast iron	15000	64	0.027	16

Splice to Turbine – Old Route

Pipe Section	Length [ft]	Roughness Coefficient	Mood Friction Factor	Diameter [inches]
16" 60yr old cast iron	500	64	0.027	16
10" new plastic	200	150	0.014	10
8" 50yr old steel	200	100	0.017	8
10" 50yr old steel	1000	100	0.018	10
10" new steel	500	140	0.016	10

Splice to Turbine – New Route

Pipe Section	Length [ft]	Roughness Coefficient	Moody Friction Factor	Diameter [inches]
16" new cast iron	20	130	0.018	16
12" new cast iron	2200	130	0.02	12
10" new steel	600	140	0.016	10

Table 1. Compilation of friction head loss coefficients for each section, material, and age of pipe.

Minor Losses

To calculate the head loss due to the many, many fittings encountered by the penstock, the familiar minor loss correlation was used. To estimate the minor loss coefficient, K_L, for each fitting, tables were consulted. Fittings were counted by following the route of the penstock and noting each protruding valve controller or tap. Geometry fittings, such as elbows and T's, were accounted for by inference or by consulting one of several incomplete pipeline maps. There is still much uncertainty regarding exactly how many fittings exist and of what sort they are, but the estimates presented here are close enough.

Head Source to Splice

Fitting	Quant.	Minor Loss Coefficient	Diameter [inches]
16" welds every 40'	375	0.001	16
16" T straight pass	3	0.9	16
16" Y	1	1.2	16
16" 45	4	0.4	16

Splice to Turbine – New Route

Fitting	Quant.	Minor Loss Coefficient	Diameter [inches]
12" joints every 20'	110	0.08	12
10" welds every 40'	15	0.001	10
16"-12" reducer	1	0.21	14
12"-10" reducer	1	0.14	11
12" gate valve	1	0.2	12
10" gate valve	2	0.2	10
10" 22 splice	1	0.1	10
12" 45	2	0.4	12
12" T straight pass	1	0.9	12
10" T straight pass	1	0.9	10
10" T cornering	1	2	10

Splice to Turbine – Old Route

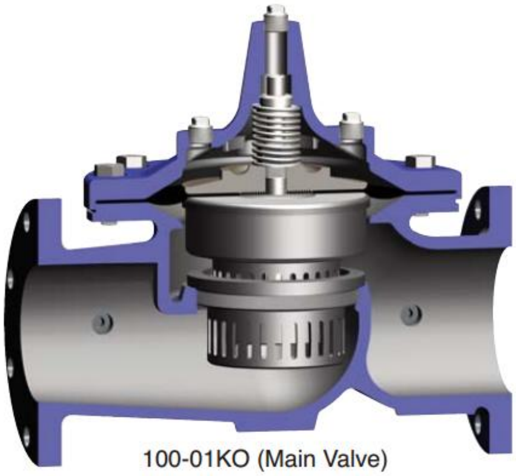
Fitting	Quant.	Minor Loss Coefficient	Diameter [inches]
16" welds every 40'	12	0.001	16
10" joints every 20'	20	0.08	10
8" welds every 20'	25	0.001	8
10" welds every 20'	50	0.001	10
10" welds every 40'	12	0.001	10
16"-10" reducer	1	0.31	13
10"-8" reducer	1	0.17	9
8"-10" enlarger	1	0.136	9
16" Clay press. reducer	1	6.8	16
16" gate valve	2	0.2	16
10" gate valve	9	0.2	10
8" gate valve	1	0.2	8
10" plastic-steel splice	1	0.08	10
16" Y	1	1.2	16
16" 45	2	0.4	16
16" 22	1	0.8	16
10" 90	2	1.5	10
10" 45	4	0.4	10
10" T straight pass	10	0.9	10
10" T cornering	3	2	10
8" 90	3	1.5	8
8" T straight pass	3	0.9	8
8" T cornering	2	2	8

Table 2. Compilation of minor head loss coefficients for each fitting and joint of pipe.

Cla Val Inclusion

In one section of the penstock – the older, soon-to-be-abandoned section – there exists a Cla Val brand pressure reducing valve that is set to Full Open. To include the head loss due to flow through this valve, information about the thing was gathered from the manufacturer's website.

Figure 8. Schematic of the Cla Val to the right. The full-open pressure reducing valve can be considered as two pipe joints, four 90° bends, a reducer, and an enlarger; totaling to a minor loss coefficient of about $K_L = 6.8$.



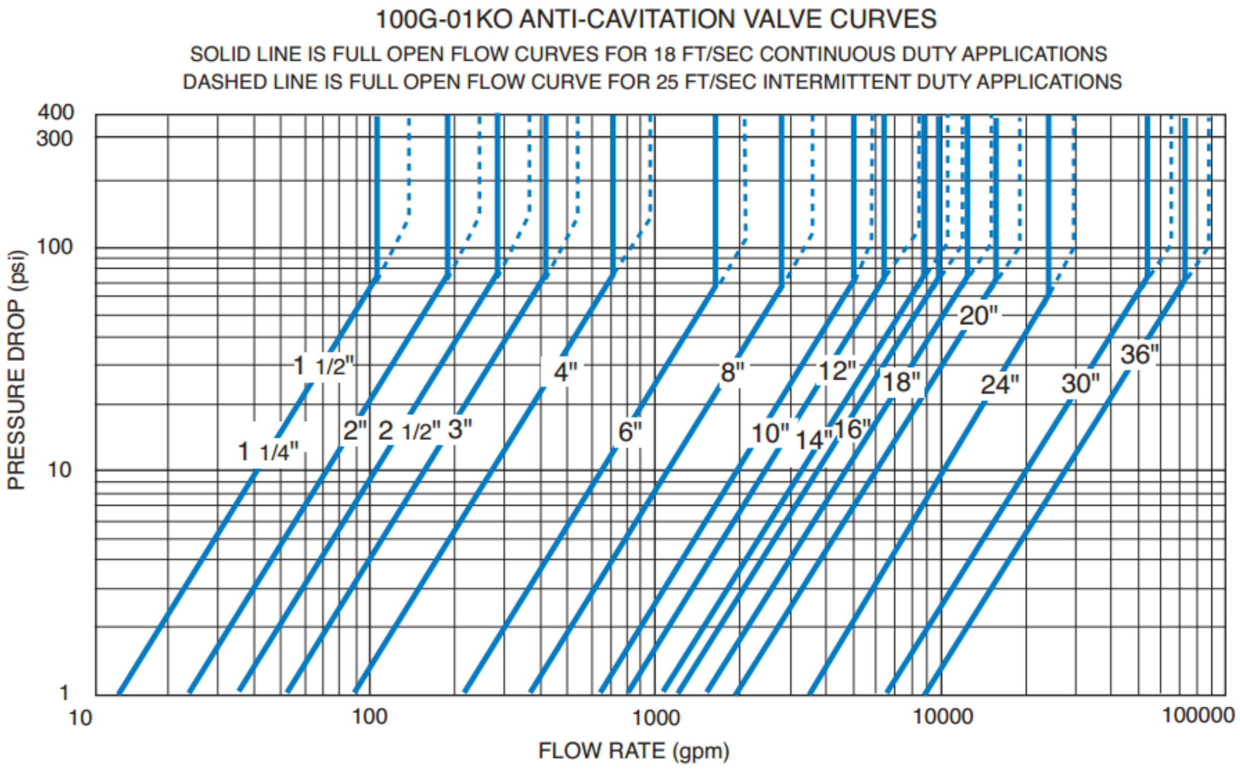


Figure 9. Headloss due to Cla-Val at different flow rates through various diameter pipes. This figure may be used to corroborate the head-loss calculations for a 16" pipeline.

Results

Theoretical head loss and available power were calculated at several representative flow rates: 0.9, 1.5, 2.0, 2.5, 2.5, 3.3, 4.7, and 6.2 cubic feet per second. These flow rates were chosen to allow for direct comparison with the 2001 measurements, which were taken at the same flow rates. Flow of 2.5 ft^3/s was used in calculations to estimate the maximum legal power available, since this is the allowable water right. The results of the calculations are demonstrated in the following plots.

EXAMPLE POWER CALCULATION [Flow Rate = 2.6 ft^3/s = 0.0736 m^3/s]

Friction Losses – 16 inch section of pipe

d = 16” = 0.4064 m
$\mu = 1.002 \times 10^{-3}$ Pa·s
$\rho = 998\ kg/m^3$
C = 64

$f = 0.027$
L = 4572 m
$g = 9.81\ m/s^2$
H = 144.2 m

Velocity = V = [flow rate] / (πr^2) = 0.0736 m^3/s / ($\pi (0.4064\ m)^2/2$) = 0.5674 m/s

Re = (998 kg/m^3)(0.5674 m/s)(0.4064 m) / (1.002x10^{-3} Pa s) = 229,671 {*Turbulent*}

$L_e = 10\ d = 4.064\ m$

Hazen-Williams

$$h_{f,Hazen} = 10.67\ (4572\ m + 4.064\ m)\ (0.0736\ m^3/s)^{1.85} / (64^{1.85}\ (0.4064\ m)^{4.87}) = 14.31\ m$$

Darcy-Weisbach

$$h_{f,Darcy} = (0.027)(4572\ m + 4.064\ m)(0.5674\ m/s)^2 / ((0.4064\ m)\ 2\ (9.81\ m/s^2)) = 4.99\ m$$

Minor Losses – 16 inch pipe welds every 40 ft (roughly 375 welds)

V = 0.5674 m/s

$K_L = 0.001$

$$h_L = (0.001)\ (0.5674\ m/s)^2 / (2\ (9.81\ m/s^2)) = 0.0062\ m$$

Totals – for 16 inch pipe section and welds (using Hazen/Darcy average)

$h_{tot} = (h_{f,Hazen} + h_{f,Darcy})/2 + h_L$ = 9.66 m head loss

$\Delta P = (998\ kg/m^3)(9.81\ m/s^2)(9.66\ m)$ = 94,575 Pa pressure loss

$W = (0.0736\ m^3/s)(998\ kg/m^3)(9.81\ m/s^2)(144.2 - 9.66)$ = **96.0 kW available** considering only head loss in 16 inch pipe with welds.

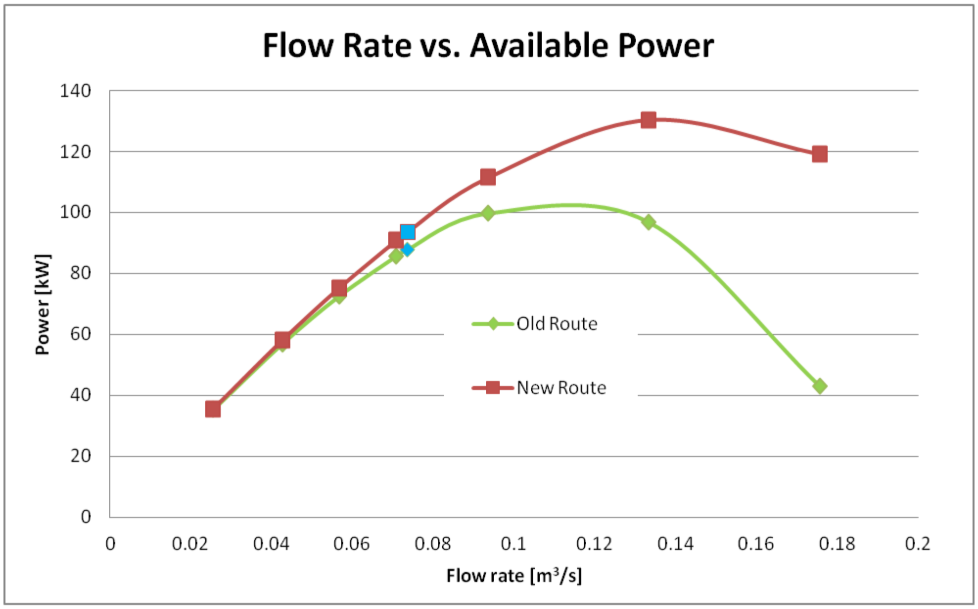


Figure 10. The available power is plotted as a function of different flow rates. Note the increasing divergence between the old route and new route at higher flow rates. This trend is due to the importance of flow velocity in friction and minor head loss.

Predict. [2.6 CFS]	**HEAD LOSS [m]**		**AVAILABLE POWER [kW]**	
	Darcy	**Hazen**	**Darcy**	**Hazen**
OLD ROUTE	16.0	28.6	92.6	83.5
NEW ROUTE	9.5	18.9	97.3	90.5

Table 3. Head loss and available power calculation results for a flow rate of 2.6 CFS, slightly higher than legally permitted. Note the discrepancy between Darcy and Hazen methods for estimating results. Also note the unanimous improvement in power availability due to the new route.

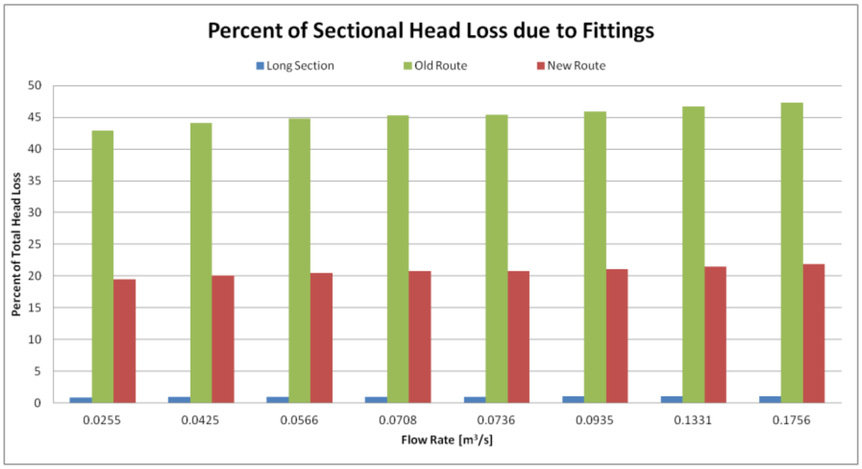


Figure 11. Head loss as a result of fittings, called minor loss, is plotted for different flow rates. Of note is the miniscule minor loss exhibited by the long, fitting-less section of pipeline which spans the length from Tony Creek to the old/new route splice. The new route was expected to be, and was designed as an improvement over the old route by virtue of its lack of fittings. This expectation is fulfilled, as demonstrated by the over 50% decrease in minor head loss along the new route versus the old route. However, minor loss as a percentage of total loss is only significant if the total loss of the analyzed section is large.

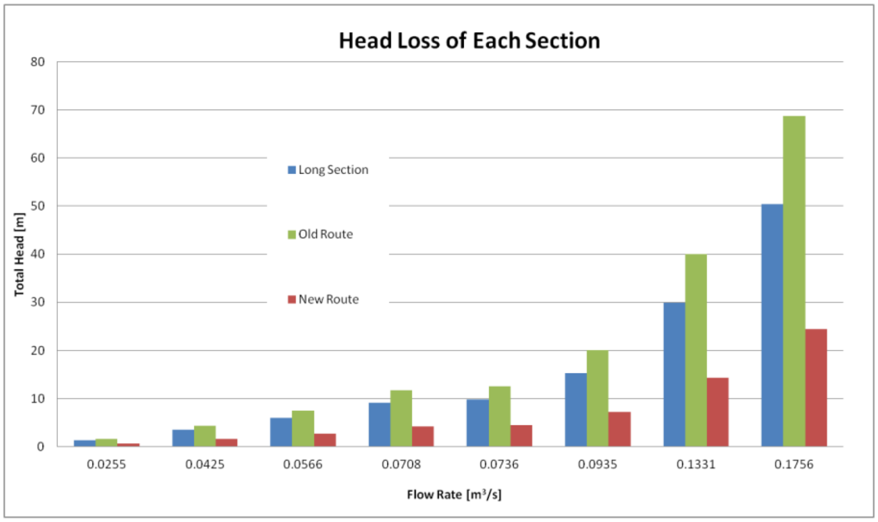


Figure 12. Total head loss in each section of pipeline is plotted as a function of water flow rate. While head loss increases across the board with increasing flow rate, head loss in the old section of pipeline increases proportionally more than in the new section or long section. This is because a higher percentage of the old section head loss is due to minor losses than in the new section or long section, as evident in Figure 11. The equation for calculating minor loss is a function of the square of flow velocity. The equation for calculating friction loss is an average of the Darcy correlation, which is a function of the square of flow velocity, and the Hazen correlation, which is a function of flow rate to the power of 1.85, slightly less than squared. Higher flow rates will therefore increase minor losses by a greater proportion than the increase in average friction head loss. Fittings are proportionally more detrimental that friction, relative to flow.

Original Flow Measurements

In 2001, flow measurements were taken by the old route using the device shown in Figure 13. Pressure was measured in the 10 inch diameter section of pipeline before flow was routed through a reducer fitting, of K = 0.8, and into a 3 inch diameter new steel pipe. There it passed a small, fully open gate valve, of K = 0.2, before shooting out a well-machined nozzle, with nozzle coefficient assumed to be 1. Because the pressure measurements were taken upstream of the last two fittings and 3 inch section of pipe, the measurements must be modified to correct for the additional head loss due to these bits. Using Bernoulli's principle, and assuming incompressible flow, it is possible to calculate the pressure at the nozzle, given the 10 inch section pressure, and thereby correct the flow and power data in Table 4.

Bernoulli's Principle:

$$\frac{v^2}{2} + gz + \frac{p}{\rho} = \text{constant}$$

PENSTOCK PRESSURE (PSI)	NOZZLE DIAMETER (INCH)	CALCULATED FLOW POWER (KW)	CALCULATED FLOW (FT^3/S)
205	static	0	0
200	1.0	35.6	0.9
193	1.3	56.9	1.5
186	1.5	72.2	2.0
170	1.75	85.8	2.6
153	2.0	95.1	3.3
125	2.5 (female pipe thread)	110	4.7
110	3.0 (3 inch gate valve, open)	131	6.2

Table 4. Compilation of pressure per nozzle size measurements from which flow and power were calculated. The last two rows used open, threaded pipe ends as nozzle and are thus likely subjected to additional, confounding head loss due to their poor nozzle coefficients. Nozzle coefficients are assumed otherwise as 1.

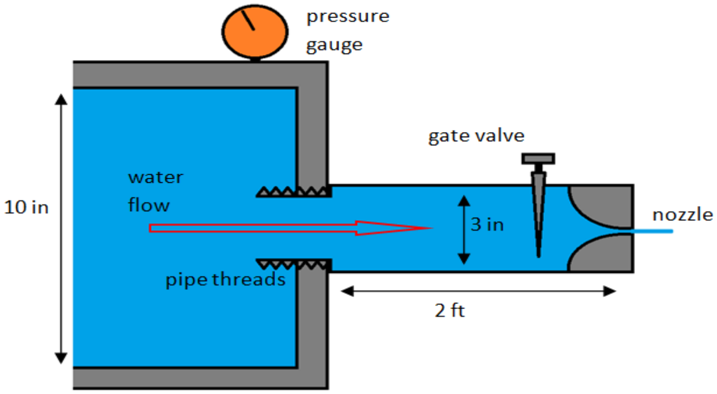


Figure 13. Schematic of pressure measuring device used to make 2001 flow and pressure measurements. Note the location of the pressure gauge far upstream from the nozzle. Using Bernoulli's principle, the pressure readings can be corrected to account for the poor design of the device, moving the effective pressure gauge readings to reflect pressure at a position immediately before the nozzle, much like Figure 17.

Corrected Flow Measurements

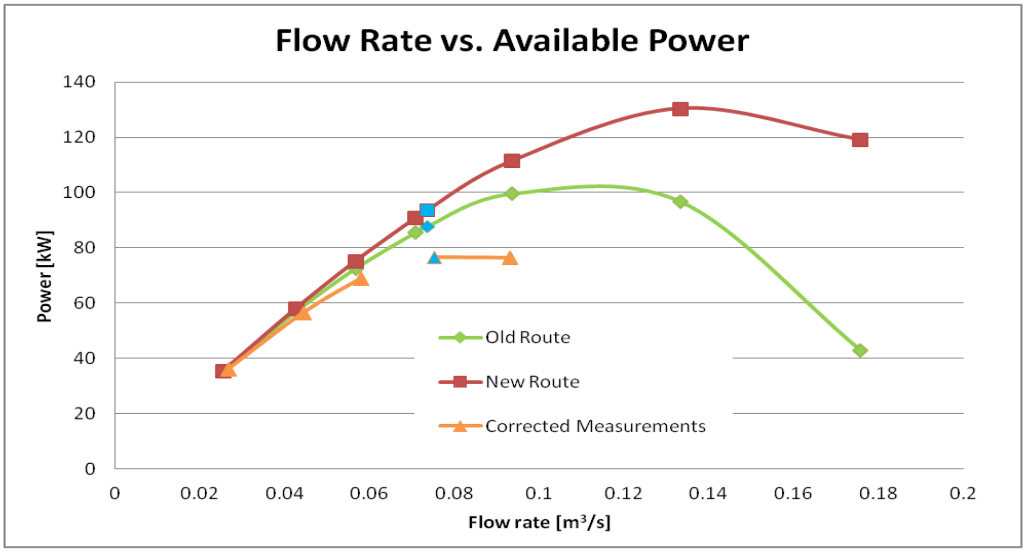


Figure 14. The available power is plotted as a function of different flow rates for the new route, the old route, and the correct old route measurements, with several unreliable data removed. Note the significantly lower predicted power of the corrected measurements. This is due to the tiny, 3 inch tube down which the flow was made to squeeze. Since flow velocity increases fourfold with each halving of diameter, and head loss increases with the square of velocity, power is a fourth order polynomial function of pipe diameter.

At 2.6 CFS	HEAD LOSS [m]			AVAILABLE POWER [kW]		
	Darcy	Hazen	Meas.	Darcy	Hazen	Meas.
OLD ROUTE	16.0	28.6	40.1	92.6	83.5	76.6
NEW ROUTE	9.5	18.9	NA	97.3	90.5	NA

Table 5. Select head loss and power prediction data, at a flow rate of 2.6 CFS, including the corrected measurement numbers. Although the corrected measurements are markedly lower that what was estimated theoretically, they are likely more representative of the power that will be delivered to a turbine some day. Suffering from increased pressure drop due to the slight 3 inch section through which the measured flow must pass is similar to the pressure drop in a narrowing Pelton nozzle apparatus, as seen in Figure 16.

Conclusion

All three objectives addressed in this report were satisfied by the end of the project. The route was accurately mapped, with consideration to both overall length and elevation changes, using several different methods. Fittings were counted and pipe material and size were noted. Loss coefficients appropriate to each governing correlation were estimated with the help of tables.

Both Darcy-Weisbach and Hazen-Williams correlations were used to predict friction head loss. Minor head loss was estimated via the minor loss correlation. The construction of a Cla Val pressure reducing valve was analyzed, and the manufacturer's website was consulted, to estimate the minor loss of such a fitting. From head loss and flow rate, available power could be estimated. Discrepancies between the estimates produced by the two different friction head loss correlations were shown to be a result of the differing sensitivity of each correlation to flow velocity. Sample calculations for available power were used to clarify this point.

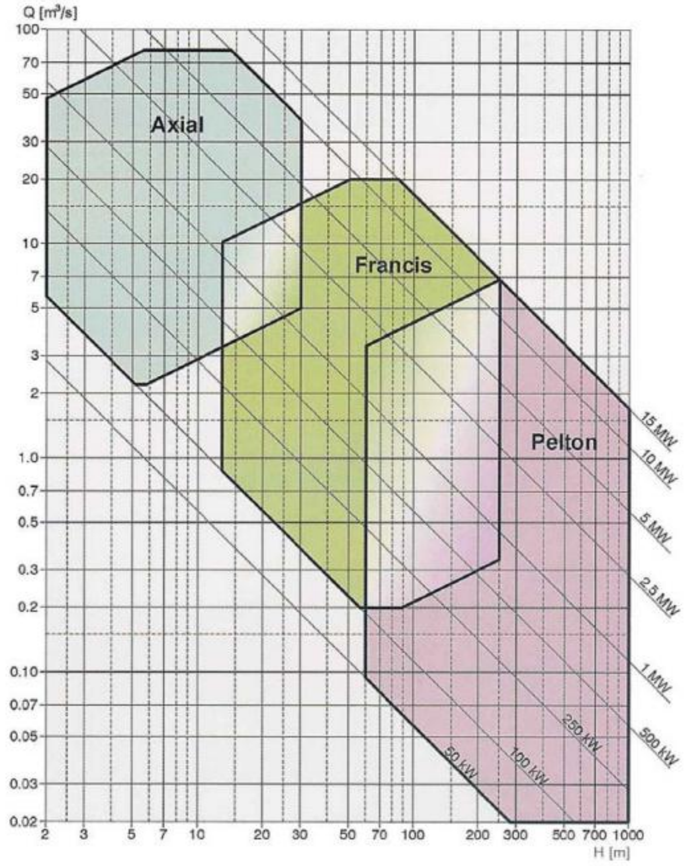


Figure 15. Broadly generalized chart using flow rate and head combinations to estimate available power. The useful point demonstrated here is turbine selection: Peltons are used at high head, low flow installations.

Head loss was shown to be a function of not only flow rate, but also differentiated by penstock section. Head loss due to fittings in each penstock section was compared. The new route demonstrated much lower head loss due to fittings than the old route. Total head loss in each section was compared, again showing the improved performance of the new route relative to the old route. The new penstock route hosts fewer fittings than the old route, both overall and as a percentage of total head loss. The new penstock route also exhibits less overall head loss than the old route, especially at higher flow rates where minor losses become dominant due to their greater sensitivity to flow velocity. The new route is certainly an improvement over the old route.

To verify the estimates of head loss and available power, the theoretical numbers calculated for the old route were compared with experimental measurements taken in 2001. First, the measurements were corrected to compensate for the design of the measurement apparatus. Then, corrected head loss and power data were compared to both the new route and old route theoretical data.

The original measurements, once corrected, suggested an available power considerable less than that predicted theoretically for the old route; 77 kW for the measurement data versus an average theoretical prediction of 86 kW at a flow rate of 2.5 cubic feet per second. This discrepancy in available power prediction is due to a thin section of pipe used in the testing apparatus but not found in the theoretical calculations. However, such a thin section of pipe can be expected in a turbine setup, just prior to the nozzle, as shown in Figure 16.

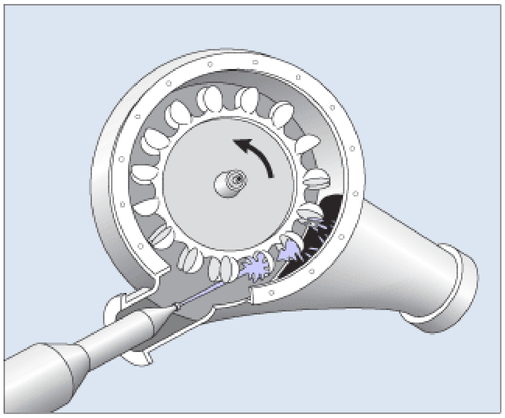


Figure 16. A Pelton wheel and nozzle.

Running at the full water right of 2.5 cubic feet per second, and estimating an overall new route head of around 427 feet, the power available in the penstock is expected to be close to 93 kW. Given this power estimate, head, and flow, and consulting Figure 15, the recommended turbine is a Pelton wheel. Pelton wheels are generally used for high head, low flow hydroelectric installations, like this one.

However, due to the lower estimate for available power found by measurement corrections versus theoretical calculations in the old route, it is reasonable to suspect that the new route will also supply about 12 percent less power that theoretically surmised, or about 80 kW. Therefore, unless more accurate measurements for the new penstock route can be obtained before turbine installation, it would be wise to install a turbine optimized to perhaps half of the 93 kW, with the option of a second turbine to be installed in parallel, if available hydraulic power would make doing so viable.

In future, once the new penstock route is completely finished and filled, it would be well advised to construct a more accurate pressure and flow measuring device to retake the 2001 data via the new route. Such a measuring device may look like the schematic in Figure 17. Preferably, the measuring device would be used at regular intervals over a year-long study to estimate a normal high and low flow rate. Turbine selection could then be revised as necessary to provide the most efficient design.

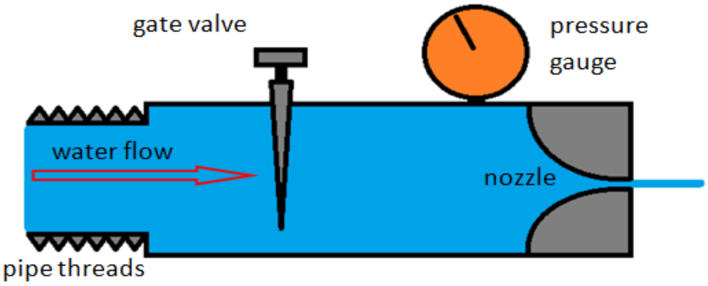


Figure 17. A corrected flow and pressure measuring apparatus.

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