Proceedings of the Sixth International Permaculture Conference
September-October 1996, Perth, Western Australia

Water Wheel Engineering

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[Submitted Paper]

Design decisions

Which water wheel technology best suits your situation? The answer to this question rests mainly in three parts, assuming money is no object:

- How much 'head' of water is available and what is it's flow rate?
- What civil engineering works are needed to make it useful?
- What is the level of available technology?

Head of Water is a term that is characterised by the difference in height of the first availability of the water (ie where you take it under your control) and the location of the device utilising the water's potential energy to produce a useful form of energy for human consumption, like electricity, for instance. The taller the height that the water descends before you attempt to extract energy from it, the greater the effects of gravity on it's acceleration from that height and the greater the available potential energy will be. Potential energy is energy in a latent or stored form. A heavy concrete block suspended from a thick rope has potential energy; it can potentially descend to provide energy that is 'kinetic', or dynamic, in nature. This energy might be used to drive a pile into the ground, for instance. The energy is potential while ever it may happen, but currently isn't. Kinetic energy is energy due to velocity. The faster the velocity, the greater the energy for any given mass that is in motion.

Head of water is potential energy; litres per second of water is kinetic energy or 'happening' energy. Water stored in an over-head tank or a hill-top dam is potential energy, waiting to be tapped for use. Water soaked into the ground is indirect potential energy. You could use it to grow trees for fuel.

What civil engineering is required?

Do you have to build a hill-top storage dam to store rain run-off, an over-head water tank, a weir across a stream, or are you so fortunate as to have a natural water-fall available to provide energy from hydro-electric water turbines? Best of all is to have a perennial stream. This requires little engineering on your part to produce pumped water or electricity.

Each of these scenarios has it's own in-built problems and engineering works.

A hill-top storage dam presupposes a hill-top catchment area. You will need to have the collected water channelled into the dam and this may involve earth-works in a (for heavy machinery) sometimes dangerous location. This danger will add to the cost and difficulty of 'delving' needed drains and channels. The right location for the dam is vital, too. Read Yeomans' book "Water for Every Farm" or hire an hydrological engineer.

Water is heavy stuff (a kilolitre weighs a tonne) so dams and stands for water-tanks must be carefully engineered if they are to do their job. This means they have to be 'substantial' which is another way of saying expensive. On the other hand, a cheap dam or tank-stand is only temporary, at best.

The water from a water-fall needs to be controlled and contained before it can become useful energy. This usually, but not always, means a large tube and a cliff-top collection weir to gather the water and direct it to the turbine for conversion into rotating mechanical energy suitable for driving machinery.

What level of technology?

One of the simplest and most efficient types of water turbine for small-scale use is the Australian Michell or 'Banki' turbine. This is easy to construct in a backyard workshop with welding and plate-metal engineering facilities because of it's simplicity. It is similar to the 'barrel' fan often seen in water-evaporative air conditioners and in some small 'blower-heaters' for home use.

Other types of water turbine may be purchased from specialist suppliers. There are Pelton Wheels, used in high pressure systems that have relatively low flow rates but very high 'head'; Francis-type turbines for use in higher flow rates and lower 'heads'; and Tyson turbines that are mounted on a raft for anchoring in flowing streams. This latter is another recent Australian invention and provides surprising performance at very slow flow-rates. It is most often used to pump water but can be adapted to provide electricity or both at the same time! At the bottom end of the technology scale are the water-wheels. These are proven and mature technology, albeit at a simple level, having been around for some six thousand or so years. If you work in wood, the simplest hand-tools are sufficient to build a basic water-wheel.

Water-wheels come in two basic flavours – under-shot and over-shot, with the former having two basic variants depending on the height of the water feed to the wheel. The over-shot wheel has the water being fed in to the wheel disk at the top so as to collect in buckets on the wheel causing the front of the wheel to be heavier than the rear. The weight of water causes the wheel to rotate forwards, emptying the buckets into the 'tail-water' stream which then flows on to the sea, or where-ever. High efficiency comes from full utilisation of the water flow which is directed into the wheel buckets with little or none flowing elsewhere, unlike an under-shot wheel with 'bypass' leakage below and around the wheel. Even so, there's not much in it between the two, although the over-shot wheel has fewer problems with water-borne debris. The narrow clearance below and to the sides of the over-shot wheel are an invitation to jamming by even small branches and logs if no special precautions are taken to filter them out of the feed water.

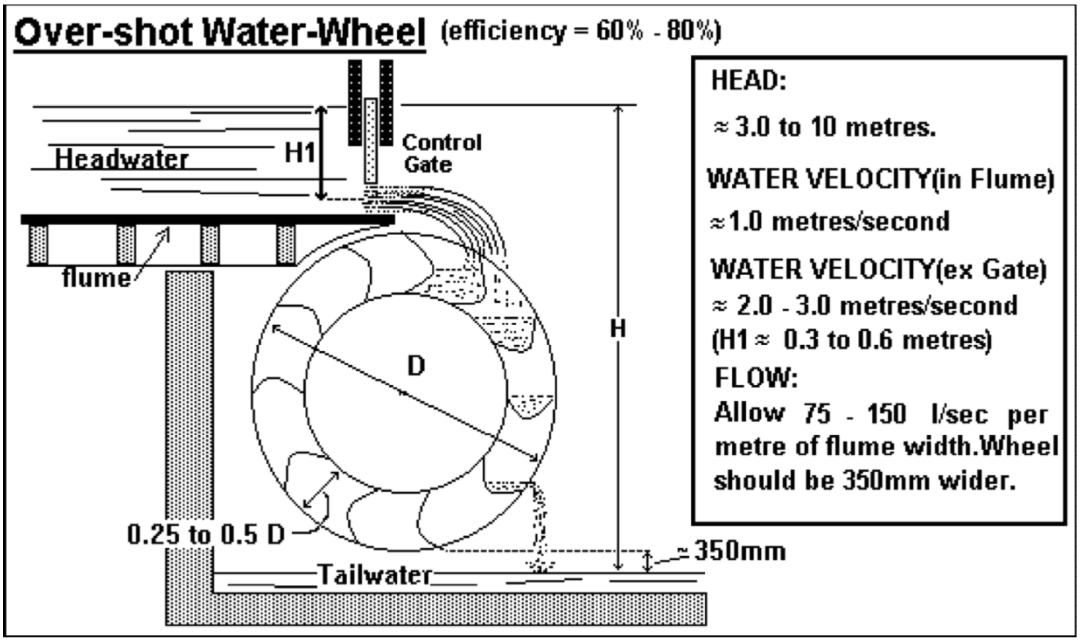

Figure 1: *Over-shot water-wheel*

The oldest variant of the under-shot wheel is like a paddle wheel on a paddle steamer. It has its lowest extremities immersed in the flowing stream which causes the wheel to rotate backwards. It powered the English Industrial revolution in its early stages until the advent of steam-power.

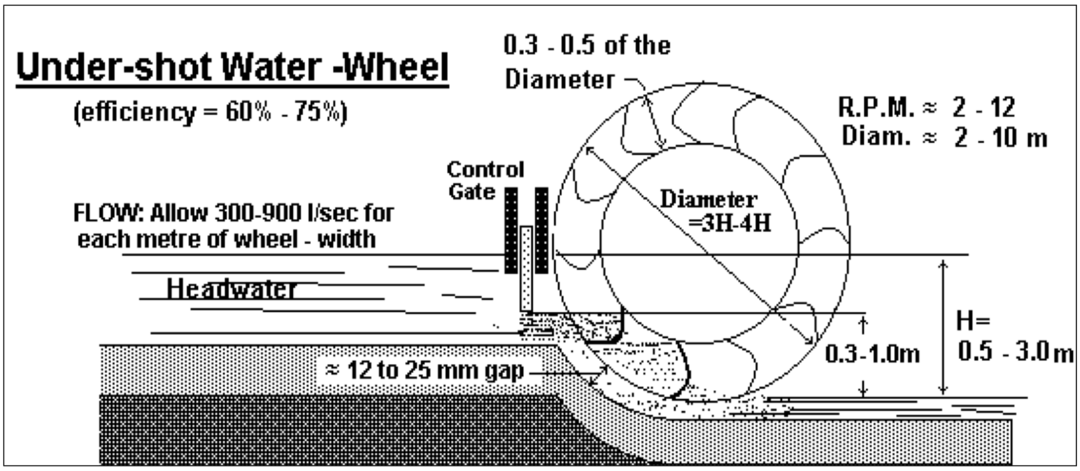

Figure 2: *Under-shot water-wheel*

A more efficient version of the under-shot wheel has the water fed into the wheel a bit less than half-way up. The water feed channel (or Flume) continues to follow the curve of the wheel downwards to a point directly underneath the axle where it flows into the tailwater stream. This curved channel is closely fitted to the dimensions of the wheel, trapping the water in such a way as to closely couple it to the wheel structure and not allowing much 'slippage'. In some respects it combines the best of both over- and under-shot wheels. This is a type of wheel suited to home handy-man construction. The shaped flume can be built from concrete, cement-rendered brick, steel or even wood. Provision must be made to filter out all water-borne debris that is likely to cause harm to the wheel mechanism by impact or jamming. An overflow reservoir is a useful method of allowing floating debris to be bypassed around the wheel, while filter screens will be needed for other rubbish. In some situations the filter will need fairly constant attention to keep it clear and the wheel turning, so design ease-of-filter-cleaning into the system.

Whilst the design rules allow for any width of wheel, for structural strength it is wise to keep the ratio of diameter to width as near as practicable to 8 : 5. This is not a hard and fast rule, however, and D:W ratios of up to 1:2 are used. Beyond this, the strength of standard-sized timbers and steel structural members tend to be insufficient to the task and heavier construction is called for which will increase expenses dramatically. Bear in mind that torque is the product of force times leverage. This means that larger diameter, narrower wheels are preferred, consistent with flow rate. 'Work the numbers' first before you start building to see what you are up against. One or more extra reinforcing rims may be necessary across the width of the wheel.

Pelton wheels

Pelton wheels are high-speed, highly engineered devices that would be beyond the ordinary resources of a home handy-man. Someone with an industrial lathe, milling machine and a foundry could perhaps manage to build one but the design requires detailed metallurgical knowledge and experience, accurate machining and heavy-duty workshop equipment. It is not for the hobbyist. However, it is possible to purchase the difficult-to-manufacture rotor and case assembly for use in your own set-up from specialist turbine manufacturers.

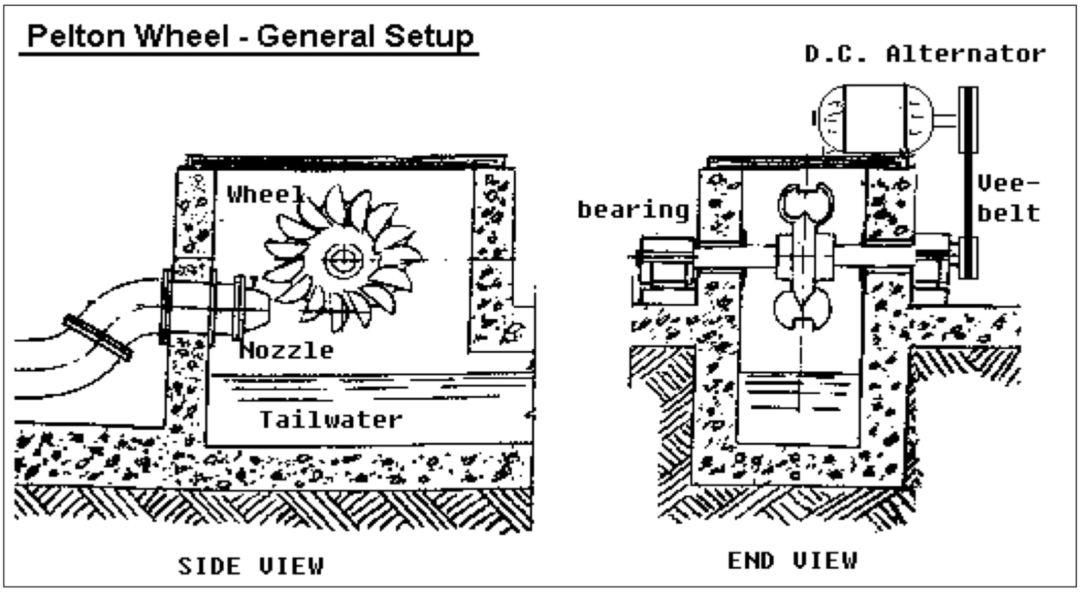

Figure 3: *Pelton wheel – general setup*

Figure 4 shows details of the typical pelton wheel showing the complex, stress-resistant construction. (lots of bolts!). Not a task to be taken lightly.

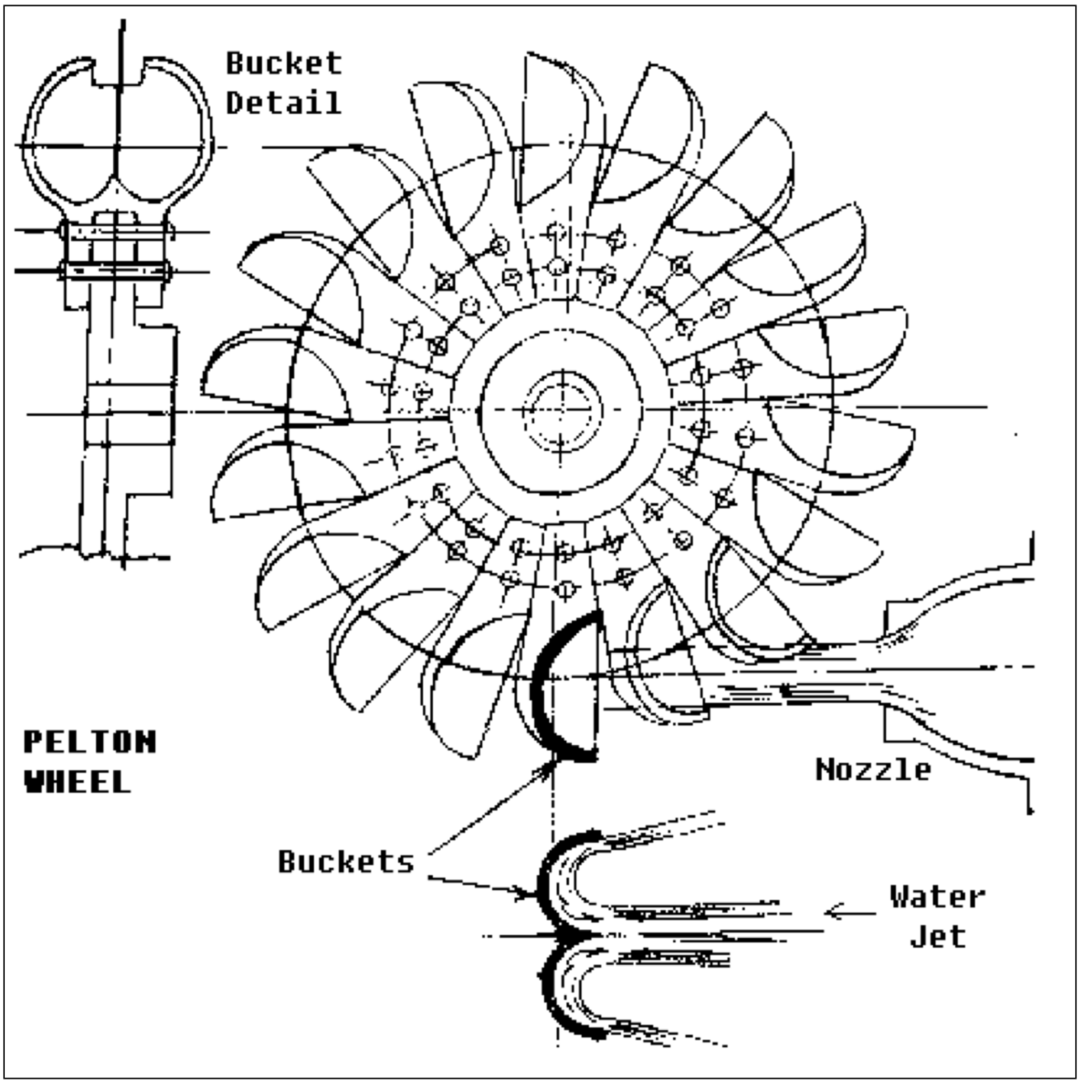

Figure 4: *Pelton wheel detail*

Pelton wheels typically have more than the one nozzle and some have 'throttleable' nozzles for power control. Another variant switches multiple nozzles on or off to achieve a similar result but without the fine control.

Control of water wheels and water turbines presents some problems in the case of electric power generation. Normal domestic electricity in Australia runs at 240 Volts and 50 cycles (or Hertz). To maintain both the voltage and the frequency within limits requires fine power control and load regulation. Now, while this is possible (hydroelectric power companies do it all the time), in a small scale system for a single home the control problems can be very difficult. Most people opt to generate Direct Current (DC) instead for a number of reasons:

1. DC can be stored in batteries and generated using readily and cheaply available technology, mostly from motor vehicles.

2. the batteries also provide the scope to store power from other sources such as photo-voltaic (solar) cells, wind or diesel genset for those instances when

water flow is insufficient to supply power for the home. Some domestic appliances will require an 'Inverter' to provide the 240 volt, 50 cycle power normally provided in suburban homes. This is an added expense.

3. the presence of other power sources allows for pumping water when the water wheel can't.

If you have a fairly reliable and constant, high-volume flow of water then an Alternating Current (AC) supply is a possibility. The most difficult part of this type of system is the control of water flow to the turbine to provide first; a constant alternating frequency, and second; a constant voltage with changing loads as different appliances are used then turned off again, such as the fridge. So what, I hear you say, the extra savings in not needing battery storage or charge regulators can be used to give accurate load regulation. Not necessarily.

A water wheel responds too slowly to changes in flow to allow straight-out flow-volume regulation of power parameters. That is, more load, more flow; less load, less flow. When a fridge compressor starts up it wants 240 volts, 50 cycles *right now*, not in three or four seconds time. There is the danger of burning out the motor if the voltage 'sags'. To overcome this problem of response time, it customary to have a limited capacity battery bank with a 'sine-wave' inverter to provide the extra 240 volt power temporarily while the water-wheel or turbine gets 'up to speed' to provide for the higher load. In addition you will need some fancy mechanisms to vary the turbine inlet water flow as required by the electrical load.

The Tyson turbine

The *Tyson turbine* (Figure 5) is mounted on a floating pontoon platform and is usually moored in mid-stream of a flowing river or creek. It is relatively light and with the turbine itself cranked out of the water the system can be towed by a light boat to a new location. Both rotating and reciprocating outputs are available from the gearbox. The latter being used to operate a positive displacement pump for water and the former being used for rotating machinery such as two alternators to provide DC power to charge batteries directly at the riverside or for conversion to AC for longer distance transmission up to five kilometres from the site.

How much power will I get?

The power generated by moving water is a product of *Net Head* and *Flow Volume* (through the water wheel or device). What is Net Head? Net Head is derived from Total Head minus Head Losses. This, of course, begs the questions: what is Total Head and what are Head Losses?

Total Head is the total vertical distance that the water is falling or moving from while Head Losses are those factors that reduce the effective head such as bends in a stream, changes in stream wall and floor 'roughness', stream cross-sectional area, obstructions, etc. So a Head Loss is caused by anything that obstructs or limits the ready flow of water. How do we work this out? First we need to know the Total Gross Head (before losses are subtracted). We do this by finding the difference in height between the source water (Headwater level) and the level of the discharge water from the turbine (the tailwater level). If you can't afford a surveyor, try the

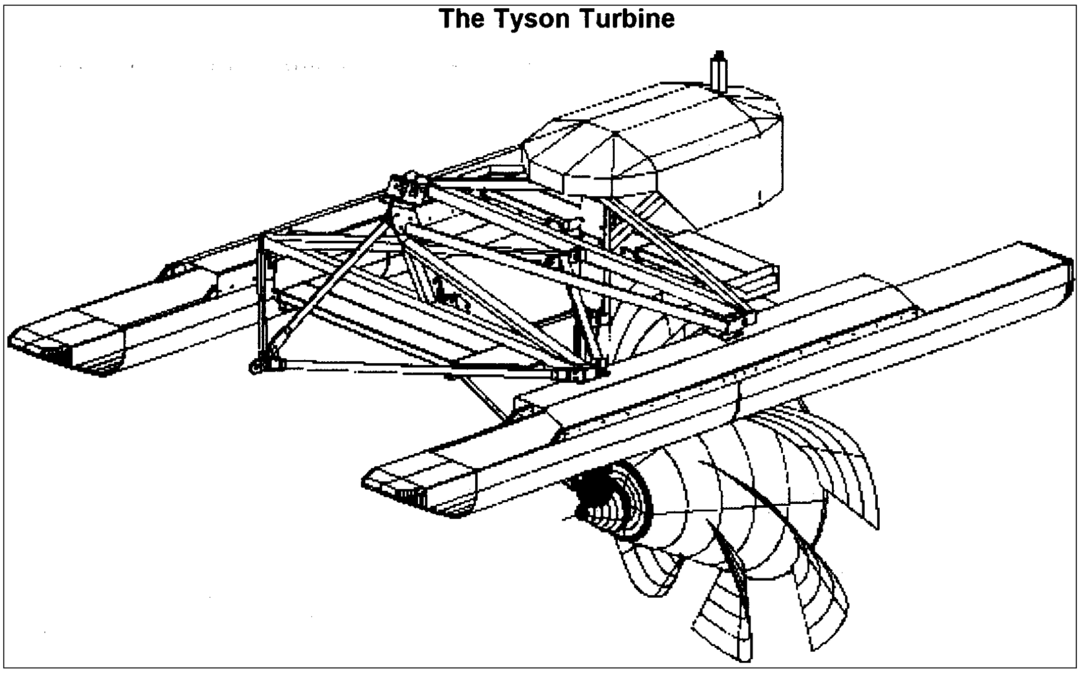

Figure 5: *Tyson turbine*

method shown in Figure 6. With care, it can be quite accurate. Accuracy is not a real issue, however, because within +/- 10% is good enough; after all, we only want to get some idea of performance for evaluation purposes at this stage.

Having determined our gross head, we will now have to determine the losses in our water delivery system from the Headwater Dam to the turbine. This will vary depending on the type of system. For a pipe, the losses per linear length are fairly well documented by the pipe manufacturer, given the flow rate in cubic metres/second (or maybe cu. feet/second). Any bends, joins or other restrictions will add to the figure and the manufacturer can supply figures for these, too. For an open drain (or flume, as it's known), you will have to refer to an hydrology engineer or a good publication dealing with losses in open flumes. Such things as soil types, linings (if any), cross-sectional area and shape all affect losses. Soil type also affects the maximum water velocity you can utilise in a flume and this will, in turn, impact on your maximum flow rate and therefore power generated.

To calculate the Gross Power Available from a particular flow of water, use the following formulae:

$$GMHP = \frac{MWF \times NH}{75}$$

where:

$GMHP$ = Gross Metric Horse Power
MWF = Minimum Water Flow (1000 m^3/s)
NH = Net Head (m)

Don't forget, no machinery is perfect and will not, therefore, convert *all* energy presented to it into useful energy for your use. Assume about 80% efficiency for most

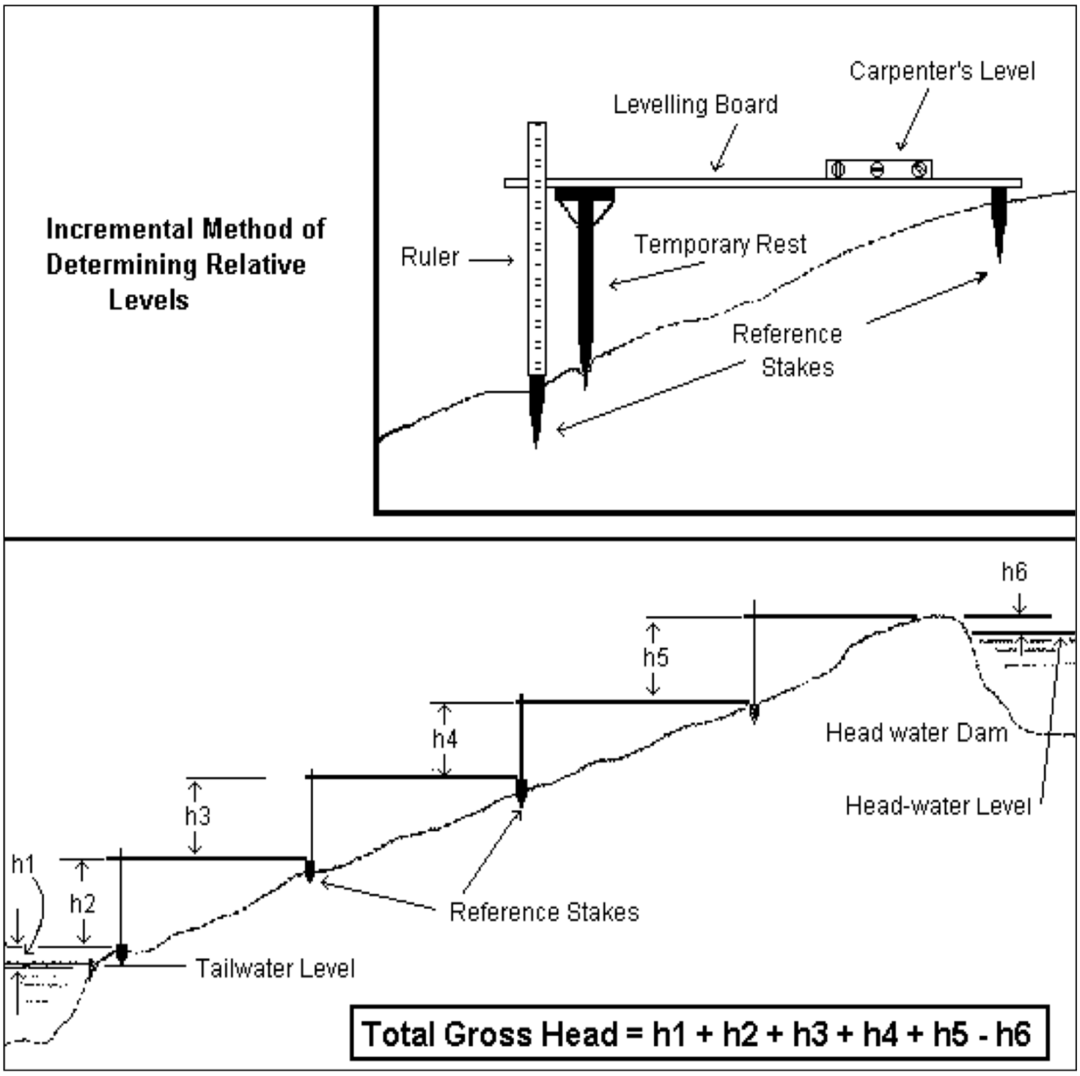

Figure 6: *Determining levels*

turbines, in the absence of knowledge to the contrary. This means that Net Horsepower output will be 80% of the calculated Gross Horsepower.

What we need, still, but don't yet know, is how to calculate the flow rate of the water. This is pertinent to the *type* of water-wheel/turbine as well as the amount of available power. Some water-wheels or turbines work better in some situations than others because they are inherently, by design, built for particular conditions.

In Australia it is not uncommon to have 'winter creeks' that only flow for a few months of the year. In that period the flow rate may vary over a range of several hundreds down to one. Obviously a turbine that worked more efficiently at low volume flows would provide useful power for a longer period of the year than one designed for fast-flowing waters. It would be important to extract power even when the flow had slowed to a trickle and less important when the creek was in spate, especially for a home electricity generation system. This scenario would also apply to the situation of using irrigation waters from a farm dam to provide power because the water level, and therefore the Gross Head, would vary enormously. So, there are, as always, horses for courses. You will have to decide.

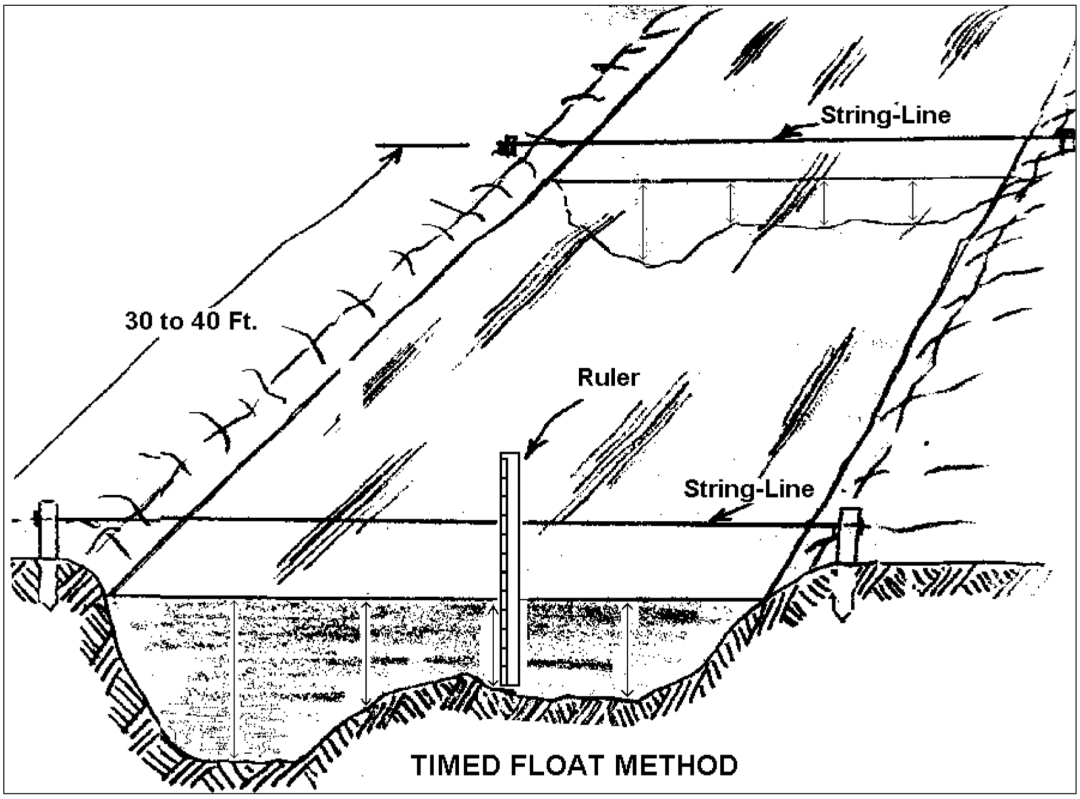

Figure 7: *Determining flow rate*

The Michell (or Banki) turbine

A sound choice, however, would be the Banki turbine (Figure 8) in situations of variable flow and volume because it is readily 'throttlable' to maintain a high conversion efficiency level, even over a 100:1 (or more) ratio of flow or head. They are also cheap and simple to build and have the endearing virtue of extracting power from the flow twice; once on entry to the wheel and once on exit from the wheel and, therefore, constitute a 'double-acting' turbine. The physical design is simple and lends itself to 'backyard' fabrication. Don't be fooled, though, these turbines mean business. For instance, a 900 mm diameter, 600 mm wide Banki turbine running from a head of 20 metres at one cubic metre per second will produce in excess of 260 shaft horsepower at about 500 RPM. This is serious power!

The Banki turbine consists of a rotor that is not unlike that in a 'Barrel' blower-fan. It has two circular endplates with the shaft running through the middle of them and curved vanes strung longitudinally between them. With the shaft horizontal, the water is let into the turbine 'runner', as the rotating bit is known, at the '9 o'clock' position (as viewed from the end) where it imparts some of it's energy to the vanes. The water then jets across the hollow interior of the runner to impart more energy to the vanes on the opposite side at about the '5 o'clock' position, hence the 'double-acting' function because the water is used twice before it is exhausted to tailwater. The Michell turbine is very amenable to power control by means of narrowing the feed-nozzle width and for fine control by means of a throttle plate in the throat of the feed-nozzle. In some designs, coarse control is accomplished by means of dividing the feed-nozzle horizontally into independent sections that can be

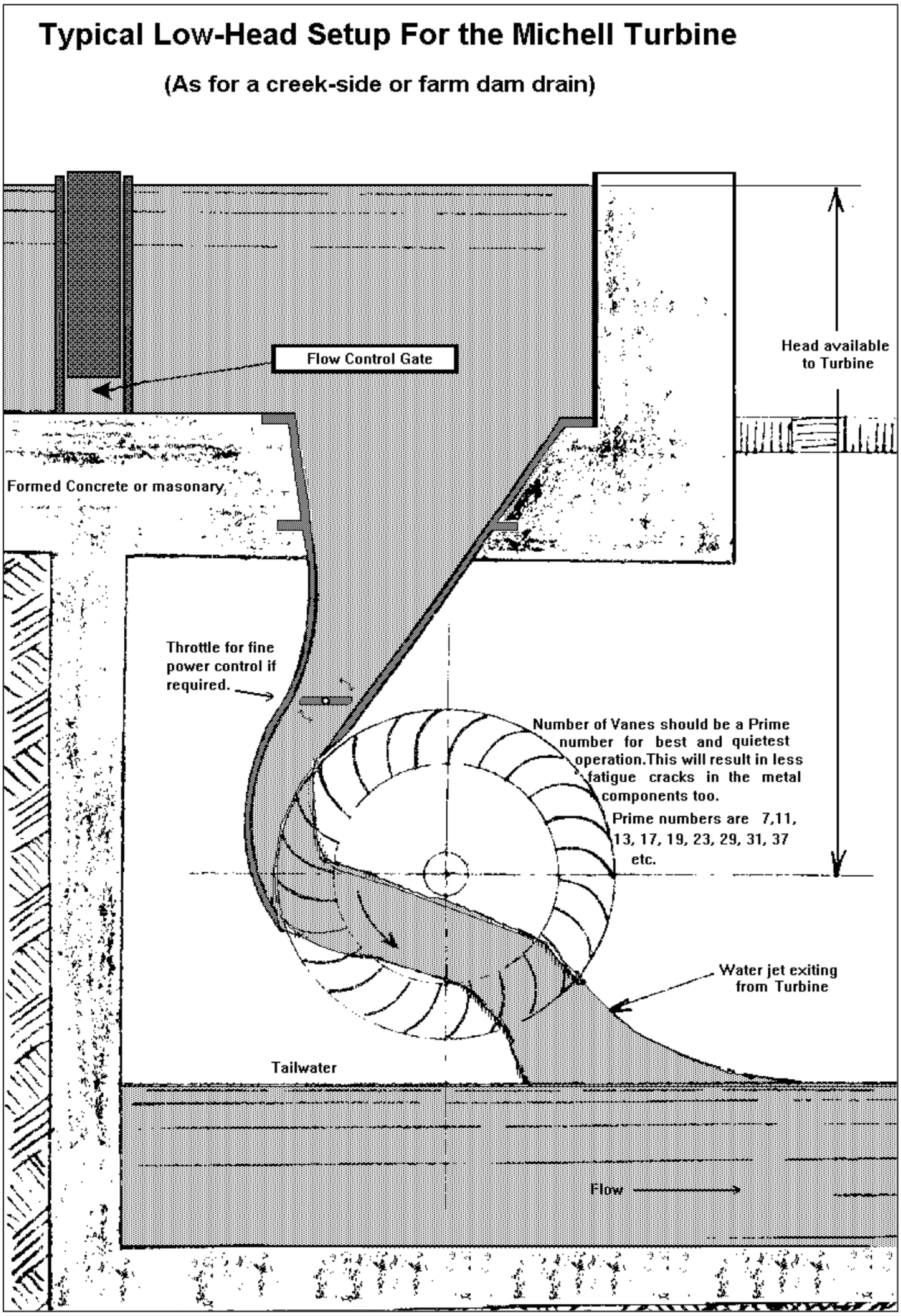

Figure 8: *Michell turbine*

fed, or not, with water. This allows conservation of feed water stocks and maintain output power to specification by shutting off one or more feed-nozzle sections under light loads. This is a similar tactic to that used to vary output power of multi-nozzle Pelton wheels and steam turbines.

Whilst being fairly compact in size, the construction of a Michell turbine requires substantial structures since a small runner can still produce output power comparable to a Mack truck. Bearings and their mountings need to be solidly built and protected from water ingress while the runner, itself, needs attention to detail to ensure structural rigidity and good balance since rotational speeds of up to 600 RPM may be reached easily. An out-of-balance runner will soon destroy it's bearings and support structures, as well as being noisy.

On the topic of noise, be aware that rotating machinery, no matter how well balanced, will still vibrate due to harmonic resonances if the number of vanes is an even number. To alleviate this problem, make sure that you build with a 'Prime' number of vanes. Prime numbers are those divisible only by one and themselves. The first few are seven, eleven, thirteen, seventeen, nineteen, twenty-three, twenty-nine, thirty-one, etc. So use one of these numbers of vanes. There will still be substantial noise generated by fast revving alternators or pumps and their associated drive-belts, pulleys or gearboxes which will necessitate siting the machinery away from habitation and in a reasonably sound-proof enclosure. Belt noise can be minimised by correct alignment and adjustment, but not eliminated. Make sure that vermin can't get access into the runner compartment where they could throw the rotating machinery temporarily out of balance and thereby create destructive chaos.

A 'trash-rack' will be necessary to filter out water-borne matter substantial enough to jam or catch on the rotating vanes whilst an overflow tank can be used to reject any floating debris. Get your feed-water as clean as you can to improve the longevity of the runner. Water-borne dust and grit will quickly wear away metal parts but can be mostly removed by settling out in the same pond used for rejecting the floating debris. This pond needs to be large enough for the feed-water velocity to be reduced to 2% or less of the feed flume velocity. This then dictates that the pond dimensions should be fifty or more times the width of the flume and at least one and a half to two times the depth. The pipe that feeds the feed-water to the runner flume from the settling/overflow pond is called the penstock. An ideal arrangement would be to feed the penstock from the centre of a circular pond, via suitable trash-racking, from near-surface waters and feed replenishment water into this pond tangentially at the edge so as to cause the feed waters to swirl around the edge. This has the advantage of depositing silt and grit at the edges where it is readily dredged out, as required, and forcing floating debris away from the trash-racking by centrifugal force until it has the time and the position to exit via the overflow flume. An appropriately positioned metal-strip slide on the outside of the floating rubbish exit could be arranged to filter out and deposit firewood for winter use, if sufficient were to be found in the source water.