Small-Scale Hydroelectric Power Generation Potential: A case study of Washpen Falls

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Abstract:

Small-scale hydroelectric power generation provides an attractive alternative power source for homeowners that have a river or stream running through their property. The power generation potential of a stream is dictated by two main factors: the hydraulic head and the discharge. Estimating these two factors is the first step in assessing the feasibility of installing a small hydroelectric generator. This paper details methods for a pre-feasibility study and describes a case study performed at Washpen Falls in the Southern Malvern Hills, New Zealand. Using a Global Positioning Systems is an accepted method for measuring head for a pre-feasibility study, so it warrants little discussion. However, the float and weir methods for measuring the discharge of the stream are discussed in detail. For the case study, the observed discharge and head were input into a simple formula to estimate the power generation potential of the stream. Using the power estimate, a potential annual savings of $4,500 NZD was calculated. Based off this potential savings, the owner of Washpen Falls can make a better-informed decision whether or not to contact professionals about installing a hydropower system. The simple to follow methods used in this study are widely applicable to other streams and rivers. Armed with a free tool for investigating their own stream or river, more people will gain interest in small-scale hydropower. Those who build such a system will generate monetary benefits for themselves, and improve the overall environmental health through the reduction of the use of fossil fuels.

1. Introduction:

The average New Zealand household uses 11,410 kWh per year of electricity (Isaacs, Camilleri, Burrough, Saville-smith, & Cresa, 2010). As the population keeps growing, the demand for energy also increases steadily. This electricity mostly comes from large-scale hydroelectric dams and fossil fuel burning power plants (Elliot, Moore, Field, Hunt, Lawrence, & Thornton, 2011). As the price of electricity rises, more people are looking for alternative sources of energy (Brazier, Cuthbert, Tones, Williams, McClean, & Wellington, 2010). Small-scale hydroelectric power (SHP) systems will help people reduce their energy costs, make them more energy independent, and reduce their carbon footprint.

SHP generation offers a promising alternative for many New Zealand residents, because of the landscapes present around the Southern Alps. There are many small rivers and streams running through the foothills surrounding the Southern Alps, which translate to real potential for SHP. One such area is the Malvern Hills in Canterbury, New Zealand. One of the property owners in the Malvern Hills, Tom McElrea, has expressed interest in a small-scale hydropower system. He is the owner of Washpen Falls, which has been used for SHP before. One of the previous owners of Washpen Falls installed a system over 30 years ago, but it has since stopped functioning. With the owner's permission, a pre-feasibility study for a SHP system was conducted at the falls.

A pre-feasibility assessment is the first step in developing a SHP project. In figure 1 Singal (2009) shows the complete process for planning a SHP project. For a pre-feasibility study, the hydraulic head, which is the change in height of the water, and stream discharge, or flow, are measured because they are the driving factors behind power generation potential. For this paper, the float and weir methods are discussed for measuring small flows. Using a Global Positioning System (GPS) or a surveying level is discussed for estimating the head of a stream or river.

When looking into SHP planning, it is important to know some of the basic mechanics and set up of the systems. SHP systems involve highly specialized parts that are dependant on the head, the magnitude of the flow, and several other factors. For this reason SHP is typically broken down into four categories: small (< 25 MW), mini (< 2 MW), micro (< 500 kW), and pico (< 10 kW) (Paish, 2002). Small-scale systems are also categorized by how the water is moved to power the turbine. There are run-of-the-river systems (RoR), dam toe systems, and canal based systems (Singal, 2009). A RoR system uses a weir to divert a portion of the stream into a pipe called a penstock. Using a RoR system does not change the natural head of the stream. A dam toe design puts a dam in the stream, which blocks the passage of water down stream creating artificially high head for more power generation. The dam toe design offers the potential for more power generation, but is more disruptive to the local ecology. Canal based designs can be used in the canal itself or in its bypass channel (Singal, 2009. Because of their unobtrusive design, SHP systems have much smaller impacts on the environment than their large-scale counterparts that require large areas to be flooded.

There are several other important features to consider in designing a small-scale hydropower system. These features include a turbine, power channel, desilting tank, forebay, penstock, powerhouse building, and tailrace channel (Brazier et al., 2010). The powerhouse contains the turbine, which is the most important piece of the design after sign selection. There are many different models that can be used, depending on the site specifics. Turbines are broken down into two categories, impulse turbines and reaction turbines. The technical differences between impulse and reaction turbines are beyond the scope of this paper, but generally impulse turbines are used for relatively higher head (Arndt, 2010).

2. Methods

It is possible for a homeowner interested in a small hydropower system to get an order of magnitude estimate of power generation. To estimate power generation, the hydraulic head and flow of the stream need to be measured. The measured values can then be input in to the equation

$$P = (Q)*(H)*(g)*(\eta)$$

Where P is power generation in kW, Q is stream flow in m^3/s, H is hydraulic head in m, g is acceleration due to gravity in m/s^2, and η is a system efficiency factor (Brazier et al, 2010).

2.1. Stream Discharge Measurement

There are several ways to measure the discharge of a stream. The two discussed in this paper are the float method and the weir method. For the case study in the Southern Malvern Hills the float method was used due to time and resource constraints, as well as to be unobtrusive on the property.

2.1.1. The Float Method

The float method is the simplest way to measure the flow of a stream because it requires the least equipment and time. This method uses the product of the cross section of the stream and the average velocity of the water to calculate the flow. This is represented by the equation

$$Q = A * v$$

Where Q is the flow in m^3/s, A is the cross-sectional area in m^2, and v is the average velocity of the stream in m/s. To measure the cross section of the stream, a cloth tape was laid across the surface, perpendicular to the direction of the flow. The length across the stream was measured from the tape and then depths were measured using a meter stick at regular intervals across the stream. An example cross-section from Washpen Falls can be seen in figure 2.

To measure the velocity of the stream, two markers were set one meter apart along the flow of the river near where the cross section was taken. An orange was then place in the water slightly above the upstream marker and was timed as it moved from the first marker down to the second[1]. Where it was possible to avoid rocks and eddies, the orange was placed at different starting positions to get a more accurate average velocity. Usually between three and six trials were conducted at each cross section depending on the width of the stream and regularity of the current. For larger streams, it is possible to use a mechanical current meter to measure the velocity, which is more expensive, but more accurate than using a float (Penche, 2004).

2.1.2. The Weir Method

The weir method is a more accurate method for measuring the flow of a relatively small stream ($<4m^3/s$) and currents < 0.15 m/s (Citation). For this method, a portable weir is constructed with a notch of a prescribed size and placed into the stream so all of the flow is channeled through the notch. The dimensional ratios for constructing a weir can be found in “Guide on How to Develop a Small Hydropower Plant” by Penche, 2004. Once the weir is in the stream, the upstream height of the waters surface is measured and

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[1] An orange was listed as the optimal float in (“Volunteer Stream Monitoring: A Methods Manual Section 5.1 Stream Flow”, 2012; Harrelson, Rawlins, & Potyondy, 1994).

put into a formula to calculate the flow. The equations for a rectangular notched and a right triangular notched weir are:

$$Q = 1.8(L - 0.2*h)* h^{3/2} \qquad \text{(rectangular)}$$

$$Q = 1.4 * h^{3/2} \qquad \text{(triangular)}$$

Where Q is the flow (m^3/s), L is the length of the opening and h is the height of the water flowing through the notch (both in meters) (Penche, 2004). The triangular notch is better suited for extremely low flows, while the rectangular notch can handle a wider variety of flows.

2.2. Gauging the Hydraulic Head

Measuring the head of a stream is a simple task using a GPS with a built in altimeter. For this case study, the height of the stream was recorded periodically down the river at the points where the flow was measured. This gave a relative change in elevation along the river, which is a suitable estimate for the head of the stream. For a more accurate estimate of the head, a leveling survey can be conducted for the region, but this requires more sophisticated equipment and training in its use.

3. Results

The results of the flow measurements and elevations are given in Table 1. There is substantial variation in the flow as the measurements move downstream; the flows measured range from 0.015 m^3/s at Point 2 to 0.055 m^3/s at Point 9. The elevation of each point was recorded using a Garmin GPS. The total change in elevation over the recorded area is approximately 72 meters and the difference between the base of the waterfall and the lowest point is 61 meters.

There were several other points of interests were recorded in the GPS. These included the desilting tank, inlet, and power station of the old system that is on the stream. The desilting tank is a relatively large pond located on a flattened hillside about 15 meters from the stream. The lowest elevation point recorded was the power station, which is located on the stream bank at the base of the hill that the desilting tank is on.

For estimating the power output, the flow and initial elevation were taken from point 9 because of its close proximity to the existing inlet. The lowest point mapped was used for the second elevation to calculate the head. Using a conservative efficiency factor of .5 (Brazier et al., 2010) and the equation of power generation found in the method section, the power was calculated to be 4.4kW. This was then converted to annual energy produced (assuming a constant flow, but adjusted for seasonality of flow using a .5 capacity factor (Brazier et al., 2010)) to get a savings value of $4,483.00 NZD per year.

4. Discussion

4.1 Errors in Methods

The goal of this study was to provide an order of magnitude estimate of the power generation and a corresponding potential savings. In order to achieve this estimate in an efficient manner, accuracy was sacrificed for simplicity of methods. An answer was calculated using exact values, but due to the different levels of accuracy and precision in certain variables, calculated values should only be considered to two significant figures.

The literature makes it clear that there are many sources of error (Brazier et al., 2010; Penche, 2004; Harrelson, Rawlins, & Potyondy, 1994) that need correction when using the float method. There are blatant inconsistencies in the data collection, an example of which is that the flow is cut in half between Points 1 and 2, but jumps back up to a value similar to the first measurement at Point 3. While taking the measurements, no feature was found that could have caused this radical and short-term drop in the flow. There are several potential causes for the errors. The EPA suggests taking the float measurements over straight and calm 20ft section (“Volunteer Stream Monitoring: A Methods Manual Section 5.1 Stream Flow”, 2012). The stream was too small and winding to find any sections that were 20ft long and suitable for a float measurement, so 1m or 1.5m lengths were used (these were the longest areas that were straight and calm). Due to the rocky nature of this stream, there were also eddies that could have disrupted the float and biased the measured velocity. Thirdly, the EPA also suggests that the stream be at least 6in deep for measurements (“Volunteer Stream Monitoring: A Methods Manual Section 5.1 Stream Flow”, 2012). For several measurement locations, the stream was shallower than the EPA’s suggestion. All three of these errors could have been avoided if the weir method were used. So it is recommended that the weir method be used for any future studies.

The GPS has errors built into it for elevation as well as coordinates. It also becomes less accurate in valleys where it experiences poor reception. The base of the waterfall (Point 4) is in a deep and steep sided valley, which may explain why the altimeter read 516m and then 536m at Point 5. Point 5 was down stream of the waterfall and should have an elevation lower than that of the base of the waterfall, because water can't flow uphill. This error is unavoidable, but is the only convenient method for this level of survey. If a more serious survey is conducted, a survey level should be used for a much greater degree of accuracy (Brazier et al., 2010; Penche, 2004).

4.2. The Next Step

The potential annual savings was calculated to be approximately $4,500 NZD. Micro scale SHP projects can cost between $8,000 and $30,000 NZD, which means the breakeven period would be between two and seven years[2]. If properly maintained, a micro hydropower system has a much longer useful life than that (Penche, 2004) so it would probably be worthwhile for Mr. McElrea to contact a professional and get their opinion. Because there is an existing, although nonfunctioning, system already in place, there is the potential for additional savings by upgrading that system as opposed to installing an entirely new one. The Cutterne Mill Hydro project (South Somerset District Council, 2006) is an example where there was substantial savings from existing infrastructure. If Tom moves ahead with this project, the next step is to get quotes from different installation companies and contract one to do a more detailed feasibility study.

SHP generation has large potential for any area with small streams and rivers and varying topography. More research could also look into developing a method for estimating the potential number of sights in a region where a SHP system could be installed. From this, a regional energy savings amount could be estimated. For areas with high potential, it would be beneficial for both engineering companies and government to promote installing SHP systems. This would reduce energy costs for the

[2] This estimate does not include serious economic analysis i.e. depreciation of assets, interest, ect. It is simplely the cost of the project divided by the annual savings.

landowners, create more work for the engineering companies, make the country more energy independent from fossil fuels, and most importantly, reduce CO_2 emissions and promote a healthier environment.

Abbasi, T., & Abbasi, S. a. (2011). Small hydro and the environmental implications of its extensive utilization. *Renewable and Sustainable Energy Reviews*, *15*(4), 2134-2143. Elsevier Ltd. doi:10.1016/j.rser.2010.11.050

"Appliance Running Costs." *Contactenergy.co.nz*. Contact Energy, 2012. Web. 11 June 2012. <http://www.contactenergy.co.nz/web/saveenergy/appliances>.

Arndt, R. E. A. (2007). Hydraulic Turbines. *Energy Conversion* (pp. 1-20). Taylor & Francis Group, LLC.

Brazier, S., Cuthbert, A., Tones, N., Williams, B., McClean, C., & Wellington, G. (2010). *Power from the people : a guide to micro-generation*. Wellington.

Bunn, S. E., & Arthington, A. H. (2002). Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management*, *30*(4), 492-507. doi:10.1007/s00267-002-2737-0

Elliot, T., Moore, B., Field, B., Hunt, P., Lawrence, S., & Thornton, S. (2011). *New Zealand Energy Data File*. Wellington.

Fursdon, G. (2010). Case study summary, (April), 2010.

Harrelson, C. C., Rawlins, C. L., & Potyondy, J. P. (1994). Steam channel reference sites: an illustrated guide to field technique. Gen. Tech. Rep. RM-245. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Isaacs, N., Camilleri, M., Burrough, L., Saville-smith, K., & Cresa, R. F. (2010). *Energy Use in New Zealand Households Final Report on the Household Energy End-use Project (HEEP)*. *Science And Technology* (Vol. 221).

Isaacs, N., Camilleri, M., French, L., Pollard, A., Saville-smith, K., Cresa, F., Rossouw, P., et al. (2006). *Energy Use in New Zealand Households Report on the Year 10 Analysis for the Household Energy End-use Project (HEEP)*. *Science And Technology* (Vol. 155).

Paish, O. (2002a). Micro-hydropower: status and prospects. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *216*(1), 31–40. Prof Eng Publishing. Retrieved from http://pep.metapress.com/index/756355V20257222G.pdf

Paish, O. (2002b). Small hydro power: technology and current status. *Renewable and Sustainable Energy Reviews*, *6*(6), 537-556. doi:10.1016/S1364-0321(02)00006-0

Penche, C. (2004). Guide on How to Develop a Small Hydropower Plant. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Guide+on+How+to+Develop+a+Small+Hydropower+Plant#0

Quintas, M. C., Blanco, C. J. C., & Amarante Mesquita, A. L. (2011). Analysis of two schemes using micro hydroelectric power (MHPs) in the Amazon with environmental sustainability and energy and economic feasibility. *Environment, Development and Sustainability*, *14*(2), 283-295. doi:10.1007/s10668-011-9322-8

Singal, S. (2009). Planning and Implementation of Small Hydropower (SHP) Projects. *Hydro Nepal: Journal of Water, Energy and*, (5), 21-25. Retrieved from http://www.nepjol.info/index.php/HN/article/viewArticle/2480

South Somerset District Council. (2006). *Cutterne Mill Hydro*.

Taylor, P., Stark, J. D., Maxted, J. R., Beach, W. P., & States, U. (n.d.). New Zealand Journal of Marine and Freshwater Research A biotic index for New Zealand ' s soft - bottomed streams A biotic index for New Zealand ' s soft-bottomed streams, (April 2012), 37-41.

Trussart, S., Messier, D., Roquet, V., & Aki, S. (2002). Hydropower projects: a review of most effective mitigation measures. *Energy Policy*, *30*, 1251-1259. Retrieved from http://www.sciencedirect.com/science/article/pii/S0301421502000873

Turbine, F. (2004). CHAPTER 6 : ELECTROMECHANICAL EQUIPMENT.

Wheaton-Green, K. (2005). *South Somerset Hydropower Electricity generation from historic water-mills*.

"Volunteer Stream Monitoring: A Methods Manual Section 5.1 Stream Flow." *EPA.gov*. EPA, 6 Mar. 2012. Web. 10 June 2012. <http://water.epa.gov/type/rsl/monitoring/vms51.cfm>

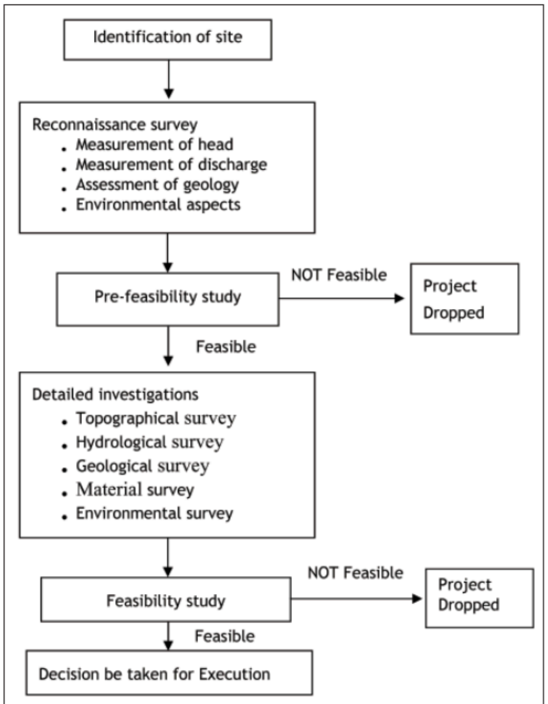


Figure 3. Steps for Project Planning

Figure 1

Taken from Singal, 2009. This flow chart shows the progression of surveying needed to plan a SHP system. Due to the technical nature these systems, all of the literature agrees that a professional should carry out all steps past the pre-feasibility study. Singal included assessment of geology and environmental aspects in the data collection for a prefeasibility study, but Brazier et. al. (2010) discusses how these two factors are more important for larger systems. If there is any uncertainty in what should be examined, Brazier et. al. (2010) suggests consulting a professional for the pre-feasibility study.

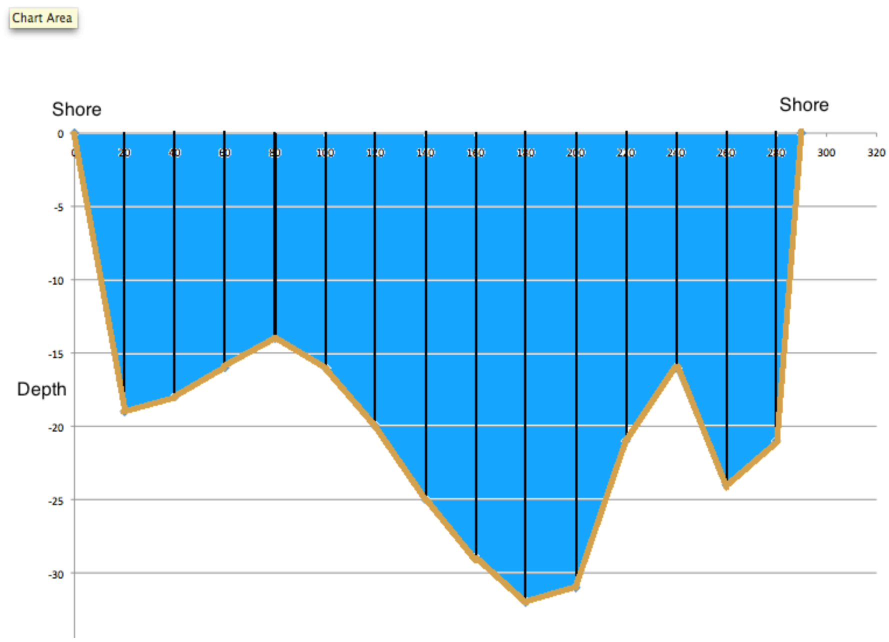
Table 1

Corrected Flows and Elevations at Measuring Points along Stream

Point	Corrected Flow	Elevation (m)
Headwaters		546.6312256
1	0.026	541.1037598
2	0.015	541.1037598
3	0.032	540.8634033
4	0.037	516.8305664
5	0.054	536.0567627
6	0.046	527.1646729
7	0.045	521.3967285
8	0.025	510.5820313
9	0.055	490.8751221
Low Point		474.7731934

The corrected flows and elevations measured at Washpen Falls. The EPA recommends a correction factor of .8, which was used due to the rocky streambed (Volunteer Stream Monitoring: A Methods Manual Section 5.1 Stream Flow, 2012)

Figure 2



This is the cross section taken at point 6. The black vertical lines represent the measured depths, taken at 20 cm intervals over the length of the cross section creating trapezoids with equal bases (except the last section).

Table 2

Power Generation Variables and Calculations for Savings

n	0.5
g (m/s^2)	9.81
H (m)	16
Q (m^3/s)	0.055
P (kW)	4.4
CF	0.5
Hours/Year	8760
E (kWh)	19077
Cost* NZ cents/kWh)	23.5
Savings($NZD)	4483.03

*Cost per kWh estimate was taken from Contact Energy's website ("Appliance Running Costs."). Coefficients "n" and "CF" were taken from Brazier et. al. 2010.