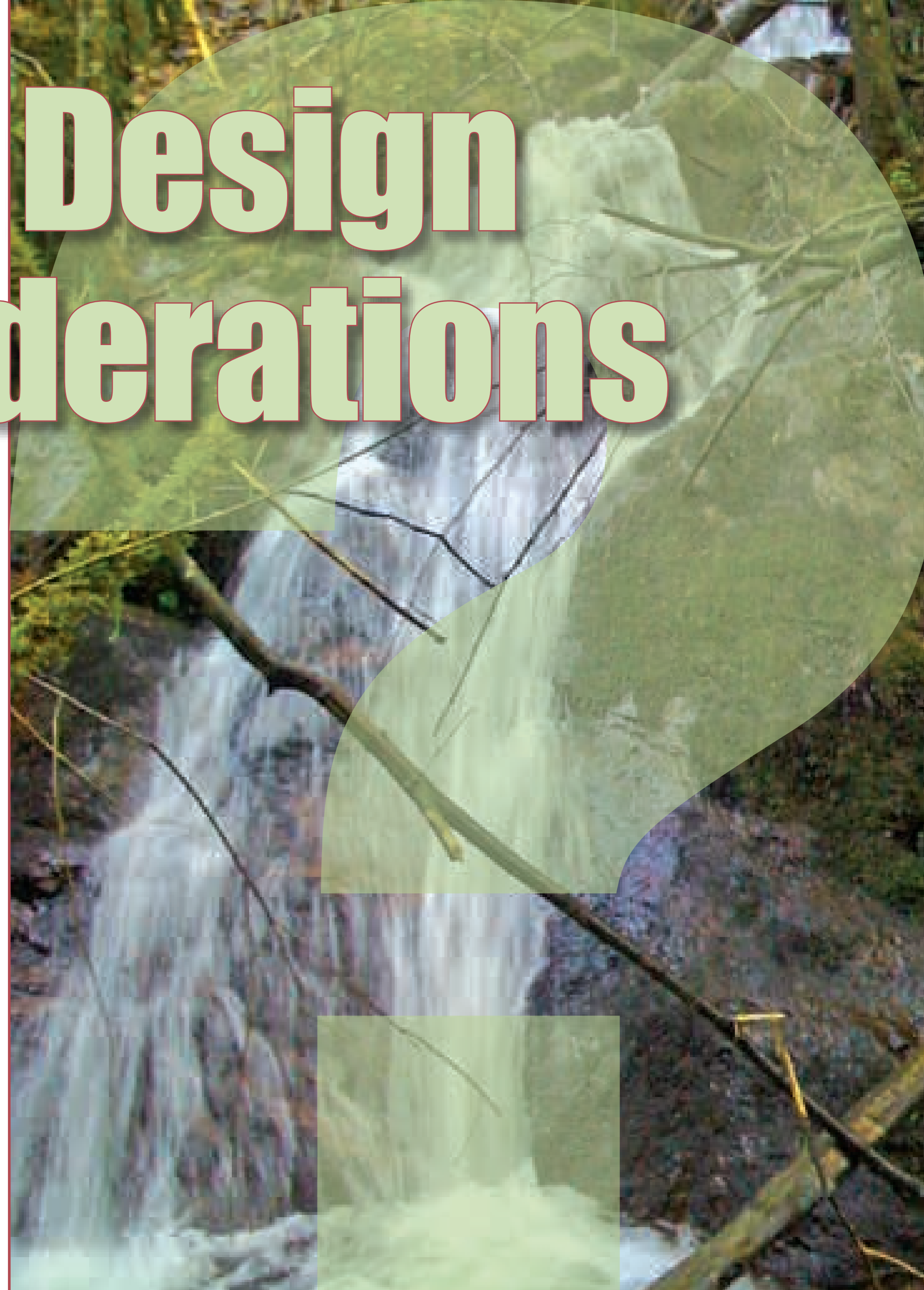
Hydro Design Considerations



by Ian Woofenden

If you are blessed with water flowing downhill on your property, you are fortunate indeed. Small-scale hydro-electricity can be the most cost-effective and reliable form of renewable energy (RE) for your home. But tapping this resource responsibly requires careful planning and implementation.

Assessing Head & Flow

Hydropower is the result of two basic characteristics inherent in the stream you tap. The first is the vertical drop, commonly called "head." This correlates directly with the pressure available, since every 2.31 feet of vertical drop equals 1 psi. The other factor is flow, and specifically, the amount of the stream's flow that you are comfortable with or allowed to take. For home-scale systems, this is typically measured in gallons per minute (gpm). For background on hydro system basics and measurements, see articles in *HP103, 104, 105,* and *117*.

When measuring the head and flow at your hydro site, it's a good idea to plot your results on a map of your property. Perhaps you have a site with 220 feet of total head over a projected pipe run of 1,200 feet. The cost of 1,200 feet of pipe is high, and it may not be cost-effective to tap all of the head. Mapping the head in segments will give you the information needed to make the best decision about where your intake and hydro plant should be.

Perhaps you gain 150 feet of head in 400 feet of run, but gaining the other 70 feet of head requires 800 more feet of pipe. In this case, you might decide not to tap all of your head. In a more extreme case, you might have a 50-foot waterfall where you gain 50 feet of head with 60 feet of pipe. You might have another 20 feet of head on your property, requiring several hundred feet of pipe to tap. Often the decision is clear—tap the head that is cheapest or easiest. In other cases, the head may be gradual; with low-flow situations especially, you may be pushed toward tapping every foot of head available, from property line to property line.

Flow can vary across a property, too. Tributaries join streams as they move downhill. Water can be lost to seepage, and whole streams can go underground for portions of their course. It's important to take flow measurements at the top of each segment you're mapping, so you can calculate power (watts) and energy (kilowatt-hours) for each scenario. Factors you should consider are:

- Head gained per 100 feet of pipe
- Flow
- Pipe cost
- Energy needed
- Location of loads relative to the turbine

Choice of Intake & Location

In a hydro system, the "intake" is where water is diverted from the stream. It consists of some sort of screen to remove debris, and also helps remove suspended air bubbles from the water. The preferred intake options are simple, durable, self-cleaning, and safe for stream life.

Too often, microhydro intakes are scaled-down versions of utility-scale hydro intakes, with a dam, a "stilling pond" or reservoir, perhaps a trash rack, a diversion channel, and then a final screening. These civil works are very expensive, intrusive, and often unnecessary. When possible, find a spot in the stream to incorporate a modest self-cleaning screen that will only minimally disturb the natural flow of the watercourse. For instance, 1 square foot of the Hydro-Shear screen, which can accommodate flows up to 200 gpm according to the manufacturer, is adequate for most home-scale hydro systems. Often, existing rocks can be incorporated into the structure—I've seen intakes that only use a few cubic feet of concrete to cement in a screened intake at a narrow, natural drop in the stream.

Look for a place where the stream drops naturally and you can slip a screen underneath the falling water. Ideally, the stream will be narrow and stable at this point, so it will be unlikely to change course with winter floods. If there is some nonturbulent water upstream from the intake, all the better—this will allow the sediment to settle. One practical consideration for installation is selecting a spot where stream water can be temporarily diverted while you construct the intake.

In addition to the screened intake itself, you need to consider the penstock (pipeline) and, especially, how to get it out of the streambed. Though a tough screen cemented in at an appropriate angle can withstand heavy flooding and battering from logs and boulders, a penstock exiting the screen box may be more vulnerable. Have it exit the stream and stream bed as quickly as possible, being sure to keep it lower than the level of the intake. If the pipe is not kept below the level of the intake, the flow will be impeded and a siphon will need to be created. Protect the pipe with rock and concrete where it leaves the intake and as far down as it may be subjected to damage. For more information on hydro intakes, see the article in *HP124* and the letter in *HP125.*

Ian Woofenden (3)

Complex and expensive intakes are sometimes necessary (inset), but more often, a simple and inexpensive, self-cleaning intake right in the stream flow (above) does the trick.

Pipe Sizing

If a hydro turbine is the "engine," the penstock is the fuel line, delivering the power of water to the turbine. For optimum performance, it's critical that this pipe be sized properly. Using too small a pipe could mean losing much of the potential energy to friction. Too big of a pipe, and you'll be spending more money than needed for no significant increase in energy.

To balance cost with efficiency, hydro designers typically aim for 10% to 15% pipe friction loss (also called "head loss"). Measuring the pressure (psi) at the bottom of the full penstock with no water flowing gives the "static pressure." When the valve is opened and water flows at the rate the turbine requires, you can measure the "dynamic pressure," or net head. The difference between these two numbers is the friction loss of the penstock, which can be identified in psi or feet of head.

To size pipe correctly, you need to know the total static head, the design flow—the amount of water you will take out of the stream (which will generally be some fraction of the stream flow)—and the penstock length. Friction- or head-loss tables give losses in feet per hundred feet of pipe for various pipe types and sizes, so you can do the math to figure out what pipe to buy. If you're on the fence between two pipe sizes, round up!

Here's an example: Let's say you have a fairly steep site with 120 feet of head in 500 feet of run, and a design flow

Step-By-Step Pipe Sizing

1. Measure head
2. Measure flow
3. Measure penstock length
4. Consult charts for friction loss per 100 feet of pipe
5. Multiply by number of 100-foot sections in pipeline
6. Calculate head loss percentage, aiming for 15% or less
7. Repeat on other sizes and pipe types until choice is clear

of 100 gpm. Tables for PVC pipe show head losses of 14.53 feet per hundred feet for 2-inch pipe, 2.125 for 3-inch pipe, and 0.578 for 4-inch pipe. Multiplying the head loss by 5 (for 500 feet of pipe) gives 72.65 feet for 2-inch, 10.625 for 3-inch, and 2.89 for 4-inch. Dividing these by the 120 feet of static head, we get about 61% loss for 2-inch, about 9% for 3-inch, and less than 3% for 4-inch. In this example, the right pipe to choose is 3-inch, as head loss is significantly lower than the 2-inch pipe option, and the higher cost of the 4-inch pipe will probably outweigh the minimal 6% decrease in head loss.

Pipe Choice

You'll also need to choose the type of pipe to use. Hydro penstocks can be made out of steel, PVC, or polyethylene (usually high-density polyethylene—HDPE). Pipes of the same material can come in different wall thicknesses to handle different amounts of pressure. Your choices will depend on the pressure rating required, the size of your pipeline, what is available locally, friction losses, and your budget.

Penstocks must have appropriate pressure rating! When you map out the head, you can also convert to psi at various stages along the pipe run, adding a 40% safety factor. Most often, you'll buy one type of pipe that can handle the highest pressure in the system, which is at the turbine. But if the pipeline is long or the pipe is costly, you may opt to use pipe with a lower pressure rating at the top of the penstock, and switch to an appropriately higher pressure-rated pipe as it gets closer to the turbine.

Pipe availability depends on local demand. If you live in an agricultural area, you'll find a wide variety of irrigation and other pipe available. PVC sewer pipe in the 3- to 8-inch range can be a low-budget option for lower-head systems. However, it is not pressure-rated, so you'll have to get some inside advice on what it will actually handle. Standard schedule 40 PVC pipe is often a readily available option, and bell-and-socket gasketed versions are commonly used. PVC is subject to ultraviolet light degradation and physical damage, so it is normally buried, covered, or sometimes painted. HDPE is the toughest of the

(continued on page 82)

Friction Losses Per 100 Feet of Pipe

PVC Schedule 40 at Various Sizes

Flow (GPM)	2-In. Pipe		3-In. Pipe		4-In. Pipe	
	PSI	Ft.	PSI	Ft.	PSI	Ft.
10	0.09	0.208	0.01	0.023	—	—
20	0.32	0.739	0.05	0.116	0.01	0.023
30	0.68	1.571	0.10	0.231	0.03	0.069
40	1.15	2.657	0.17	0.393	0.04	0.092
50	1.74	4.019	0.26	0.601	0.07	0.162
60	2.44	5.636	0.36	0.832	0.11	0.254
70	3.25	7.508	0.48	1.109	0.13	0.300
80	4.16	9.610	0.61	1.409	0.16	0.370
90	5.18	11.966	0.76	1.756	0.20	0.462
100	6.29	14.530	0.92	2.125	0.25	0.578
110	7.51	17.348	1.10	2.541	0.29	0.670
120	8.82	20.374	1.29	2.980	0.34	0.785
130	10.23	23.631	1.50	3.465	0.40	0.924
140	11.74	27.119	1.72	3.973	0.46	1.063
150	13.33	30.792	1.95	4.505	0.52	1.201
160	15.03	34.719	2.20	5.082	0.59	1.363
170	16.81	38.831	2.46	5.683	0.66	1.525
180	18.69	43.174	2.74	6.329	0.73	1.686
190	20.66	47.725	3.02	6.976	0.81	1.871
200	22.72	52.483	3.33	7.692	0.89	2.056

Source (also includes tables for other pipe types): www.hunterindustries.com/Resources/PDFs/Technical/Domestic/LIT091w.pdf

4-Inch Pipe of Various Materials

Flow (GPM)	Plastic		New Steel		Corroded Steel	
	PSI	Ft.	PSI	Ft.	PSI	Ft.
10	0.00	0.01	0.01	0.01	0.01	0.03
20	0.01	0.03	0.02	0.04	0.04	0.09
30	0.03	0.06	0.04	0.09	0.09	0.20
40	0.05	0.11	0.07	0.16	0.15	0.34
50	0.07	0.16	0.11	0.24	0.22	0.51
60	0.10	0.23	0.15	0.34	0.31	0.72
70	0.13	0.30	0.20	0.45	0.42	0.96
80	0.17	0.38	0.25	0.58	0.53	1.23
90	0.21	0.48	0.31	0.72	0.66	1.53
100	0.25	0.58	0.38	0.88	0.80	1.86
120	0.35	0.81	0.53	1.23	1.13	2.60
140	0.47	1.08	0.71	1.63	1.50	3.46
160	0.60	1.38	0.91	2.09	1.92	4.43
180	0.75	1.72	1.13	2.60	2.38	5.51
200	0.91	2.09	1.37	3.16	2.90	6.69
250	1.37	3.16	2.07	4.78	4.38	10.11
300	1.92	4.43	2.90	6.69	6.13	14.17
400	3.26	7.54	4.93	11.39	10.44	24.12
500	4.93	11.39	7.45	17.22	15.78	36.45

Source: www.tasonline.co.za/toolbox/pipe/velfirc.htm

Example Hydro Placement Scenarios

Icehouse Creek, North Fork Options

	Pipe Section	Scenarios 1	2	3	4	5	6	7	8	9
Head (Ft.)	A–B	18	18	18	18	18	–	–	–	–
	B–C	13	13	13	13	13	–	–	–	–
	C–D	–	14	14	14	14	14	–	–	–
	D–E	–	–	18	18	18	18	18	–	–
	E–F	–	–	13	13	13	13	13	13	–
	F–G	–	–	–	13	13	13	13	13	13
	G–H	–	–	–	–	12	12	12	12	12
	Total Head	31	45	76	89	101	70	56	38	25
	Flow (GPM)	60	60	60	60	60	60	60	60	60
	Power (W)*	143	208	351	411	466	323	258	175	115
	kWh/Day	3	5	8	10	11	8	6	4	3
	Penstock Length (Ft.)	200	300	500	600	700	500	400	300	200
	Wire Length (Ft.)	1,360	1,420	1,470	1,500	1,550	1,550	1,550	1,550	1,550

Icehouse Creek, Middle Fork Options

	Pipe Section	Scenarios 10	11	12	13	14	15	16	17	18
Head (Ft.)	A–B	12	12	12	12	12	–	–	–	–
	B–C	15	15	15	15	15	–	–	–	–
	C–D	–	16	16	16	16	16	–	–	–
	D–E	–	–	13	13	13	13	–	–	–
	E–F	–	–	–	0	0	0	–	–	–
	F–G	–	–	–	30	30	30	30	–	–
	G–H	–	–	–	25	25	25	25	25	–
	H–I	–	–	–	25	25	25	25	25	–
	I–J	–	–	–	–	25	25	25	25	25
	J–K	–	–	–	–	20	20	20	20	20
	Total Head	27	43	56	136	181	154	125	95	45
	Flow (GPM)	85	85	85	85	85	100	100	110	110
	Power (W)*	177	281	366	889	1,183	1,185	962	804	381
	kWh/Day	4	7	9	21	28	28	23	19	9
	Penstock Length (Ft.)	200	300	400	800	1,000	800	500	400	200
	Wire Length (Ft.)	500	610	700	880	1,300	1,300	1,300	1,300	1,300

*P (W) = [Head (Ft.) x Flow (gpm)] ÷ 12

Choosing intake and turbine location often becomes a balancing act between the energy needed and the cost of the pipeline and wire. Note that flow increases along the length of the Middle Fork while it remains the same on the North Fork. See text starting on page 79 for more information.

Shawn Schreiner

The double-cup design of the Pelton runners is best for a very high head-to-flow ratio.

plastic options. This material can be fused together with a "welder," and is tough enough to drag behind a tractor or mule to get it into place.

Aluminum and steel pipe are used less often because of cost and higher friction losses. They can sometimes be found surplus and are very durable, though there are concerns with rust and corrosion. I've seen steel used for the lower ends of penstocks, where the pressure is higher, and at high-wear points like road crossings and places where the pipeline comes to the surface. Common aluminum irrigation pipe cannot handle much pressure, nor can it be buried, since it will corrode.

Every hydro designer has their own pipe preferences, based on the site, experiences, and values. For exposed penstocks 3 inches and larger, I lean toward HDPE. For buried pipelines, the additional expense may not be warranted. Evaluate your situation, educate yourself about the benefits and costs, and make a choice that will serve your needs.

Turbine & Runner Selection

Most home-scale hydro sites in North America are "high-head" systems, with drops from 10 feet to hundreds of feet. While there are many potential "low-head" (18 inches to several feet) sites, they require more flow and can be subject to more political challenges, since the complete stream or river flow is often diverted, requiring a dam across the whole water course. We'll primarily focus on high-head systems.

A hydro turbine includes a "runner"—the wheel that receives the water's kinetic energy to drive a shaft. Two types of runners—the Pelton and the Turgo—are used in most of

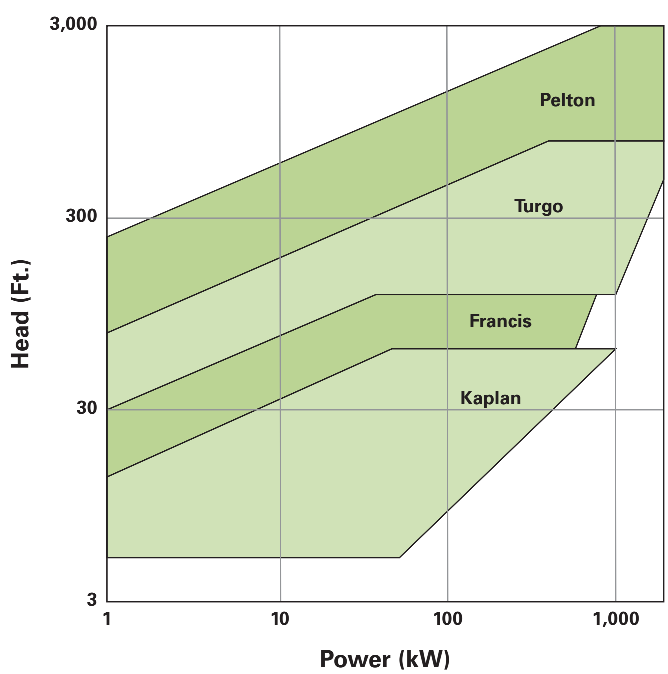
Courtesy www.microhydropower.com

The design of the Turgo runner performs better with more flow than a Pelton runner, but is also a pressure-dependent design.

the small, high-head turbines. In general, the Turgo tends to work more effectively at lower heads and higher flows than the Pelton. But there is a broad range of overlap between the two runners, and each turbine manufacturer will have a preference and point of view. Other runner types, such as the Francis, propeller, and cross-flow, are generally used in low-head, high-flow conditions, and may be appropriate for your site. Pumps used as turbines are another option that some designers use in a number of different situations.

When deciding on turbine type, ask the manufacturers for information and get more than one opinion. Most of us will never be experts at selecting the perfect runner for a specific site, and most hydro homeowners only make this decision once or twice. Most manufacturers will fully disclose their products' limitations, and in this small industry, a few phone calls can net you much of the available information. Ask the suppliers what they recommend for your site. Look at what

Turbine Runner Choices



Choices shown are for one manufacturer's line of turbines. Courtesy Tyco Tamar.

they offer, and whether they have choices of different runners in their lines. And realize that different runners can do a reasonable job on the same site.

System Configurations

Home-scale hydro systems have four basic configuration possibilities. **A stand-alone system with batteries** looks very much like an off-grid PV or wind-electric system. It's not important how the batteries get charged—hydro, wind, PV, or generator. You'll need a controller to protect the batteries and a diversion load to accept excess energy as the batteries approach full.

A batteryless stand-alone system, or AC-direct system, is only appropriate for larger hydro plants (rated at 3 kW or more), to provide the peak power required to start motors and make sure there is enough power to run all the concurrent loads. In these systems, there is no storage, buffer, or surge capacity. To keep the turbine fully loaded all the time and keep the combined load consistent, a load-control system turns staged diversion loads on and off depending upon how heavily the home is loading the system. The fewer loads that are turned on in the home, the more dump loads will be switched on.

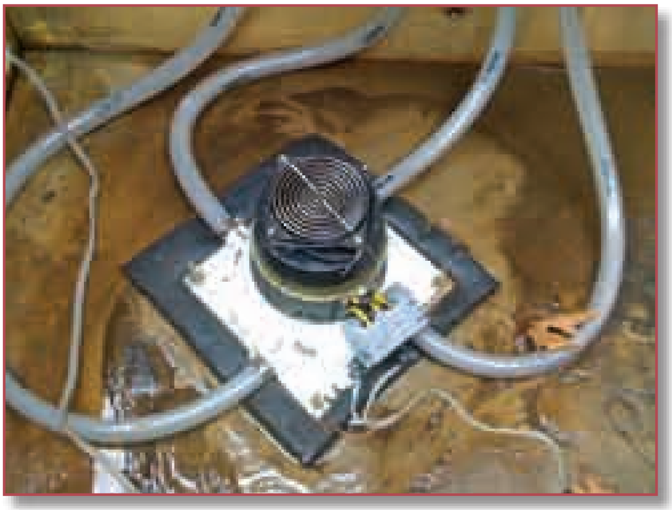
A battery-based grid-tie system closely resembles a stand-alone system with batteries. You'll need the charge controller and diversion load, but these will really only come into play during grid outages. While the grid is up, the grid-tied inverter will regulate the batteries, and any surplus hydro electricity will be fed to the utility grid.

Batteryless grid-tied systems can take at least two different forms, depending on the size of the system and local connection regulations. Larger systems may use induction motors and directly tie to the grid, and they rely on controllers to divert or shut off the water flow if the grid goes down. Smaller systems will likely use a modified batteryless PV inverter, sometimes with added electronics, and also use a controller and dump load for grid outages.

Take a look at what your goals are, how close the grid is, and the scale of your system. Then build a robust system to work within those parameters. See articles on going off-grid or staying on-grid in *HP128*, and on basic hydro system configurations in *HP117*.

Choosing Nozzles

Once your system is installed, you'll need to learn the nuances of operating it. Many systems have variable flow over the seasons and varying loads. This means that you won't necessarily be able to run the turbine in the same way or at full output year-round. Pelton and turgo turbines offer the option of varying the number or size of nozzle to adjust the flow. If you don't wish to take the time and effort to adjust nozzle sizes and numbers, you should find a single flow level to run the turbine so you will always have enough energy. In times of higher flow, this means you'll be sacrificing additional available energy for the benefit of simplicity. Most streams undergo periods of flooding and times of low flow due to freezing or low precipitation. This can create a design challenge, since you want a turbine that can run at reasonable efficiency over a range of flows.



Four different-sized nozzles on this turbine allow 15 possible combinations of flow and power.

Christopher Freitas (2)

Four valves control flow to the four nozzles, while a pressure gauge monitors system head.

While the total head, available flow, and pipe friction affect the amount of water hitting your runner, the nozzles are the primary flow regulators. These precision-made pieces direct a jet of water at the runner's cups through holes that can be $^1/_8$ to 1 inch in diameter. The nozzles control the flow, and you can determine the flow through each size of nozzle from information available from your turbine manufacturer (see "Nozzle Flow Rates" table for an example).

Small turbines can have one to four nozzles, each controlled by a valve. By installing a variety of nozzle sizes on the multiple inputs, a wide variety of flow configurations are available. This minimizes nozzle changing, which can be cumbersome with some turbines and setups, and uncomfortable depending upon the season. Often, it's useful to buy a turbine with three or four nozzles even if you will only use one or two at a time, just to be able to microadjust the flow to the runner based on the amount of water available.

Penstocks should have a pressure gauge installed just upstream of the stop valve(s) or turbine manifold, where the pipeline is divided to go into multiple nozzles. When all nozzle valves are shut, the gauge will show the static pressure. When

Nozzle Flow Rates

Head (Ft.)	Pressure (Psi)	Flow (Gpm) Per Nozzle Diameter (In.)										
		1/8	3/16	1/4	5/16	3/8	7/16	1/2	5/8	3/4	7/8	1
5	2.2	—	—	—	—	6.2	8.4	11.0	17.1	24.7	33.6	43.9
10	4.3	—	—	3.9	6.1	8.8	11.6	15.6	24.2	35.0	47.6	62.1
15	6.5	—	2.7	4.8	7.4	10.7	14.6	19.0	29.7	42.8	58.2	76.0
20	8.7	1.4	3.1	5.5	8.6	12.4	16.8	22.0	34.3	49.4	67.3	87.8
30	13.0	1.7	3.8	6.7	10.5	15.1	20.6	26.9	42.0	60.5	82.4	107.0
40	17.3	1.9	4.4	7.8	12.1	17.5	23.8	31.1	48.5	69.9	95.1	124.0
50	21.7	2.2	4.9	8.7	13.6	19.5	26.6	34.7	54.3	78.1	106.0	139.0
60	26.0	2.4	5.4	9.5	14.8	21.4	29.1	38.0	59.4	85.6	117.0	152.0
80	34.6	2.8	6.2	11.0	17.1	24.7	33.6	43.9	68.6	98.8	135.0	176.0
100	43.3	3.1	6.9	12.3	19.2	27.6	37.6	49.1	76.7	111.0	150.0	196.0
120	52.0	3.4	7.6	13.4	21.0	30.3	41.2	53.8	84.1	121.0	165.0	215.0
150	65.0	3.8	9.0	15.0	23.5	33.8	46.0	60.1	93.9	135.0	184.0	241.0
200	86.6	4.3	9.8	17.4	27.1	39.1	53.2	69.4	109.0	156.0	213.0	278.0
250	108.0	4.9	10.9	19.9	30.3	43.6	59.4	77.6	121.0	175.0	238.0	311.0
300	130.0	5.3	12.0	21.3	33.2	47.8	65.1	85.1	133.0	191.0	261.0	340.0
400	173.0	6.1	13.8	24.5	38.3	55.2	75.2	98.2	154.0	221.0	301.0	393.0

a valve or valves are open, the gauge will show the dynamic pressure. Under normal operation, by watching the gauge, you'll be able to record baseline pressures for various flows. Then, if you turn on too many nozzles, which causes too much water to be taken in and the pipe to empty, the decreasing dynamic pressure and loss of power will alert you that you should switch to a smaller nozzle. The dynamic pressure can also help you diagnose problems with the system: too high can mean a plugged jet, and too low can mean a clogged intake.

Hydro Design

After you've completed some basic research and reading (see Access), consulting with local and regional hydro dealers/installers is an excellent next step. Turbine manufacturers' Web sites often have extensive planning information available at no charge.

Designing and operating a small hydro-electric system is not simple. A number of key decisions are involved in both design and operation. But thinking ahead can save you time and money, and help you tap your valuable resource carefully and responsibly.

Access

Ian Woofenden (ian.woofenden@homepower.com) can only dream of hydro electricity from his flat-island home. He plays in other people's streams in western Washington and Central America.

Recommended Reading:

"Intro to Hydropower" by Dan New, *HP102, 103* & *104*

"Microhydro-Electric Systems Simplified" by Paul Cunningham & Ian Woofenden, *HP117*

Articles on hydro intakes, pipelines, and transmission by Jerry Ostermeier and Joe Schwartz can be found in *HP122, 125* & *126.*