Hydrology for the Small-Scale Water Well

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Okay, enough of the lawyer talk. Start hydrologizing!

1. Introduction

If you don't have drinking water, you will die. If you have your own well, you're safe from interruptions of the municipal water supply, but if your well has an electric water-pump, loss of grid electricity can shut your water off. Making sure you can get water from your well in times of failure of the infrastructure is, quite simply, a matter of life and death.

2. How this Article is Structured

This paper explains basic concepts of water-well engineering, emphasizing photovoltaics (PV) as an approach to power your well pump.

This article consists of three files: [1] The file you're reading now: HYDROLOGY.DOC (MS-Word Format) or HYDROLOGY.TXT (text format); [2] HYDROLOGY.JPG, a graphic of the well and storage system; and [3] HYDROLOGY.XLS, a spreadsheet which will enable you to calculate how much electricity you will need for your particular well and water needs. Once downloaded, you may embed the JPG file in the text document or keep it separate.

Section 3 of this document overviews basic hydrology, well engineering theory, and an important power equation. Section 4 looks at different power sources for our well, and Section 5 provides a real-life example of water-well design, using photovoltaic modules as a power source.

There area lot of specialized words and acronyms in this paper; the first time I use one, I will **bold** it, then define it or spell it out.

3. Wells and Well Engineering

3.1 Hydrology 101

Rain and snow fall on the ground. Some evaporates, some runs off in rivers, and some is taken up by plants and animals. The rest of it seeps deep into the ground and collects in underground water pockets called **aquifers**. These aquifers usually aren't pools of water; they're **strata** (layers) of porous rock like sandstone that is permeated with the water. These are called water-bearing strata. Underneath (and sometimes above) these water-bearing strata are other strata of rock which the water can't penetrate, called **impervious strata**. Impervious rock (like schist or basalt) is usually tough to drill through, which is why getting a well drilled can sometimes cost an arm and a leg.

Figure 1 shows three different wells. There's a sandstone aquifer sitting on top of a schist layer. Well A's owner can drill down, say, 50 feet, hit the water level in the sandstone, and start pumping. Good.

Well B's owner drills down about 60 feet, hits an unexpected layer of schist, breaks a drill bit or two, and finally hits the water-bearing sandstone at a hundred twenty feet. He's had to pay the well driller more, and needs more power to pull his water out of a deep hole. Bad.

Well C's owner laughed all the way to the bank. She drills down ten feet, hits the sandstone; and, since the water level is actually above ground level, watches the water seep out of the hole and collect in a pool on the ground. Her pumping costs are minimal.

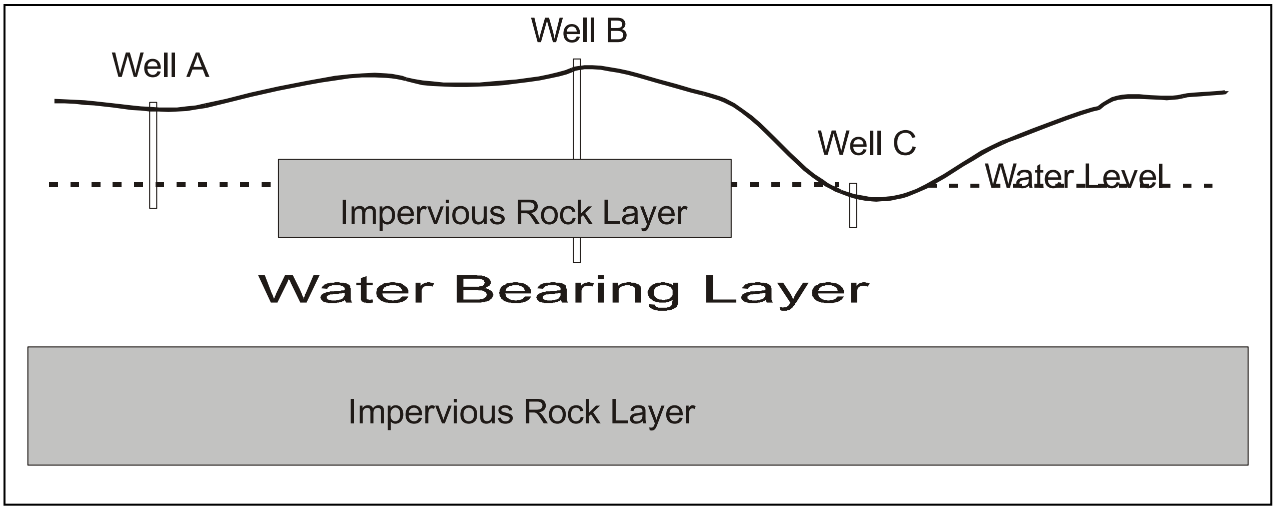

Figure 1. Different Well-Drilling Scenarios

This third kind of well is called an **artesian** well. If the water were seeping out of the side of the hill, it would be, of course, a **spring**.

One more thing to think about. What if the area around Well B had been a farm where the old owner used pesticides? Some of those pesticides might have seeped down 60 feet or so, where that first layer of schist stopped them. The well-driller could have found this contaminated water at the 60-foot level, then drilled through the schist to get down to the uncontaminated aquifer. When you hear about a "bad" layer of water with a "good" layer further down, it's usually because there's that impervious layer of schist or basalt in between.

3.2 Recharge and Drawdown

Earlier I said that aquifers usually aren't pools of water, they're layers of porous rock like sandstone. If you drill a hole in this layer, the water doesn't necessarily gush in the hole; it often seeps in slowly. How fast or slow it seeps, or **recharges**, depends on how porous the rock is, and what the pressure of the water in the rock is.

This is an important thing, because the recharge rate of your well determines how much further below the water level you have to drill to make sure the hole doesn't run dry when you're pumping water out of it.

Suppose you drill a well a hundred feet. Fifty feet down, you hit a sandstone aquifer. After you pull the bit out, the water from the aquifer seeps back into the hole and you're left with a hundred-foot-deep hole, filled to the halfway point with water. The level at which the water starts (fifty feet down) is called the **static water level**.

Now suppose you lower an electric motor pump into the well at the end of a 60-foot pipe. The pump is ten feet below the static water level. If you start pumping at, say, one gallon per minute (**GPM**), the water is pumped out and its level goes down. Once the water level drops five feet, the seepage from the surrounding sandstone matches the rate that the water is pumped out (one GPM). At a pumping rate of 1 GPM, the **drawdown** is 5 feet, and the **recharge rate** matches the **pumping rate**. Figure 2 show how recharge and drawdown works.

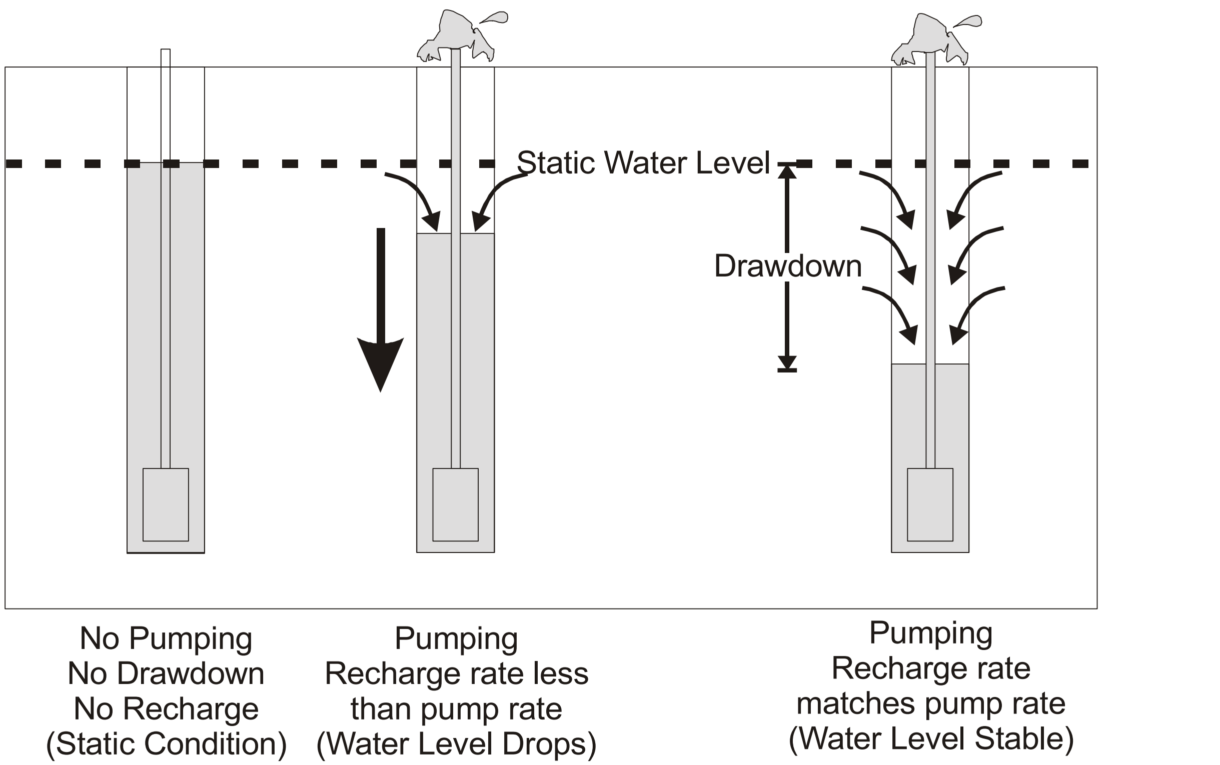

Figure 2. Drawdown and Recharge

But suppose you want to pump faster – say 5 GPM? Now you're pumping the water out faster than the well can recharge. The drawdown goes all the way down to the pump (ten feet below static water level), and now you start pumping air! Bad plan. So you add another 20-foot length of pipe and place the pump at thirty feet below static water level. At the higher pump rate, the well will draw down 25 feet, which is still above the pump inlet, and you're good to go. At a pumping rate of 5 GPM, the drawdown is 25 feet, and the recharge rate matches the pumping rate.

When a well driller puts in a well, he often puts the pump 30 feet below the static water level, then pumps at, say, 5 GPM for a few minutes. If the well continue to produce water, he'll raise the rate to 7 GPM. He will increase the pumping rate (waiting a few minutes each time) until the pump begins to suck air. At that rate, he knows that the pumping rate exceeds the recharge rate at a 30-foot drawdown, and he'll back off a couple of GPM to determine the highest safe rate to pump.

In some cases, the water table is sparse or the sandstone is not very permeable. Then, the well driller might put the pump head a hundred feet below the static water level in order to be able to pump at whatever rate is required. Since the water level in the well may go down in times of drought, the well-driller might add fifty feet or so to that total level to make sure your pump will never run dry (as long as you don't exceed the specified pumping rate).

So don't complain when the well driller says he reached good water at a hundred feet and presents you with a bill for 250 feet worth of drilling and casing. He understands about drawdown and recharge rates – and now you do, too.

3.3 Moving that Water Around

The further and faster you have to pump the water, the more energy you need. The energy needs are **linear**. That means if you have to pump the water twice as high or twice as fast, you'll need twice the energy. If it takes 20 Watts to pump 1 gallon per minute (gal/min) 50 feet up, it would take 40 Watts to pump 2 gal/min 50 feet up or 1 gal/min 100 feet up. If you want to do both (100 ft at 2 gal/min), it would take 80 Watts.

When you calculate the distance to pump the water, you can't just measure from the static water level to the ground surface. You have to add the static water level, the drawdown, the distance above the ground (like to an elevated water tank) and a small factor for **pipe friction**. This sum is called **total dynamic head (TDH)**.

Calculating the power required is not that difficult. The most common formula used is:

Power (in Watts) = TDH (in feet) X Flow Rate (in gal/min) X 0.18 (conversion factor) X 1.15 (for a safety factor of 15%) / Pump efficiency (usually around 50%)

If you needed to pump 3 GPM from a well with 100 ft TDH and a 50% efficient pump, you would need

(100) X (3) X (0.18) X (1.15) / (0.5) or 124.2 Watts (that's about one-sixth of a horsepower).

This would actually give you 3.45 GPM (because of the 15% engineering safety factor).

The spreadsheet HYDROLOGY.XLS is already set up to allow you to enter the numbers for TDH, flow rate, and pump efficiency, and it will give you the power requirements.

4. Power Sources

If you are concerned about power interruptions, you will probably want something as reliable as possible. Let's look at some alternatives.

Gensets (electrical generators powered by gasoline or diesel engines) are often the user's first choice, but they have several disadvantages.

1. A genset requires you to keep a lot of fuel – flammable liquids/explosive gases – stored on your property.

2. Gensets are complex machines. I would not want to bet my life on a device that could break down leaving me with neither the parts nor the expertise to repair it.

3. Gensets are noisy. If you're concerned about civil unrest (or just want peace and quiet) you might prefer a low-profile lifestyle. A generator can attract people whom you might not want as dinner guests.

Gensets do have advantages. They can produce a lot of power, both ac and dc, and they're pretty portable. You could use a genset to pump a lot of water in a short time and still have enough power to operate your blender and Nintendo Gameboy. But I think the disadvantages of the genset outweigh its advantages.

Windpower brings to mind the old-time homestead on the prairie. There is nothing as romantic of seeing the old ranch house with the windmill slowly turning in the background. The problem is, windmills are probably the worst choice for most of us. Here's why:

1. Windmills have moving parts besides the generator: the rotating windmill blades, the rudder assembly that keeps the blades into the wind, and often a clutch assembly. Every moving part requires critical engineering analysis; this means additional cost and more things to break or go out of adjustment.

2. Windmills generate electricity only when the wind is blowing. To ensure 24-hour-a-day electricity, you will need a hefty bank of backup batteries. This will require:

   a. A larger windmill and generator (since you need to produce usable electricity and store some at the same time);

   b. Increased operating costs (typically, storage batteries lose most of their storage capability within five years); and

   c. Environmental problems: freezing and cracking batteries, potentially explosive hydrogen produced during battery charging, and storing and disposing of lead and sulfuric acid compounds and by-products.

3. It's difficult to design a wind generator for a particular location, since the amount of wind can vary between two locations a hundred yards apart. You should measure the wind at your proposed location over at least a one-year period to find out how big the generator should be. This is important, because a windmill strong enough to stand and extract power from a 50-mile/hour wind will not work with light breezes; a windmill efficient enough to extract power from 5-mile/hour breezes will be destroyed by high winds.

This doesn't mean that wind generators are useless. If you're in a place where the wind blows at a constant rate from the same general direction, wind generators can be a good choice. If you're using wind power to pump water into a reservoir, constant and steady wind is not required. If you want to set up a small system to charge batteries for radios, etc., little windmills are easy to build and operate. But as a prime electricity source, windmills will probably not be your first choice.

Photovoltaic (PV) panels (modules) are large (typically 18" X 48") transistor-like devices that turn sunlight directly into DC electricity. PV systems have no moving parts, are silent, can last for at least 30 years, and require almost no maintenance. Unless you live where there's no sunlight, PV can be the ideal power supply -- except for two things.

First, PV only supplies electricity when the sun is shining. Electrical output is directly proportional to insolation (the amount of sunlight) on the array (bank of modules). Even on a cloudy day, you will get some electricity. But you won't get any at night! This means that if you want 24-hour-a-day electricity, you will need battery storage. As mentioned in the section on wind-driven generators, batteries impose a heavy penalty in cost, engineering, and reliability. PV **BOS** (Balance Of Systems -- batteries, diodes, support structures, etc.) cost about as much as the PV array itself.

Second, PV is expensive. A PV module that produces 50 W at full sun conditions can cost up to $400. Double that cost (for the BOS) and 50 W of electricity on demand could cost up to $800. 50 W will give you three high-efficiency DC fluorescent lights or a black-and-white TV – and probably isn’t enough to pump your well.

But in the final analysis – after you’ve looked at cost, long-term reliability, and home-security considerations, photovoltaics usually wins. In the last section, we’ll look at....

5. A Real-Life Water Well Design

The well driller just left. He told you that you hit good water at 75 feet, but he drilled an additional 100 feet, because at ten GPM, your well drew down 50 feet (15-ft drawdown at 2 GPM and 30-ft drawdown at 3 GPM). Like most wells, your brand-new hole is cased with perforated 6-inch PVC pipe, with the first 30 feet being unperforated steel pipe – no worries about groundwater contamination. Your next task is to finish destroying your MasterCard by getting a couple of PV modules, a pump, a storage system, and the plumbing and wiring to hook them all together.

5.1 The Pump and Motor

Since you’re going to use PV (which produces dc current) to run your pump, you’ll probably want to get a dc motor/pump combination. (If you already have an ac motor pump – that is, if you're retro-fitting an existing well and motor – you'll need to buy an inverter, which is an electronic component that converts dc current from the PV array into ac current for the motor. But let's assume you're working from scratch.)

You'll need to figure out how big a motor to get. In order to do this, you'll need to figure out the power required, and get a dc brushless motor of a bit higher power rating. Since brushless dc motors run at different speeds depending on how much current is applied, your motor will operate at much less current than it's rated for. Of course, it won't pump as fast, but that's okay.

There are several types of motors, but a typical brushless, 12-volt submersible motor pump system is probably your first choice. Of course, you'll want to discuss your options in detail with the folks that sell you the stuff.

5.2 The PV System

Remember, PV only produces electricity when the sun is shining, but you'll probably need water at night, too. You must make sure water is available 24 hours a day. There are two ways to do this

1. Design your PV array large enough to charge a big bank of batteries that will run your pump at night or during cloudy weather. In addition to increasing cost for the additional modules, you'll have to buy batteries and replace them all about every five years.

2. Design your system to pump constantly when the sun is shining. The water will be pumped into a large elevated tank, which will provide you with water by gravity flow. Although you won't have to buy as many modules (since you won't be charging any batteries) you will have to buy a large tank, place it on a hill near your house (or build a tower if you don't have a hill available), and plan for additional piping.

The second approach makes the most sense. By pumping water up from the ground and then another thirty or so feet higher into the elevated tank, you're increasing your well's TDH by 30 feet, but that's not that big of a deal

Based on the well that will produce 3 GPM up a 135-foot TDH (105-ft TDH to ground level, plus an additional 30 feet for the elevated tank) with a 15% safety factor and a 50% efficient pump, you will need 167.67 Watts at your array. If you can get four 40-Watt modules you'll have the desired flow rate with a safety factor of about 14%. Since 167 Watts as a bit more than 1/6 horsepower, getting a 1/3 hp motor for your pump provides you with a good safety factor.

5.3 Insolation

Since water pumping is based on the power which, in turn, is based on the amount of sunlight, knowing how much sun to expect will help you predict the total amount of water you will get per day. Your motor will pump at different speeds, depending on how much sunlight there is. A 160-Watt array will produce 160 Watts under **full sun** conditions, roughly equal to high noon with no clouds at summer. Under full sun conditions, you will receive 1000 Watts per square meter of area.

In the morning, when the sun rises, your array will only put out a fraction of its 160 Watts. This amount of power (and thus the amount of water pumped) will rise until mid-day, then gradually decline back to zero at sunset. **Insolation**, or the amount of sunlight, is measured in **full-sun equivalent hours per day (sun-hours)**. In the deserts of Central Arizona, summer insolation is about six sun-hours per day; in the winter, it's about 4.5.

This means that, in the summer, I would pump the equivalent of 3 GPM for six hours (1,080 gal); in the winter it would be the equivalent of 3 GPM for 4.5 hr (810 gal). Now, inasmuch as good conservation practices say that 100 gallons per person per day will take care of all that person's needs, including irrigating a garden to feed him, this well design should provide for the needs of eight to ten people.

So you have all the water you need pumped from you well, but you still have to worry about two more things: what happens when you have several days of overcast weather, and how do you get that water into your shower at night, when the sun isn't shining to operate the pump? The last paragraph talks about ....

5.3 The Water Tank

The one energy source that works day in and out (and night in and out, too) is gravity. By adding that extra thirty feet of TDH to your calculations, you developed enough power to pump that water to a plastic or metal tank on the hill behind your house.

How big should it be? If you think there will be a long stretch of sunless or overcast days, you'll need enough water already stored to provide for most of your needs (you can cut back on watering the garden for a couple of days). A 3,000 gallon tank (imagine a tank about eight feet in diameter and eight feet high) will provide you with water for up to a month, if you rationed it carefully. Since 3,000 gallons of water weighs twelve tons, it's probably much more cost-effective to put the tank on a hill above the house.

Water coming through a four-inch pipe from an elevated tank with a fall of 20 feet will provide you with all the water pressure you'll need.

6. Conclusion

Although this paper seems long and complicated, it's really too short and to simplistic to make you into a hydrologist or an engineer. But what it has done (hopefully) is to give you some ideas of the work involved in designing a self-sufficient water system that will provide you and yours potable water for as long as you need it to.