Intro to Hydropower

Part 1: Systems Overview

Dan New

Hydropower is based on simple concepts. Moving water turns a turbine, the turbine spins a generator, and electricity is produced. Many other components may be in a system, but it all begins with the energy already within the moving water.

What Makes Water Power

Water power is the combination of *head* and *flow*. Both must be present to produce electricity. Consider a typical hydro system. Water is diverted from a stream into a pipeline, where it is directed downhill and through the turbine (flow). The vertical drop (head) creates pressure at the bottom end of the pipeline. The pressurized water emerging from the end of the pipe creates the force that drives the turbine. More flow or more head produces more electricity. Electrical power output will always be slightly less than water power input due to turbine and system inefficiencies.

Head is water pressure, which is created by the difference in elevation between the water intake and the turbine. Head can be expressed as vertical distance (feet or meters), or as pressure, such as pounds per square inch (psi). Net head is the pressure available at the turbine when water is flowing, which will always be less than the pressure when the water is turned off (static head), due to the friction between the water and the pipe. Pipeline diameter has an effect on net head.

Flow is water quantity, and is expressed as "volume per time," such as gallons per minute (gpm), cubic feet per second (cfs), or liters per minute. Design flow is the maximum flow for which your hydro system is designed. It will likely be less than the maximum flow of your stream (especially during the rainy season), more than your minimum flow, and a compromise between potential electrical output and system cost.

You need not have this kind of head and flow to have a good hydropower site—but you could fantasize.

Head and flow are the two most important things you need to know about your site. You must have these measurements before you can seriously discuss your project, how much electricity it will generate, or the cost of components. Every aspect of a hydro system revolves around head and flow. In Part 2 of this series, we will discuss how to measure them.

Power Conversion & Efficiency

The generation of electricity is simply the conversion of one form of energy to another. The turbine converts the energy in the moving water into rotational energy at its shaft, which is then converted to electrical energy by the generator.

Energy is never created; it can only be converted from one form to another. Some of the energy will be lost through friction at every point of conversion. Efficiency is the measure of how much energy is actually converted. The simple formula for this is:

Net Energy = Gross Energy x Efficiency

While some losses are inevitable as the energy in moving water gets converted to electricity, they can be minimized with good design. Each aspect of your hydro system—from water intake to turbine-generator alignment to transmission wire size—affects efficiency. Turbine design is especially important, and must be matched to your specific head and flow for best efficiency.

A hydro system is a series of interconnected components. Water flows in at one end of the system, and electricity comes out the other. Here is an overview of these components, from the water source to the electrical controls.

Water Diversion (Intake)

The intake is typically the highest point of your hydro system, where water is diverted from the stream into the pipeline that feeds your turbine. A diversion can be as simple as a screened pipe dropped into a pool of water, or as big and complex as a dam across an entire creek or river. A water diversion system serves two primary purposes. The first is to provide a deep enough pool of water to create a smooth, air-free inlet to your pipeline. (Air reduces horsepower and can damage your turbine.) The second is to remove dirt and debris.

Trash racks and rough screens can help stop larger debris, such as leaves and limbs, while an area of quiet water will allow dirt and other sediment to settle to the bottom before entering your pipeline. This helps reduce abrasive wear on your turbine. Another approach is to use a fine, self-cleaning screen that filters both large debris and small particles.

Useful Hydro Conversions

Power*

1 horsepower = 746 watts

1 kilowatt = 1.34 horsepower

* Efficiency not accounted for

Static Head & Pressure

1 foot of head = 0.43 pounds per square inch (psi)

1 psi = 2.31 feet of head

Flow

1 gallon per minute (gpm) = 0.0022 cubic feet per second (cfs)

1 gpm = 0.000063 cubic meters per second

1 gpm = 3.8 liters per minute

1 cfs = 449 gpm

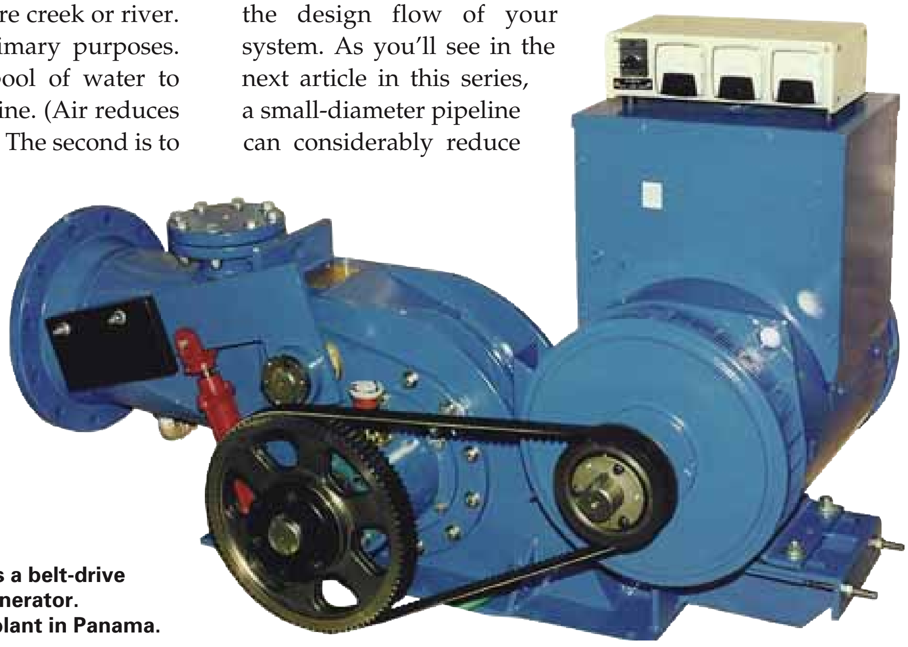
1 cfs = 0.283 cubic meters per second

1 cfs = 1,700 liters per minute

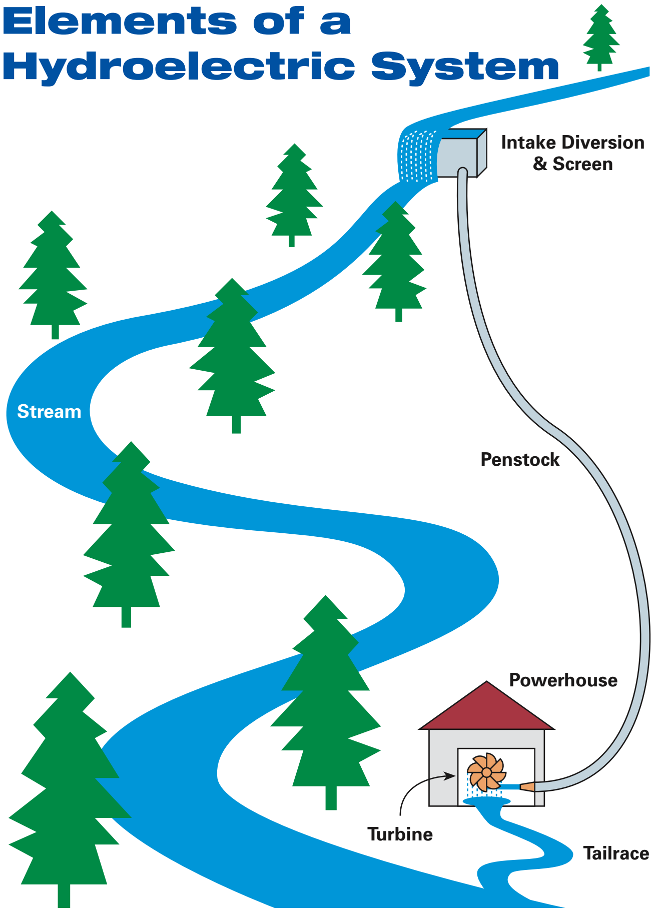
Pipeline (Penstock)

The pipeline, or penstock, not only moves the water to your turbine, but is also the enclosure that creates head pressure as the vertical drop increases. In effect, the pipeline focuses all the water power at the bottom of the pipe, where the turbine is. In contrast, an open stream dissipates the energy as the water travels downhill.

Pipeline diameter, length, material, and routing all affect efficiency. Guidelines are available for matching the size of your pipeline to the design flow of your system. As you'll see in the next article in this series, a small-diameter pipeline can considerably reduce



This variable-flow, crossflow turbine uses a belt-drive coupling to a 40 KW synchronous generator. It supplies electricity to a coffee processing plant in Panama.



your available horsepower, even though it can carry all available water. Larger diameter pipelines have less friction as the water travels through.

Powerhouse

The powerhouse is simply a building or box that houses your turbine, generator, and controls. Its main function is to provide a place for the system components to be mounted, and to protect them from the elements. Its design can affect system efficiency, especially with regard to how the water enters and exits your turbine. For example, too many elbows leading to the turbine can create turbulence and head loss. Likewise, any restrictions to water exiting the turbine may increase resistance against the turbine's moving parts.

Turbine

The turbine is the heart of the hydro system, where water power is converted into the rotational force that drives the generator. For maximum efficiency, the turbine should be designed to match your specific head and flow. There are many different types of turbines, and proper selection requires considerable expertise. A Pelton design, for example, works best with medium to high heads. A crossflow design works better with lower head but higher flow. Other turbine types, such as Francis, turgo, and propeller, each have optimum applications.

Turbines can be divided into two major types. Reaction turbines use runners (the rotating portion that receives the water) that operate fully immersed in water, and are typically used in low to moderate head systems with high flow. Examples include Francis, propeller, and Kaplan.

Impulse turbines use runners that operate without being immersed, driven by one or more high-velocity jets of water. Examples include Pelton and turgo. Impulse turbines are typically used with moderate-to-high head systems, and use nozzles to produce the high-velocity jets. Some impulse turbines can operate efficiently with as little as 5 feet (1.5 m) of head.

The crossflow turbine is a special case. Although technically classified as an impulse turbine because the runner is not entirely immersed in water, this "squirrel cage" type of runner is used in applications with low to moderate head and high flow. The water passes through a large, rectangular opening to drive the turbine blades, in contrast to the small, high-pressure jets used for Pelton and turgo turbines.

Regardless of the turbine type, efficiency is in the details. Each turbine type can be designed to meet vastly different requirements. The turbine system is designed around net head and design flow. These criteria not only influence which type of turbine to use, but are critical to the design of the entire turbine system.

Minor differences in specifications can significantly impact energy transfer efficiency. The diameter of the runner, front and back curvatures of its buckets or blades, casting materials, nozzle (if used), turbine housing, and quality of components all affect efficiency and reliability.

An in-stream screen keeps debris and silt out of the penstock at the small-stream intake for a microhydro system in Washington.

Drive System

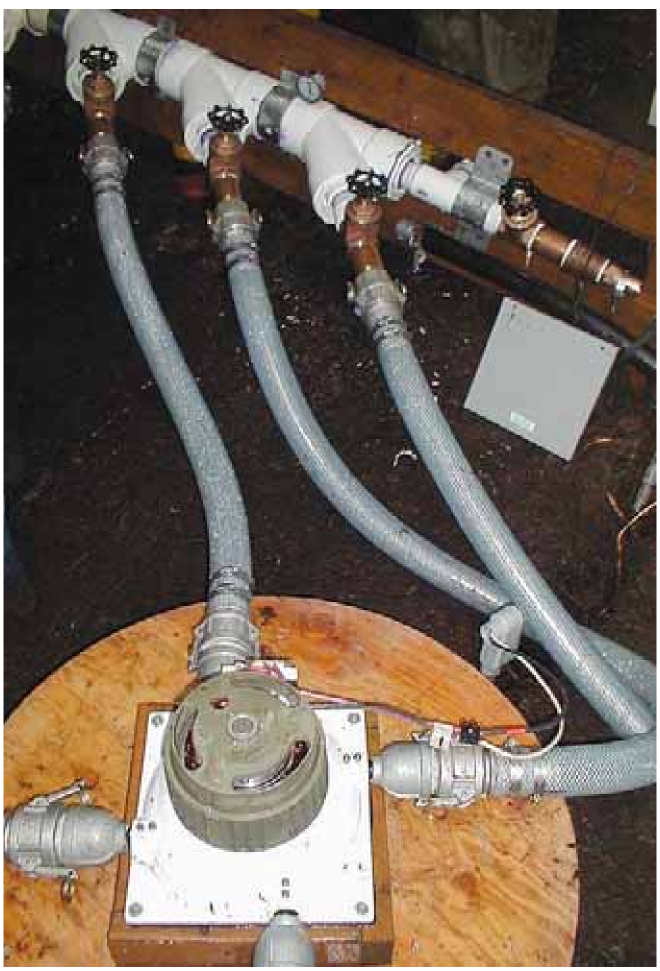
The drive system couples the turbine to the generator. At one end, it allows the turbine to spin at the rpm that delivers best efficiency. At the other, it drives the generator at the rpm that produces correct voltage and frequency—frequency applies to alternating current (AC) systems only. The most efficient and reliable drive system is a direct, 1:1 coupling between the turbine and generator.

This is possible for many sites, but not for all head and flow combinations. In many situations, especially with AC systems, it is necessary to adjust the transfer ratio so that both turbine and generator run at their optimum (but different) speeds. These types of drive systems can use either gears, chains, or belts, each of which introduces additional efficiency losses into the system. Belt systems tend to be more popular because of their lower cost.

Generator

The generator converts the rotational energy from the turbine shaft into electricity. Efficiency is important at this stage too, but most modern, well-built generators deliver good efficiency. Direct current (DC) generators, or alternators

At the bottom of the penstock, a manifold routes water to the four nozzles of a Harris Pelton turbine that drives a permanent magnet alternator.



Hydro Terms

Flow
Refers to the quantity of water supplied from a water source or exiting a nozzle per unit of time. Commonly measured in gallons per minute (gpm).

Francis Turbine
A type of reaction hydro-turbine used in low to medium heads. It consists of fixed vanes on a shaft. Water flows down through the vanes, driving the shaft.

Friction Loss
Lost energy due to pipe friction. In hydro systems, pipe sized too small can lead to serious friction losses.

Head
The difference in elevation between a source of water and the location at which the water from that source may be used (synonym: vertical drop). Expressed in vertical distance or pressure.

Headrace
A flume or channel that feeds water into a hydro turbine.

Hydroelectricity
Any electricity that is generated by the flow of water.

Impulse Turbine
Turbines with runners that operate in air, driven by one or more high-velocity jets of water from nozzles. Typically used with moderate- to high-head systems. Examples include Pelton and turgo.

Intake
The structure that receives the water and feeds it into the penstock (pipeline). Usually incorporates screening or filtering to keep debris and aquatic life out of the system.

Pelton Wheel
A common impulse turbine runner (named after inventor Lester Pelton) made with a series of cups or "buckets" attached to a hub.

Penstock
The pipe in a hydro system that carries the water from the intake to the turbine.

(continued)

More Hydro Terms

Pipe Loss (Frictional Head Loss)
The amount of energy or pressure lost due to friction between a flowing liquid and the inside surface of a pipe.

Pressure
The "push" behind liquid or gas in a tank, reservoir, or pipe. Water pressure is directly related to "head"—the height of the top of the water over the bottom. Every 2.31 feet of vertical head gives 1 psi (pound per square inch) of water pressure.

Reaction Turbine
Turbines with the runner fully immersed in water, typically used in low- to moderate-head systems with high flow. Examples include Francis, propeller, and Kaplan.

Runner
The wheel that receives the water, changing the pressure and flow of the water to circular motion to drive an alternator, generator, or machine.

Tailrace
The pipe, flume, or channel in a hydroelectric system that carries the water from the turbine runner back to the stream or river.

Trash Rack
A strainer at the input to a hydro system. Used to remove debris from the water before it enters the pipe.

Turgo
A type of impulse hydro runner optimized for lower heads and higher volumes than a Pelton runner.

with rectifiers, are typically used with small household systems, and are usually augmented with batteries for reserve capacity, as well as inverters for converting the electricity into the AC required by most appliances. DC generators are available in a variety of voltages and power outputs.

AC generators are typically used with systems producing about 3 KW or more. AC voltage is also easily changed using transformers, which can improve efficiency with long transmission lines. Depending on your requirements, you can choose either single-phase or three-phase AC generators in a variety of voltages.

Shown from beneath—the 4-inch (10 cm) turgo runner in an Australian-made Platypus turbine.

One critical aspect of AC is frequency, typically measured as cycles per second (cps) or Hertz (Hz). Most household appliances and motors run on either 50 Hz or 60 Hz (depending on where you are in the world), as do the major grids that interconnect large generating stations. Frequency is determined by the rotational speed of the generator shaft; faster rotation generates a higher frequency. In battery-based hydro systems, the inverter produces an AC waveform at a fixed frequency. In batteryless hydro systems, the turbine controller regulates the frequency.

A view into a turbine shows a relatively large (2 feet in diameter) Pelton wheel. Peltons vary in size from 3 inches to 13 feet or more, depending on head and flow.

AC Controls

Pure AC hydro systems have no batteries or inverter. AC is used by loads directly from the generator, and surplus electricity is burned off in dump loads—usually resistance heaters.

Governors and other controls help ensure that an AC generator constantly spins at its correct speed. The most common types of governors for small hydro systems accomplish this by managing the load on the generator. With no load, the generator would "freewheel," and run at a very high rpm. By adding progressively higher loads, you can eventually slow the generator until it reaches the exact rpm for proper AC voltage and frequency. As long as you maintain this "perfect" load, known as the design load, electrical output will be correct. You might be able to maintain the correct load yourself by manually switching devices on and off, but a governor can do a better job—automatically.

By connecting your hydro system to the utility grid, you can draw energy from the grid during peak usage times when your hydro system can't keep up, and feed excess electricity back into the grid when your usage is low. In effect, the grid acts as a large battery with infinite capacity.

If you choose to connect to the grid, however, keep in mind that significant synchronization and safeguards must be in place. Grid interconnection controls do both. They will monitor the grid and ensure that your system is generating compatible voltage, frequency, and phase. They will also instantly disconnect from the grid if major fluctuations occur on either end. Automatic disconnection is critical to the safety of all parties. At the same time, emergency shutdown systems interrupt the water flow to the turbine, causing the system to coast to a stop, and protecting the turbine from overspeed.

A Power Pal turbine with a Francis runner direct-coupled to the alternator above.

The underside of a low-head, high-flow Nautilus turbine showing the Francis runner, and above it, the innovative nautilus-shaped headrace.

DC Controls

A DC hydro system works very differently from an AC system. The alternator or generator output charges batteries. A diversion controller shunts excess energy to a dump load. An inverter converts DC electricity to AC electricity for home use. DC systems make sense for smaller streams with potential of less than 3 KW.

AC systems are limited to a peak load that is equivalent to the output of the generator. With a battery bank and large inverter, DC systems can supply a high peak load from the batteries even though the generating capacity is lower.

Series charge controllers, like those used with solar-electric systems, are not used with hydro systems since the generators cannot run without a load (open circuit). This can potentially damage the alternator windings and bearings from overspeeding. Instead, a diversion (or shunt) controller must be used. These normally divert energy from the battery to a resistance heater (air or water), to keep the

A Canadian-made Energy Systems and Design turbine uses a permanent magnet alternator and a turgo runner.

battery voltage at the desired level while maintaining a constant load on the generator.

The inverter and battery bank in a DC hydro system are exactly the same as those used in battery-based, solar-electric or wind-electric systems. No other special equipment is needed. Charge controller settings may be lower than used in typical PV and wind systems, since hydro systems are constant and tend to run with full batteries much of the time.

Head, Flow, & Efficiency

If you expect to sell electricity back to the utility, pay extra attention to the efficiency of your hydro system because higher output and a lower cost-per-watt will go straight to your bottom line. Your turbine manufacturer can give you guidance on the most efficient design, as well as grid interconnection controls and safeguards. If you're off-grid, and your site doesn't have lots of head and flow, high efficiency can make the difference between ample electricity for your needs and having to use a backup, gasoline-powered generator.

Whether a hydro system generates a few watts or hundreds of megawatts, the fundamentals are the same. Head and flow determine how much raw water power is available, and the system efficiency affects how much electricity will come out the other end. Each component of a hydro system affects efficiency, so it's worthwhile to optimize your design every step of the way.

Is hydropower feasible for you? The next article in this series will help you answer this question. I'll discuss methods for measuring head and flow, offer tips for determining pipeline size, and provide formulas for calculating electrical output and efficiency.

Access

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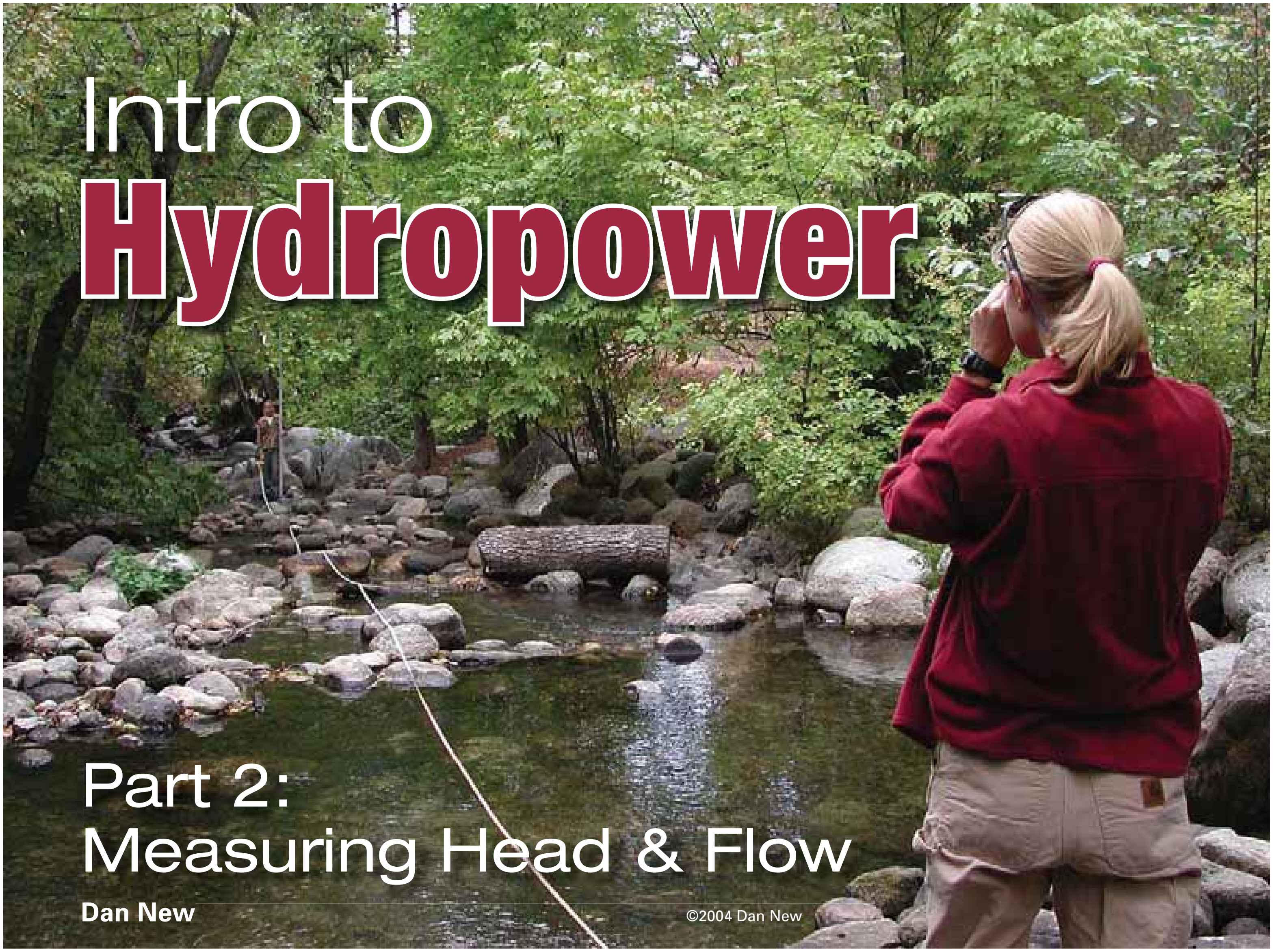
"Hydro in the Blood: An Interview with Dan New of Canyon Industries," *HP79*

"Powerful Dreams: Crown Hill Farm's Hydro-Electric Plant," by Juliette & Lucien Gunderman, *HP96*

"From Water to Wire: Building a Microhydro System," by Peter Talbot, *HP76*



Intro to Hydropower

Part 2: Measuring Head & Flow

Dan New

Measuring the stream course—Anna and Joe work downstream, shooting vertical drop (head) with a sight level, and getting a rough measurement of the pipe run at the same time.

Small-scale hydro is the only renewable energy source that works for you 24 hours a day, 7 days a week. In the first article in this series (*HP103*), I explained the basics of hydroelectric system theory, and reviewed system components. This article focuses on measuring a stream's head and flow. Before you can begin designing your hydro system or estimating how much electricity it will produce, you'll need to make four essential measurements:

- Head (the vertical distance between the intake and turbine)
- Flow (how much water comes down the stream)
- Pipeline (penstock) length
- Electrical transmission line length (from turbine to home or battery bank)

This article will discuss how to measure head and flow. Head and flow are the two most important facts you need to know about your hydro site. You simply cannot move forward without these measurements. Your site's head and flow will determine everything about your hydro system—pipeline size, turbine type, rotational speed, and generator size. Even rough cost estimates will be impossible until you've measured head and flow.

When measuring head and flow, keep in mind that accuracy is important. Inaccurate measurements can result in a hydro system designed to the wrong specs, and one that produces less electricity at a greater expense.

A handheld sight level, or peashooter, is a handy and inexpensive tool for determining the head of your hydro site.

Measuring Head

Head is water pressure, created by the difference in elevation between the intake of your pipeline and your water turbine. Head can be measured as vertical distance (feet or meters) or as pressure (pounds per square inch, newtons per square meter, etc.). Regardless of the size of your stream, higher head will produce greater pressure—and therefore higher output—at the turbine.

An altimeter can be useful in estimating head for preliminary site evaluation, but should not be used for the final measurement. It is quite common for low-cost barometric altimeters to reflect errors of 150 feet (46 m) or more, even when calibrated. GPS altimeters are often even less accurate. Topographic maps can also be used to give you a very rough idea of the vertical drop along a section of a stream's course. But only two methods of head measurement are accurate enough for hydro system design—direct height measurement and water pressure.

Direct Height Measurement

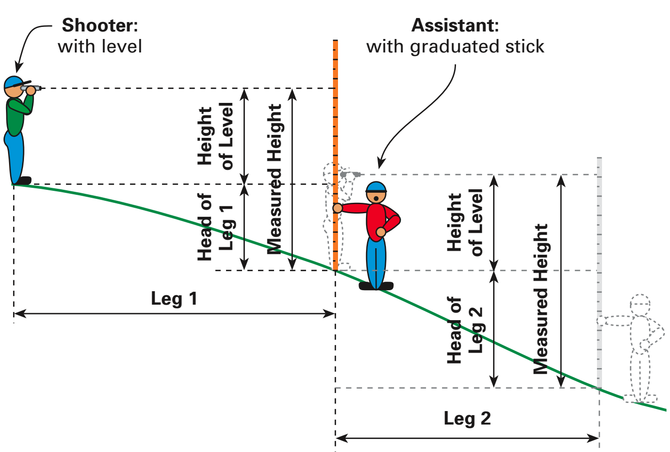
To measure head, you can use a laser level, a surveyor's transit, a contractor's level on a tripod, or a sight level ("peashooter"). Direct measurement requires an assistant.

One method is to work downhill using a tall pole with graduated measurements. A measuring tape affixed to a 20-foot (6 m) section of PVC pipe works well. After each measurement, move the transit, or person with the sight level, to where the pole was, and begin again by moving the pole further downhill toward the generator site. Keep each transit or sight level setup exactly level, and make sure that the measuring pole is vertical. Take detailed notes of each measurement and the height of the level. Then, add up the series of measurements and subtract all of the level heights to find total head.

View through the sight level—Anna measured 7 feet 4 inches on the leveling rod. By subtracting the height of her eye, she determined the head for this section to be 1 foot 8 inches.

Another method is to work uphill, with your assistant walking up the slope as you site through the transit or sight level until the bottoms of the assistant's feet are level with the transit. At this point, the head will be the same as the distance from your eye to the ground where you are standing. Once you've recorded this measurement, move to the spot where your assistant was standing, and repeat the process. Multiply the number of times you do this by the height of the shooter's eye from the ground for the total head.

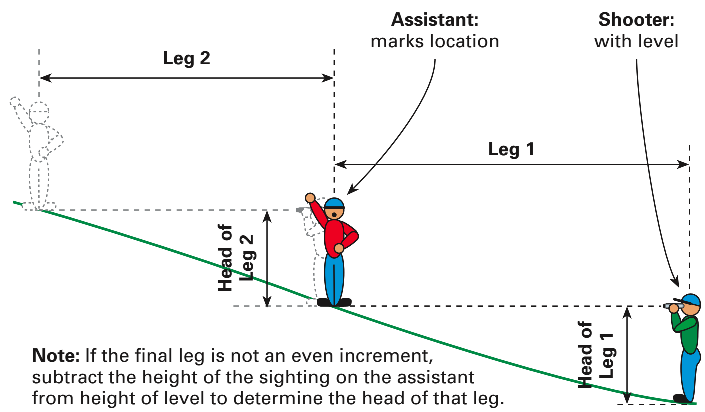
Measuring Downhill



1. **Subtract height of level from measurment on stick to determine head for each leg.**
2. **Repeat multiple legs from intake location to turbine location.**
3. **Add the head of each leg together to determine total head.**

Measuring Uphill

1. **Height of level is head for each leg.**
2. **Repeat multiple legs from turbine location to intake location.**
3. **Multiply the height of level times the number of legs to determine total head.**



Note: If the final leg is not an even increment, subtract the height of the sighting on the assistant from height of level to determine the head of that leg.

Courtesy of Liquid Sun Hydro

A pressure gauge connected to a hose can provide accurate head measurements. Convert pressure to height, or purchase a gauge like the one above and read height directly.

Water Pressure Measurement

If the distance is short enough, you can use one or more garden hoses or lengths of flexible plastic tubing to measure head. This method relies on the constant that each vertical foot of head creates 0.433 psi of water pressure (10 vertical feet creates 4.33 psi). By measuring the pressure at the bottom of the hose, you can calculate the elevation change.

Run the hose (or tubing) from your proposed intake site to your proposed turbine location. If you attach multiple hoses together, make sure that each connection is tight and leak free. Attach an accurate pressure gauge to the bottom end of the hose, and completely fill the hose with water. Make sure that there are no high spots in the hose that could trap air. You can flush water through the hose before the gauge is connected to force out any air bubbles.

If necessary, you can measure total head over longer distances by moving the hose and taking multiple readings. Keep in mind, however, that there is less than $^1/_2$ psi difference for every vertical foot. Except for very steep hillsides, even a 100-foot hose may drop only a few vertical feet. The chance for error significantly increases with a series of low-head readings. Use the longest possible hose, along with a highly accurate pressure gauge.

The pressure gauge must be graduated so that measurements are taken in the middle of its range. Don't use a 0 to 800 psi gauge to measure 5 to 15 psi pressure. Select instead a 0 to 30 psi gauge. Liquid Sun Hydro now sells pressure gauges calibrated in feet, which makes head measurement a snap.

Computing Net Head

By recording the measurements described in the previous sections, you have determined gross head—the true vertical distance from intake to turbine, and the resulting pressure at the bottom. Net head, on the other hand, is the pressure at the bottom of your pipeline when water is actually flowing to your turbine. This will always be less than the gross head you measured, due to friction losses within the pipeline. You will need to have water flow figures (described in the following sections) to compute net head. Longer pipelines, smaller diameters, and higher flows create greater friction. A properly designed pipeline will yield a net head of 85 to 90 percent of the gross head you measured.

Net head is a far more useful measurement than gross head and, along with design flow, is used to determine hydro system components and electrical output. Here are the basics of determining pipe size and net head, but you should work with your turbine supplier to finalize your pipeline specifications.

Head loss refers to the loss of water power due to friction within the pipeline (also known as the penstock). Although a given pipe diameter may be sufficient to carry all of the design flow, the sides, joints, and bends of the pipe create drag as the water passes by, slowing it down. The effect is the same as lowering the head—less water pressure at the turbine.

Head loss cannot be measured unless the water is flowing. A pressure gauge at the bottom of even the smallest pipe will read full psi when the water is static in the pipe. But as the water flows, the friction within the pipe reduces the velocity of the water coming out the bottom. Greater water flows increase friction further.

Larger pipes create less friction, delivering more power to the turbine. But larger pipelines are also more expensive, so there is invariably a trade-off between head loss and system cost. Size your pipe so that not more than 10 to 15

Head Loss in PVC Pipe*

Pipe Size (in.)	Design Flow in Gallons per Minute & (Cubic Feet per Second) 25 (.05)	50 (0.1)	100 (0.2)	150 (0.33)	200 (0.45)	300 (0.66)	400 (0.89)	500 (1.1)	600 (1.3)	700 (1.5)	800 (1.78)	900 (2.0)	1,000 (2.23)	1,200 (2.67)
2	1.28	4.65	16.80	35.70	60.60	99.20	-	-	-	-	-	-	-	-
3	0.18	0.65	2.33	4.93	8.36	17.90	30.60	46.10	64.40	-	-	-	-	-
4	0.04	0.16	0.57	1.23	2.02	4.37	7.52	11.30	15.80	21.10	26.80	33.40	-	-
6	-	0.02	0.08	0.17	0.29	0.62	1.03	1.36	2.20	2.92	3.74	4.75	5.66	8.04
8	-	-	-	0.04	0.07	0.15	0.25	0.39	0.50	0.72	0.89	1.16	1.40	1.96

*In feet per 100 feet of pipeline

percent of the gross (total) head is lost as pipeline friction. Higher losses may be acceptable for high-head sites (100 feet plus), but pipeline friction losses should be minimized for most low-head sites.

The length of your pipeline has a major influence on both the cost and efficiency of your system. The measurement is easy, though. Simply run a tape measure between your intake and turbine locations, following the route you'll use for your pipeline. Remember that you want to run the pipeline up out of the creek bed, when possible, to avoid damage during high water.

Anna gets her feet wet—the container fill method of measuring flow means getting in the stream and timing how long it takes to fill a container of known volume.

Measuring Flow

The second major step in evaluating your site's hydro potential is measuring the flow of the stream. Stream levels change through the seasons, so it is important to measure flow at various times of the year. If this is not possible, attempt to determine various annual flows by discussing the stream with a neighbor, or finding U.S. Geological Survey flow data for your stream or a nearby larger stream. Also keep in mind that fish, birds, plants, and other living things rely on your stream for survival. Never use all of the stream's water for your hydro system.

Flow is typically expressed as volume per second or minute. Common examples are gallons or liters per second (or minute), and cubic feet or cubic meters per second (or minute). Each can be easily converted to another, as follows:

1 cubic foot = 7.481 gallons
1 cubic meter = 35.31 cubic feet
1 cubic meter = 1,000 liters

Three popular methods are used for measuring flow—container, float, and weir. Each will be described in detail below.

Container Fill Method

The container fill method is the most common method for determining flow in microhydro systems. Find a location along the stream where all the water can be caught in a bucket. If such a spot doesn't exist, build a temporary dam that forces all of the water to flow through a single outlet. Using a bucket or larger container of a known volume, use a stopwatch to time how long it takes to fill the container. Then divide the container size by the number of seconds.

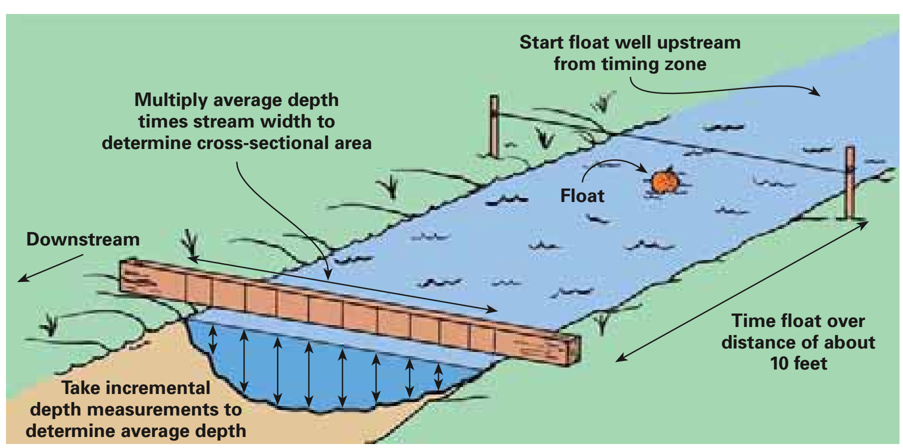
For example, if your container is a 5-gallon paint bucket and it takes 8 seconds to fill, your flow is 0.625 gallons per second (gps) or 37.5 gallons per minute (gpm).

Float Method

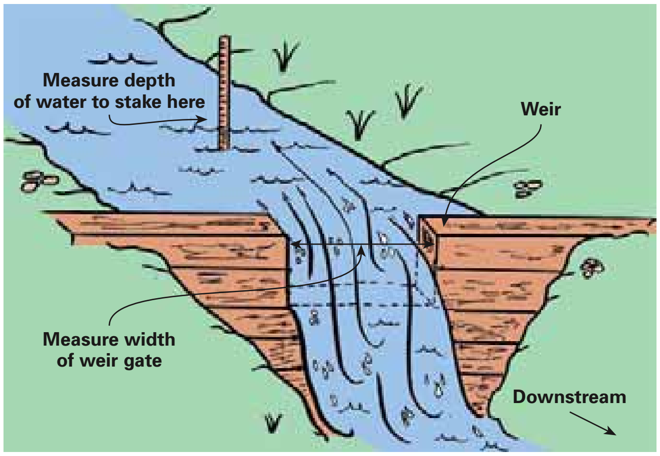
The float method is useful for large streams if you can locate a section about 10 feet (3 m) long where the stream is fairly consistent in width and depth.

Step 1. Measure the average depth of the stream. Select a board able to span the width of the stream and mark it at 1-foot (0.3 m) intervals. Lay the board across the stream, and measure the stream depth at each 1-foot interval. To compute the average depth, add all of your measurements together and divide by the number of measurements you made.

The Float Method of Estimating Flow



The Weir Method of Measuring Flow

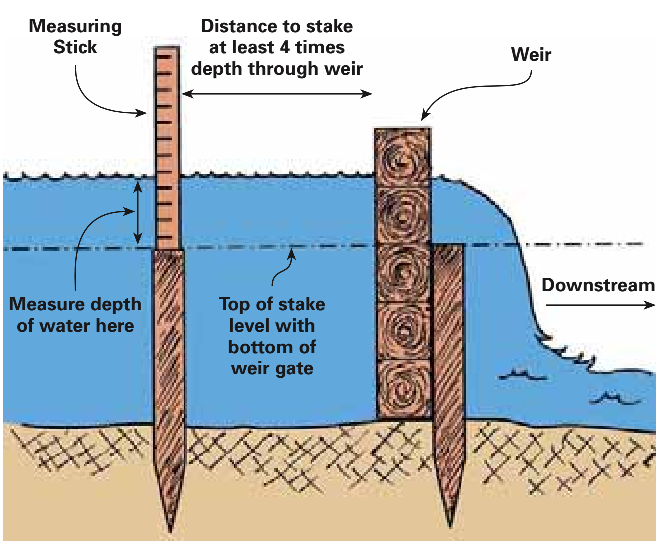


Step 2. Compute the area of the cross-section you just measured by multiplying the average depth you just computed by the width of the stream. For example, a 6-foot-wide stream with an average depth of 1.5 feet would yield a cross-sectional area of 9 square feet.

Step 3. Measure the speed. A good way to measure speed is to mark off a 10-foot (3 m) length of the stream that includes the point where you measured the cross-section. Remember, you only want to know the speed of the water where you measured the cross-section, so the shorter the length of stream you measure, the better.

Use a weighted float that can be clearly seen—an orange or grapefruit works well. Place it well upstream of your measurement area, and use a stopwatch to time how long it takes to travel the length of your measurement section. The stream speed probably varies across its width, so record the times for various locations and average them.

The Weir Method (continued)



With these time and distance measurements, you can now compute the water speed. For example, assume the float took an average of 5 seconds to travel 10 feet. That's 2 feet per second, or 120 feet per minute. You can then compute flow by multiplying the feet traveled by the cross-sectional area. Using the sample cross-sectional area and speed examples, 120 feet per minute times 9 square feet equals 1,080 cubic feet per minute (cfm) flow.

Step 4. Correct for friction. Because the streambed creates friction against the moving water, the bottom of the stream tends to move a little slower than the top. This means actual flow is a little less than what was calculated. By multiplying the result by a friction factor of 0.83, you get a closer approximation of actual flow.

Weir Method

A weir is perhaps the most accurate way to measure small- and medium-sized streams. All the water is directed through an area that is exactly rectangular, making it very easy to measure the height and width of the water to compute flow.

This kind of weir is a temporary dam with a rectangular slot, or gate. The bottom of the gate should be exactly level, and the width of the gate should allow all the water to pass through without spilling over the top of the dam. A narrower gate will increase the depth of the water as it passes through, making it easier to measure.

Weir Flow Table*

Depth (in.)	Additional Fraction of an Inch							
	None	+1/8	+1/4	+3/8	+1/2	+5/8	+3/4	+7/8
0	0.00	0.01	0.05	0.09	0.14	0.19	0.26	0.32
1	0.40	0.47	0.55	0.64	0.73	0.82	0.92	1.02
2	1.13	1.23	1.35	1.46	1.58	1.70	1.82	1.95
3	2.07	2.21	2.34	2.48	2.61	2.76	2.90	3.05
4	3.20	3.35	3.50	3.66	3.81	3.97	4.14	4.30
5	4.47	4.64	4.81	4.98	5.15	5.33	5.51	5.69
6	5.87	6.06	6.25	6.44	6.62	6.82	7.01	7.21
7	7.40	7.60	7.80	8.01	8.21	8.42	8.63	8.83
8	9.05	9.26	9.47	9.69	9.91	10.13	10.35	10.57
9	10.80	11.02	11.25	11.48	11.71	11.94	12.17	12.41
10	12.64	12.88	13.12	13.36	13.60	13.85	14.09	14.34
11	14.59	14.84	15.09	15.34	15.59	15.85	16.11	16.36
12	16.62	16.88	17.15	17.41	17.67	17.94	18.21	18.47
13	18.74	19.01	19.29	19.56	19.84	20.11	20.39	20.67
14	20.95	21.23	21.51	21.80	22.08	22.37	22.65	22.94
15	23.23	23.52	23.82	24.11	24.40	24.70	25.00	25.30
16	25.60	25.90	26.20	26.50	26.80	27.11	27.42	27.72
17	28.03	28.34	28.65	28.97	29.28	29.59	29.91	30.22
18	30.54	30.86	31.18	31.50	31.82	32.15	32.47	32.80
19	33.12	33.45	33.78	34.11	34.44	34.77	35.10	35.44
20	35.77	36.11	36.45	36.78	37.12	37.46	37.80	38.15

*In cfm per 1-inch gate width

Example Site Analysis

Gross head: 100 feet

Pipeline length: 500 feet

Acceptable head loss: 10 to 15 percent (10–15 feet)

Design flow: 100 gpm

To determine what size pipe would be best, look up your design flow (100 gpm) in the head loss chart on page 44. In this example, the maximum acceptable head loss is 10 to 15 feet, which means we cannot exceed 3 feet of loss for every 100 feet of our 500-foot pipeline. Reading down the 100-gpm column, we find that a 3-inch pipeline would have a head loss of 2.33 feet per 100 feet of pipe—within our limits.

To determine total head loss, multiply 2.33 feet times 5 (for 500-foot pipeline), which equals 11.65 feet. To calculate net head, subtract the total head loss from the gross head (100 feet minus 11.65 feet). This gives us a net head of 88.35 feet.

Note the huge difference in head loss as pipe diameter gets smaller. Using a 2-inch pipeline, head loss for this example would be 16.8 feet per 100 feet, with a total head loss of 84 feet. Net head for this example would be 100 feet minus 84 feet, and result in only 16 feet of net head! This example shows how incorrectly sized pipelines can absolutely cripple a hydro system.

Choosing a 4-inch pipe would result in less head loss than 3-inch pipe, and deliver more power to the turbine, but the performance improvement is not sufficient to justify the added cost. Your turbine manufacturer should be well versed in measuring head losses, and can be an excellent resource for pipe diameter recommendations.

The depth measurement is not taken at the gate itself because the water depth distorts as it moves through the gate. Instead, insert a stake well upstream of the weir gate and make the top of the stake exactly level with the bottom of the weir gate. Measure the depth of the water from the top of the stake.

Once the width and depth of the water are known, a weir table is used to compute the flow. The weir table shown here is based on a gate that is 1 inch (25 mm) wide. Simply multiply the table amount by the width (in inches) of your gate. For example, assume your weir gate is 6 inches wide, and the depth of the water passing over it is $7\frac{1}{2}$ inches. On the left side of the table, find "7" and move across the row until you find the column for "+$\frac{1}{2}$". The table shows 8.21 cfm flow for a 1-inch gate with $7\frac{1}{2}$ inches of water flowing through it. Since your gate is 6 inches wide, simply multiply the 8.21 by 6 to get 49.26 cfm.

A weir is especially effective for measuring flow during different times of the year. Once the weir is in place, it is easy to quickly measure the depth of the water and chart the flow at various times.

Design Flow

Even though your flow may be very high after exceptionally rainy periods, it probably won't be cost effective to design your turbine system to handle all that water for just a few days of the year. Instead, it makes sense to build a system that uses flow you can count on for much of the year. This is called design flow, and it is the maximum flow your hydro system is designed to accommodate.

Next Steps

Determining the potential of your water resource is the first step for a well-designed and viable hydropower system. As you can see, measuring head and flow are not difficult or complex tasks. With your net head and design flow, you have enough information to begin the next step—talking with turbine suppliers about potential designs. But there are still a few more issues to consider. Next time, I'll discuss losses, efficiency, transmission, and predicting the electrical output of your system. Once you have that information, you'll be ready to install your hydropower system.

Access

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Intro to Hydropower

Part 3: Power, Efficiency, Transmission & Equipment Selection

Dan New

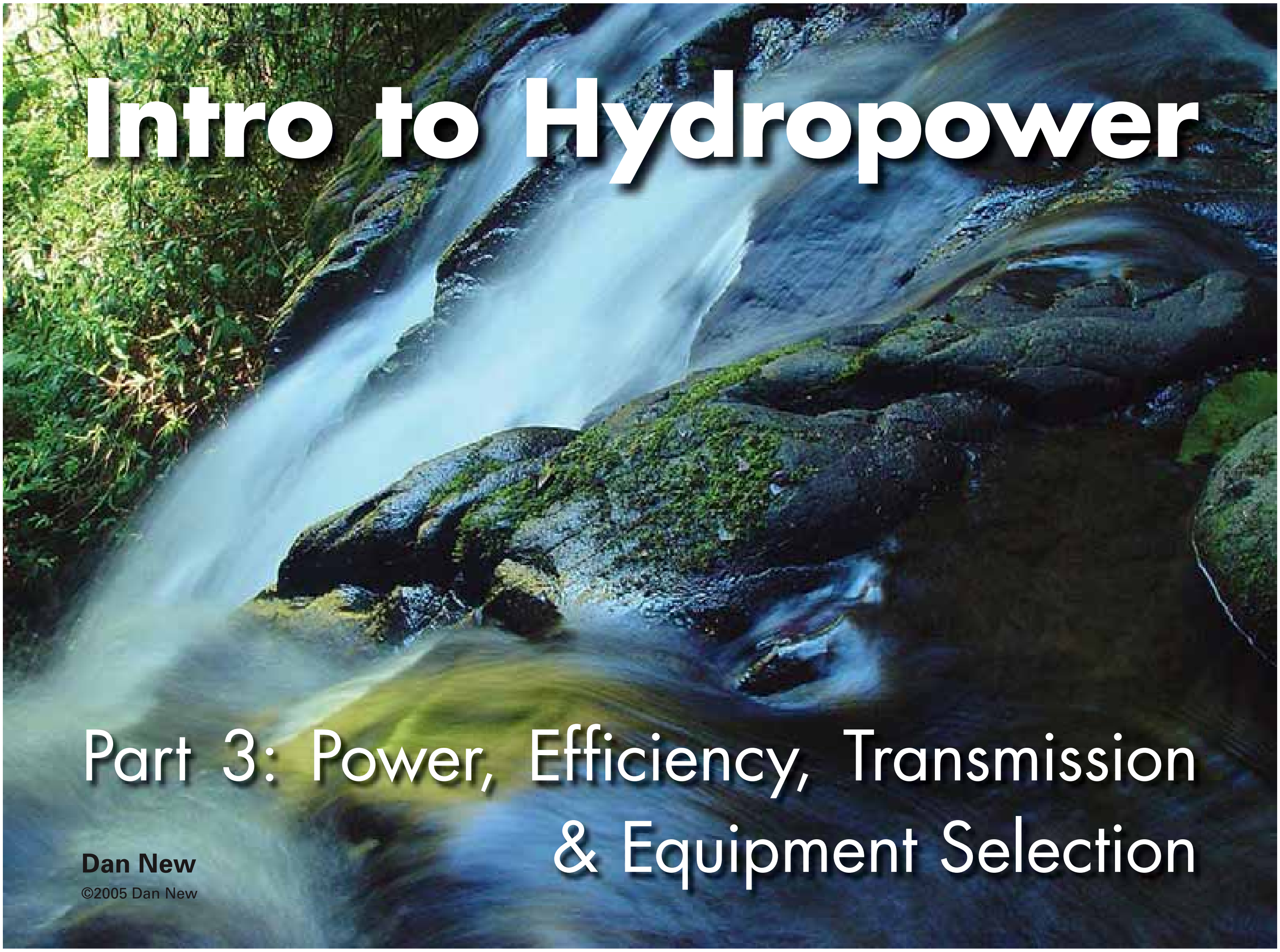

Photo courtesy of Eugenio Garcia Lopez

Compared to solar- or wind-powered systems, small-scale hydroelectric systems are almost always the least expensive way to make your own electricity. Most people don't have a stream with adequate flow and vertical drop, but if you do, pat yourself on the back. You're the envy of your renewable energy neighborhood!

In the first two articles in this series, I covered system components and design, and ways of measuring head (vertical drop) and water flow at your site. This time, I'll discuss calculating the power available from a given stream, system efficiency, options for transmitting electricity from your hydro turbine to your home, and several other factors that make a good hydro system.

Computing Water Power

Net head is the vertical drop from your pipeline intake to your turbine, adjusted for pipe friction (losses caused by water moving through a pipeline). Design flow is the amount of water you have to work with. See "Intro to Hydropower, Part 2" in *HP104* to learn how to measure these two important site variables. Once you've determined net head and design flow, you can begin to estimate the potential output of a hydro system. These computations are only rough estimates, and you should consult with your turbine manufacturer or equipment supplier for more accurate projections.

Both head and flow have a linear effect on power. Double the head and power doubles. Double the flow and power doubles. Keep in mind that total head will remain constant once your system is installed—you can count on it year-round. Increasing head is the least expensive way to increase power generation because it has minimal effect on turbine size. You can increase head by going higher up the creek to place the intake, or lower down for the turbine. Don't overlook the head that you have on your property.

In contrast, flow will likely change significantly over the course of a year, and it's rarely cost effective to size your hydro system for maximum, flood-level flow. *Always maximize head*, and work with your turbine supplier to determine the most practical design flow.

Accuracy is important! The design of your system revolves around your measurements of head and flow, and errors will directly affect the efficiency of your system. Take the time to measure head and flow carefully before you begin to evaluate hydro system components.

Efficiency & Losses

In addition to pipeline losses, small amounts of energy will be lost through friction within the turbine, drive system, generator, and transmission lines. Although some efficiency losses are inevitable, don't underestimate the importance of good design. Efficient systems produce greater output, often at a lower cost per watt. A system that is carefully matched to your site's head and flow usually won't cost any more than a less suitable design. But it will be much more efficient, producing more electricity from your available resource. Other improvements, such as larger pipeline diameter or a better drive system may yield enough added power to justify their higher cost.

Because of the many variables in system design, it is impossible to estimate efficiency without first knowing your head and flow. As a general guideline, however, you can expect a home-sized system generating direct AC power to operate at about 60 to 70 percent "water-to-wire" efficiency (measured between turbine input and generator output). Smaller DC systems generally have lower efficiencies of 40 to 60 percent, though recent testing by *Home Power* shows that some small turbines can achieve efficiencies in the low 70 percent range, depending on the system and electronics. If you have accurate measurements for your head and flow, your turbine supplier will be able to provide some preliminary estimates of efficiency, as well as ideas for optimization.

A Rough Formula

You can get pretty nerdy with power calculations for hydro systems. For larger systems, this is certainly justified, and any supplier worth dealing with can crunch the numbers. But when you're just getting an idea of the potential of your site, what's needed is a simple formula.

Net Head x Design Flow ÷ Adjustment Factor
= Power in Watts

If you multiply the net head in feet by the flow in gallons per minute and divide by an adjustment factor, you'll get the continuous potential power output of the turbine in watts. Use a factor of 9 for AC systems, and a factor of 10 to 13 for DC systems.

So if you have 100 feet (30 m) of head and 200 gallons (757 l) per minute, using 10 as the factor, you'll get roughly 2,000 watts, or 2 KW. Multiply that by 24 hours in a day and you have 48 KWH per day (which is a lot).

Transmission

The last important measurement is the distance between your generator and either your battery bank (for DC systems) or where you'll be using the electricity (for AC systems). As with your pipeline, all you need to do is measure the distance along the route you plan to run your wiring.

Transmission lines are a lot like pipelines. Instead of moving water, they move electrical energy, but the same fundamentals of friction losses apply. Longer transmission lines, higher current, lower system voltage, and smaller wires all contribute to energy losses. You can minimize these losses, but the electricity you can actually use will always be somewhat less than what your system is generating.

There are three ways to reduce or compensate for transmission line losses:

- Use a shorter transmission line
- Use larger wires
- Increase the voltage on the transmission line

Shorter lines and larger wires will reduce line losses for any system, but voltage considerations are significantly different between DC and AC systems. Transformers may be used to reduce wire size in long transmission lines, and step-down, MPPT controllers can allow your turbine to run at high voltage while charging your battery at a lower voltage. Your turbine supplier can help you determine the best solution for your site.

Example DC system

Gross head: 135 feet (41 meters)

Measured flow: 25 to 100 gpm, (1.6 to 6.3 l/s)

Pipeline length: 900 feet (274 m)

Gross power: 350 to 1,200 watts

A DC, battery-based system with an inverter is the best choice for a hydro site with the above parameters. If an AC turbine were used, peak usage would be limited to about 1,200 watts at peak flow. This peak power figure would not be sufficient to run the combined electrical loads of most households. Installation of a turbine with DC output would allow energy storage in a battery bank, and an inverter or inverters would be able to provide as much instantaneous power as was required by the residence.

With a design flow of 100 gpm, using 3-inch diameter PVC pipe would result in a head loss of 2.33 feet per 100 feet of pipe, for a net head of 114 feet (35 m), and a maximum power output of about 1,200 watts at maximum flow. Over a 24-hour period, this system would produce 28.8 KWH. As summer approached and the flow rate dropped off to the site's minimum of 25 gpm, the same 3-inch pipe would result in a net head of 133 feet (41 m), and a power output of about 350 W, or 8.4 KWH per day. This would typically be enough energy to power all the electric appliances in an efficient home, excluding cooking, space heating, and water heating.

Example AC System

Gross head: 230 feet (70 meters)

Measured flow: 220 gpm to 900 gpm (14–56 l/s)

Pipeline length: 1,700 feet (518 m)

Gross power: 5 to 20 KW

Clearly, a direct-generating AC system could be built at this site. The flow range could support development of a 5, 10, or 20 KW system, depending on the selection of pipe diameter. As an example, by choosing 6-inch diameter PVC pipe and planning on a design flow of 450 gpm (28 l/s), head loss would be about 1.3 feet per 100 feet of pipe, for a calculated net head of 208 feet (63 m), and an expected system output of 10.5 KW. This would be a very nice system to supply all the energy needs of a home/shop/greenhouse complex.

What Makes a Quality Hydro System?

Think of a hydroelectric system in terms of efficiency and reliability. In a perfect world, efficiency would be 100 percent. All the energy within the water would be transformed to the rotating shaft. There would be no air or water turbulence, no mechanical resistance from the turbine's bearings or drive system, and the runner would be perfectly balanced. The signs of energy loss—heat, vibration, and noise—would be absent. Of course, the perfect turbine would also never break down or require maintenance.

Obviously, no turbine system will ever achieve this degree of perfection. But it's good to keep these goals in mind, because better efficiency and reliability translate into more power and a lower cost per watt. Quality components and careful machining make a big difference in turbine efficiency and reliability. Here are just a few of the things to consider when selecting a turbine.

A 3.75-inch pitch diameter Pelton runner from Harris Hydro for high head, low flow sites.

Turbine Runner

The runner is the heart of the turbine. This is where water power is transformed into the rotational force that drives the generator. Regardless of the runner type, its buckets or blades are responsible for capturing the most possible energy from the water. The curvature of each surface, front and rear, determines how the water will push its way around until it falls away. Also keep in mind that any given runner will perform most efficiently at a specific head and flow. The type and size of your runner should be closely matched to your site characteristics.

Look for all-metal runners with smooth, polished surfaces to eliminate water and air turbulence. One-piece, carefully machined runners typically run more efficiently and reliably than those that are bolted together. Bronze manganese runners work well for small systems with clean water and heads up to about 500 feet (152 m). High-tensile stainless steel runners are excellent for larger systems or abrasive water conditions. All runners should be carefully balanced to minimize vibration, a problem that not only affects efficiency, but can also cause unnecessary wear on the turbine over time.

Turbine Housing

The turbine housing must be well built and sturdy, since it manages forces of the incoming water as well as the outgoing shaft power. In addition, its shape and dimensions have a significant effect on efficiency. For example, consider

The author inspects a 990-pound, 22-inch pitch diameter Turgo-style runner for an 880 KW turbine.

a Pelton-type turbine. As an impulse turbine, it is driven by one or more jets of water, but spins in air. This means that both hydrodynamic and aerodynamic forces must be considered in the design of the housing. It must minimize the resistance from splash and spray, and smoothly exhaust tail waters, yet also be sized and shaped properly to minimize losses due to air turbulence. Similarly, housings for high-flow designs like crossflow and Francis turbines must be precisely engineered to smoothly channel large volumes of water through the turbine without causing pockets of turbulence.

Look for a smoothly welded housing that is carefully matched to the proper runner for your site. Keep in mind that both the water forces and the runner will be producing considerable torque, so the housing material and all fittings should be heavy duty. Mating surfaces, such as pipe flanges and access covers, should be machined flat and leak free. Since water promotes rust and corrosion, make sure all vulnerable surfaces are protected with high-quality powder coating or epoxy paint. All bolts should be stainless steel.

Like this Energy Systems & Design alternator from a Stream Engine turbine, many small, DC, hydroelectric units now use more efficient, brushless, permanent magnet alternators.

Other Turbine Considerations

All surfaces that carry water can impact efficiency, from the intake to your pipeline to the raceway that carries the tail waters away from your turbine. Look for smooth surfaces with no sharp bends. Jets and flow control vanes should be finely machined with no discernable ripples or pits.

Efficiency is important, but so are durability and dependability. Your hydroelectric project should deliver clean electricity without interruption. The quality of components and their installation can make a big difference on the quality of your life in the years to come. Look for quality workmanship in the design and construction of seal systems, shaft material and machining, and all related components. Pay particular attention to the selection and mounting of bearings; they should spin smoothly, without grating or binding.

Alternator

In the past, most small, battery-charging, hydroelectric turbines relied on off-the-shelf alternators with brushes. These alternators work well, especially when a specific stator is chosen, based on the parameters of a given hydro site. Swapping out the stator optimizes the alternator's rpm, and increases the turbine's output. While these types of alternators are still used due to their low cost, they are not ideal. The major drawback is that the alternator's brushes need regular replacement. These days, brushless permanent magnet (PM) alternators are available, and are a better choice, since they eliminate the need for brush replacement. In addition, brushless permanent magnet alternators perform at higher efficiencies, increasing your hydro system's output.

Regardless of type, an alternator's output is always AC. The frequency of the AC will vary depending on the rotational speed of the alternator, which is a direct function of the pressure available at the turbine. This AC output is not usable as is, because AC appliances are designed to run at a specific frequency. Larger AC-direct turbines are designed to run at a specific speed (and therefore a fixed frequency), with governors to regulate the speed. The AC output of smaller, battery charging units is always rectified to DC, so the energy generated by the turbine can be stored in batteries. The system's inverter converts this DC to AC at a fixed frequency.

Alternative Power and Machine, Energy Systems and Design, and Harris Hydroelectric all manufacture turbines with brushless PM alternators. These alternators are very flexible in terms of their output voltage. The AC output of the turbine can be rectified to DC at the turbine for short transmission runs. High-voltage units operating at 120 VAC or higher can transmit the AC output of the turbine over longer distances. This AC output is then stepped down at the batteries to match the nominal battery voltage, and rectified to DC. In addition, transformers can be used to further step up the output voltage for transmission. Finally, the specific wiring configuration (delta, wye, etc.) of the alternator is flexible, allowing the output to be optimized for a specific hydro site.

For larger, AC-direct turbines, good quality alternators are available from a number of sources, and the reputation of the generator manufacturer is an excellent place to begin your selection process. Marathon Electric, Kato Engineering, and Stamford Newage, are all well known and respected small generator builders serving an international market.

For a household- or ranch-sized AC-direct turbine under 50 KW, you would normally choose a single-phase output, two bearing alternator. Quality alternators are available in a variety of voltages, phases, and output frequencies to match your local utility electricity. Three-phase units are selected for larger projects, for large motor loads, or complex distribution schemes.

If you are able to match your turbine speed to a common generator synchronous speed, then use a direct-drive coupling between the turbine shaft and generator shaft if

The balance of system components for a DC hydro system are very much like a photovoltaic system, except the charge controller shunts to a diversion load.

possible. It may be worth the investment in a slower speed generator to make this possible. If it is necessary to use a belt drive between the major components, then avoid two-pole generators, and pay the extra money to install a four-pole generator. Four-pole units have a 60-Hertz synchronous speed of 1,800 rpm, half the speed of the two-pole units, four times the weight, and six times the life. A standard feature in most industrial-quality generators will be an automatic voltage regulator (AVR). The AVR will maintain steady voltage over a broad range of generator loads.

In an AC hydro system, an electronic load governor automatically adjusts the load on the generator to maintain constant voltage.

Turbine Supplier

When it comes to suppliers, there is no substitute for experience. While the principles of hydropower can be mastered indoors, it is real world experience that teaches both the highlights and pitfalls of diverting water from a stream, pressurizing it, and forcing it through a turbine. A turbine supplier with many years of field experience will be invaluable as you design and build your hydro system.

Look for an experienced supplier that specializes in the size and type of hydro system you intend to build. A good supplier will work with you, beginning with your measurements of head and flow, to help you determine the right pipeline size, net head, design flow, turbine specifications, drive system, generator, and load management system. You should be able to count on your supplier to make suggestions for optimizing efficiency and dependability, including their effects on cost and performance. A good turbine supplier is your partner, and should take a personal interest in your success. After all, a satisfied customer is very good for business.

Next Steps

Armed with four essential measurements—head, flow, pipeline length, and transmission line length—you're ready to begin evaluating your site for a hydroelectric system. As we discussed in Part 1 of this series, there are many choices to make about DC vs. AC, intake designs, turbine types, etc. Many of these decisions will become obvious once your four measurements are complete.

Advice from turbine suppliers can be invaluable during your design process. If you provide them with your measurements, most suppliers will propose a system that is tailored to your site characteristics. You may find that a given supplier will specialize in certain types of systems (like DC or AC), but most are happy to refer you to someone else when appropriate.

Emphasize efficiency. Your head and flow determine how much raw water power is available, but efficiency determines how much of it you'll be able to transform into usable electricity. There are cost trade-offs, of course, but in many cases, a more efficient system will result in a lower cost per watt. This is especially important if you're thinking of connecting to the grid, where higher efficiency means more dollars in your pocket.

I hope you have found this series of articles on hydropower helpful. I've only scratched the surface of this substantial topic, but I hope I've whetted your appetite. As you've seen, the concepts behind hydropower are simple. Water turns a turbine, the turbine spins a generator, and electricity comes out the other side. Even a novice with little or no experience could produce some hydroelectricity—given enough water power.

Do you have a stream? Of the three most popular renewable energy technologies, hydropower delivers the most watts for the investment, and can be most accurately assessed. A few quick measurements will tell you if you have hydro potential. In any event, you'll have a great time playing in the water.

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