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More… groundwater notes

by Nick Doe

Given the anisotropic, discontinuous, heterogeneity of Gabriola's underground terrain (as a professional hydrologist might say), it's no simple matter to figure out what happens to water trickling down through the fissures in the bedrock beneath our feet. All we non-professional observers can do is keep our eyes open, watch water disappear and re-appear, guess, calculate, and hope that the results of our musings have *some* correspondence to reality, even though large variations from the norm at particular localities are inevitable. But never mind, let's give it a whirl, and see if it goes down the drain.

Watertable equilibrium

First of all, let's think about the relationship of Gabriola's groundwater with the surrounding sea.

In the centre of the island, about 150 metres above sea level, there is no shortage of wells or trees, so it would not be unreasonable to find that the watertable is at the very least something of the order of, let's say, 100 metres above sea level. What keeps the water that high? Why doesn't the watertable sink down to sea level once it stops raining? There are at least three possible reasons.

A sinking watertable

The first explanation that comes to mind is that the watertable *is* sinking as expected, but is doing so, so slowly, that the drop in its level during the dry season is slight. Sounds reasonable enough; however, the implication of this explanation is that the *conductivity* of the ground is very low. The hydraulic conductivity of parched soil certainly is low—we all know how difficult it is to moisten soil in a dried-out flowerpot—but then Gabriola doesn't have much soil. If the hydraulic conductivity of the bedrock were to be low, then at the onset of winter, water would rise rapidly to the surface and flooding and runoff would be commonplace. But that's not what happens in the interior. Although there are marshes and mires, the ground mostly soaks up the rain, no matter how long and hard it pours, and most of the runoff is in spring-fed creeks rather than directly from the surface.[1]

Floating groundwater

Another idea, one that sounds a bit cuckoo the first time you hear it, but which is nevertheless quite sound, is that the watertable is high because the island's groundwater is floating. Just as icebergs float—because ice is less dense than saltwater—so will groundwater that is confined in rocks with fissures that eventually lead down to the sea.

This "floating" groundwater model (the Ghyben-Herzberg model) has been shown to be a good one for coastal areas, and a sizable volume of floating freshwater probably does exist under Gabriola as shown in the diagram on the next page. It's common for wells to go down below sea level without encountering saltwater, even on low-bank waterfront properties. But there's a problem with this idea being the basis of an explanation as to why the watertable in the interior of Gabriola is so high.

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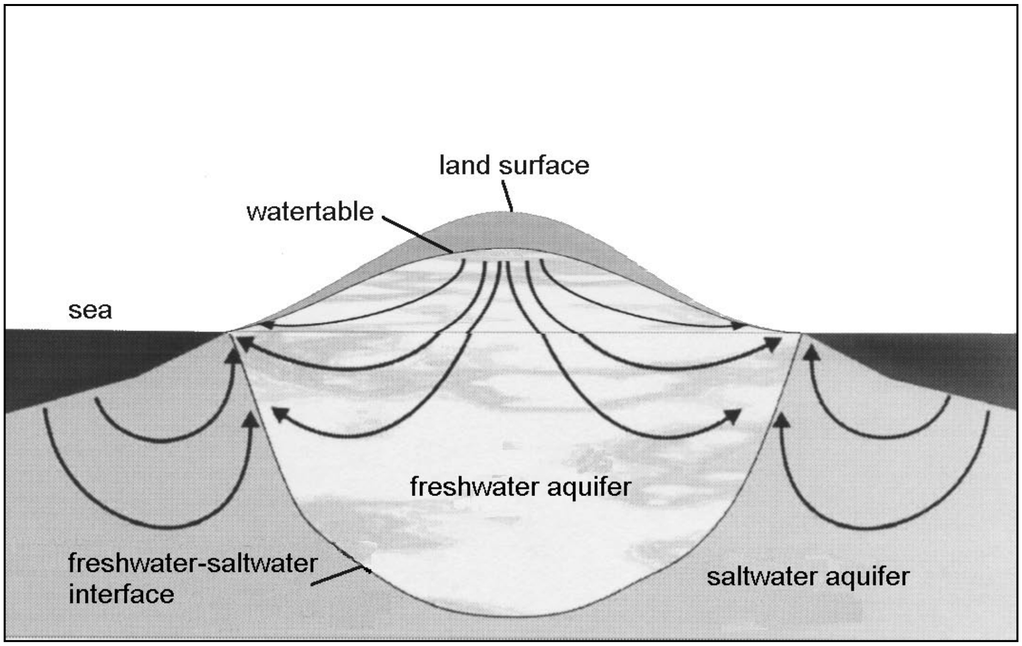
[1] About twice as much water leaves the island from springs as it does from surface runoff. See *Groundwater budgets*, *SHALE* 14, p.30.



An aquifer beneath an oceanic island has the form of a lens of freshwater maintained by a delicate balance of water pressures. At all points on the freshwater-saltwater interface, the column of freshwater (measured from the interface up to the watertable) is slightly higher than the column of saltwater (measured from the interface up to sea level); however, the weight of the two columns at the interface is always about the same because freshwater is less dense than seawater. The freshwater and saltwater are in hydrostatic equilibrium and, in effect, the freshwater is floating. When it rains, the watertable rises, the lens expands, and freshwater crosses the interface into the sea. In the dry season, the watertable sinks, seawater moves in as the lens of freshwater contracts, and wells on the coast become vulnerable to saltwater intrusion.

Adapted from D.M. Allen & G.P. Matsuo

If there is a hydrostatic equilibrium between groundwater and the sea, then for each metre of freshwater above sea level, there has to be forty metres of freshwater supporting it below sea level.[2] The top of a continuous column of freshwater will only float 100 metres above the surface of the sea if there's a column of freshwater four kilometres below it buoying it up. This can't be. The total depth of the Nanaimo Group rocks (the sedimentary rocks) is probably not more than about two kilometres, so we are talking here about conditions extending another two kilometres into a thick basement of lava, namely the basalt of the Karmutsen Formation of Vancouver Island.[3]

Anyone who'd like to convince me that the moisture in our friends' gardens at the top of

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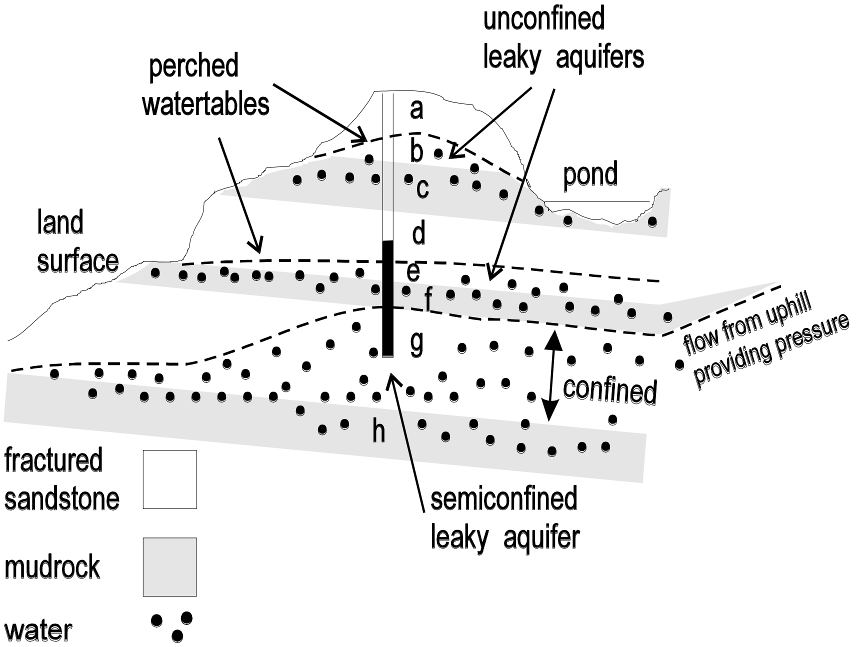
[2] $1/(\rho_s - \rho_w) = 40$ where ρ_s is the relative density of seawater, which is about 1.025, and ρ_w is the relative density of freshwater, which, by definition is 1.00. A column of seawater 40 metres high weighs the same as a column of freshwater 41 metres high.

[3] The idea that some of Gabriola's groundwater comes from far-away locations (Mt. Baker) is described nowadays as a "myth", but the concept was once seriously entertained by geologists. Brown & Erdman in 1975 estimated a flow of 2200 gpm to Gabriola through "fractured metamorphosed volcanics and quartzites" from Vancouver Island. The same report suggested that there was enough groundwater here to supply 35,000 people.



The diagram shows a well shaft penetrating bedrock comprising layers of fractured sandstone (fSS) and mudrock (MR, shown shaded).

Layers (b+c) form a perched aquifer, as do (e+f). The fSS layer (g) is an aquifer that is partially confined by the mudrock layers (f) and (h). Pressure in (g) might be enough to bring water to the surface on the hillside in some places.

Adapted from S. Davies & R. DeWiest

the island depends on what water is doing that far down is welcome to try, but I really can't believe that it is. Seems to me that, except in the coastal fringe, groundwater found in the many relatively shallow wells on the island is not in hydrostatic equilibrium with the sea and must be held up by other means.

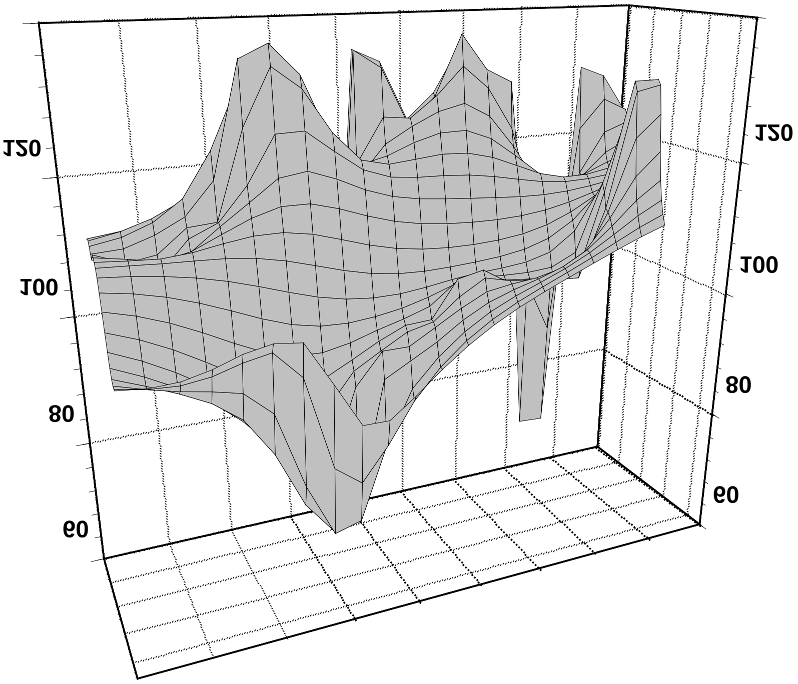
Perched aquifers

A third possible explanation is that the watertables on Gabriola are *perched*.

Perched water is groundwater that is prevented from rapidly sinking deeper into the earth by an *aquitard*. Aquitards are localized geological deposits or formations that are less permeable than those around them—like a plastic sheet buried in a garden. On the island here, they frequently consist of layers of mudrock (shale), especially mudrock with interbeds of siltstone. Other aquitards are formed by compacted (basal) glacial till; accumulations of clay from weathered sandstone; gouge-filled fractures; and deposits of marine clay that date back to the Ice Age. Barriers to the horizontal movement of water include shale with fine-grained sandstone dykes that cut through bedding planes; ferruginous-cemented faces of inclined fractures; and strike-slip faults that abut rocks with differing permeabilities.

Perched and leaky aquifers don't get much attention in hydrological literature, and in some books, they don't even make the book's index. A typical dismissive comment is "…wells tapping perched aquifers yield only temporary or small quantities of water". Such books are obviously not written for the benefit of anyone living on a small island.

Drilling down through a sequence of perched aquifers, we would expect to find, not a continuous water-bearing stratum, but a series of water-bearing strata interleaved with stretches of dry rock. Because of the relative impermeability of some of the rock, some of these aquifers might be



It is tempting to think of a "watertable" as the surface of an underground lake. The chart, left, illustrates how poor a model this is on Gabriola. It shows standing water levels above sea level in a cluster of twenty wells with a common geology. The long horizontal axis runs about 600 metres roughly west-east. The "watertable" in the wells shows a height variation of over 70 metres, indicating that the interconnectivity of the water-filled fractures is very directional or non-existent.

Some wells here may have access to perched aquifers very close to the surface.

semiconfined—that is the water in them is under a bit of pressure, which, on occasion, might be enough to produce a flowing well.[4]

Seems to me that's *exactly* how it is here on Gabriola, and we have to conclude that, in general, not all, but many of the island's aquifers above sea level are perched.

Groundwater theory

Most of the theoretical concepts in standard hydrology are based on the assumptions that the water-bearing rock is homogeneous, continuous, saturated, and unlimited in extent. None of these assumptions are valid on Gabriola. Check it out for yourself. How many of the following statements would you say are <u>true</u>:

- wells that penetrate down beyond the summer watertable sometimes go dry
- wells may give very different yields on adjacent properties, even though drilled to the same depth[5]
- the yield from a well cannot be increased by simply drilling deeper—you have to keep drilling dry rock until you "hit" another water bearing zone
- water levels in wells seldom go up and down with the tide (on Gabriola)
- the chemistry of the water in neighbouring wells is not the same—while your water may smell of sulphur, be salty, be conductive, or have a high pH, your neighbours' may not
- pumping a well does not predictably influence neighbouring wells

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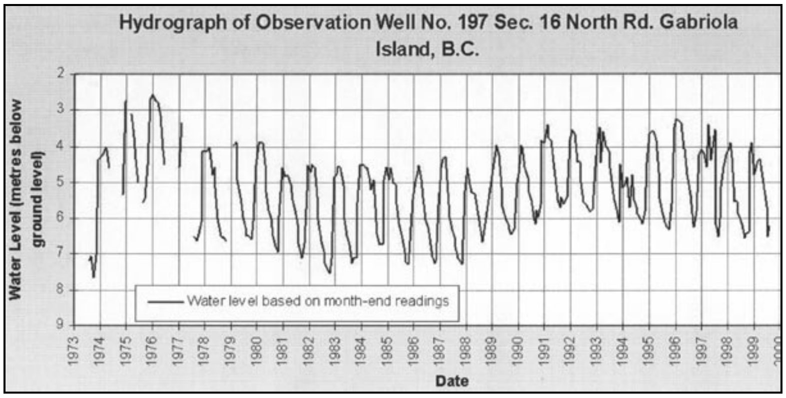
[4] "High pressures do not develop in semiconfined aquifers and water will rarely have heads of more than 5 to 10 feet above the ground surface." (Davis & DeWiest, p. 45). This exactly matches Norm Windecker's description of artesian (flowing) wells on Gabriola *SHALE* 11, pp.40–1.

[5] I've never understood why so much emphasis is put on flow rate on Gabriola. For our low-capacity aquifers, isn't it their volume that ultimately matters most?



- some springs are artesian. Groundwater does not always move downhill.

Most, probably all, of these statements are true of Gabriola's aquifers, but they wouldn't be if the aquifers were glaciofluvial deposits of sand and gravel like most of the most-productive aquifers are on Vancouver Island and in many areas of the interior of the North American continent.

In areas of complex geology like ours, the concepts of "a watertable", "zones of influence", "confined water", "unconfined water", and others are of limited usefulness. They are, as it says in one of my hydrology books, "…more of a theoretical concept than a physical reality".[6]

But whoa! let's not give up. Through the magic of "averaging" we can pretend that the geology is simple. All this does is prevent us making predictions about the groundwater at any particular part of the island, which is perhaps just as well (no pun intended).

Drainable porosity

Although I haven't kept meticulous records, I know from sporadic measurements using John Nicholas's WellWatcher instrument that the level of water in our well on El Verano (Northumberland Fm.) shows a seasonal difference of several feet. The well goes down below sea level and so is unlikely to be tapping a perched aquifer. Unpumped Government observation wells on the island show a similar variation. A typical example is shown on the left. In this well (Observation Well 197), the drop in water level in summer, and the corresponding rise in winter, is about 2.5 metres (8 feet). Let's use this figure to estimate the "drainable porosity" of the water-bearing rock.[7]

In an earlier article, I estimated that the rate at which water is removed from the island's aquifers in summer and replaced in winter is 496 L/s (litres per second).[8] This much water, accumulated for six months and spread over the 5075 hectares of the island, would be 155 mm deep. An increase and loss of 155 mm of water is therefore responsible for the 2.5-metre rise and fall of the level of the watertable.

The implied drainable porosity of the water-bearing rock (not the bedrock in general) is:

$$\eta = \frac{0.155}{2.5} = 62 \times 10^{-3}$$

or about 6%. Other estimates made independently, but using the same principle, come close to this, so the drainable porosity likely really is in the 4–8% range.

This result makes perfect sense. Many aquifers in North America occur in

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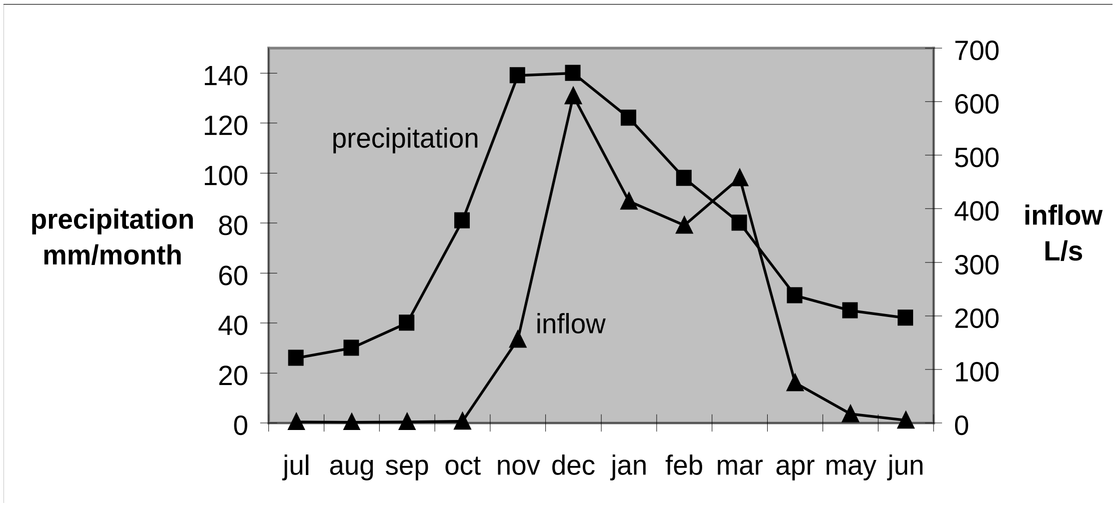
[6] Ollier, pp.88–9.

[7] "Drainable porosity" is the volume of water, not under pressure, that drains from saturated rock relative to the volume of the rock. Also known as "specific yield".

[8] *SHALE* 14, pp.31–2.



The inflow into Hoggan Lake clearly lags behind precipitation. This is because the lake is supplied primarily from springwater. The lag, based on the data in the diagram, is 23.7 days.

unconsolidated deposits of sand and gravel, and these have drainable porosities of 25–50%. Sedimentary rocks like sandstone and shale, common on the Gulf Islands, have significantly lower drainable porosities in the range 1–10% as we've just estimated. Of the sedimentary rocks, only chalk and limestone hold less.[9]

Hydraulic conductivity

Hydraulic conductivity is not something that often comes up in every-day conversation, but having a value for the hydraulic conductivity of the rock in an aquifer is useful.

The idea behind hydraulic conductivity is that it takes pressure to get fluid to flow through small gaps. Just think of your garden hose; the faster you want the water to flow, the more pressure you have to apply. Pressure is needed to overcome the friction between the water and the wall of the hose.

The smaller the hydraulic conductivity of a rock, the more pressure is required to get water to flow through it. In aquifers, the only source of pressure is gravity, so what we are talking about is how fast water moves under its own weight through permeable rock and open, or coarsely mylonitic, fractures.[10]

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[9] "Drainable porosity" is always less than the true porosity because some pores in the rock retain air even after prolonged submersion, and conversely, some water remains clinging to internal rock surfaces even after prolonged draining.

The drainable porosity of an aquifer composed of more than one kind of rock is sometimes called the "storage capacity". This is often less than "drainable porosity" because it is an average that may include non-water-bearing rock. Hydrologists in past reports on Gabriola's groundwater have used estimates of storage capacity to calculate the total volume of freshwater beneath Gabriola and quote values of storage capacity in the range 0.001–0.1%. As this range of uncertainty implies, this is simply a consultant's way of guessing the answer to the almost unanswerable question, how much water is there underground?

[10] Porous rocks are only permeable if the pores are interconnected. Some sedimentary rocks are as porous as gravel, yet are far less permeable. "Mylonitic" fractures are filled with rock fragments

Transmission delay

One way of estimating hydraulic conductivity is to calculate the transmission delay between precipitation and runoff from springs. Data for this calculation is available from Hoggan Lake. Because the lake is used for generating electricity, the lake is well monitored and inflows and outflows have been logged.

The graph shows two curves obtained from the province's WaterAllocation Plan[11] and from precipitation records for the island. One curve shows long-term average precipitation throughout the year, starting in July; the other shows long-term average inflow into the lake.

Calculating the delay between the inflow and the precipitation is an easy mathematical task—the answer is 23.7 days. Curiously, about a month seems to be a common figure all over the island for the delay between the onset of the rainy season and a rise in the level of water in wells.

The delay is strongly related to what an electrical engineer would call the "time-constant" τ of the rock.

In hydraulic terms, the time constant τ (in seconds) is proportional to η (the water storage capacity expressed as a dimensionless constant)[12] divided by its hydraulic conductivity K (in metres per second and assumed to be isotropic) times the vertical height of the aquifer, h (in metres).[13]

$$\tau = 0.5 \times \frac{\eta}{K} h$$

It is also the observed delay (in seconds) times the slope.[14]

$$\tau = \text{delay} \times \frac{h}{\sqrt{h^2 + p^2}}$$

where p is the horizontal path length (in metres), from which we can deduce that:

$$K = \frac{0.5 \times \eta \times \sqrt{h^2 + p^2}}{\text{delay}}$$

Working from a map of the lake's watershed[15] it looks like the average distance from anywhere within it to either the lake or one of the three creeks feeding the lake is about 870 metres and the average vertical drop is around 35 metres.

For p = 870 m, h = 35 m, a delay of 23.7 days, and a drainable porosity of 6%, we have:

$$K = 1.3 \times 10^{-5} \text{ m/s}$$

Now at this stage of the game, I wouldn't bet a whole lot of money on the accuracy of

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(gouge) formed when the fracture faces grind together.

[11] Welyk, p.40.

[12] Technically, the difference between the "saturated volumetric moisture content" and the "field capacity". Here, I'm equating this to specific yield.

[13] If A is the cross-sectional area of the flow (m^2), then ηhA is the storage capacity of the aquifer (m^3), which is electrically equivalent to the stored charge Q (amp.seconds) on a capacitor C (farads). KA is the flow into the aquifer (m^3/s), which is electrically equivalent to the current I (amps). Since C=Q/V (farads or amp.seconds per volt) and R=V/I (ohms or volts per amp), CR = Q/I = τ (seconds) just as $\eta hA/KA = \tau$ (seconds). The 0.5 factor is introduced in this case because, on average, the water has to travel only halfway through the rock either to reach the place where it is stored or to leave it.

[14] I am using "delay" here in the precise technical sense of the delay to a ramped input, which in a first-order linear system is a delayed ramped output.

[15] Available from the Regional District of Nanaimo.

this number, though I'd expect the (mainly horizontal) hydraulic conductivity to be within two orders of magnitude of it.

Ground absorption

Another, completely different, way of estimating the hydraulic conductivity of the bedrock is to calculate what proportion of the precipitation that soaks into the ground re-emerges as springwater. If the value of hydraulic conductivity used for the calculation is too high, most of the water will seem to sink straight down to below the level of the sea; if on the other hand it is too low, most of the water will seem to run off in creeks.[16] I'll describe how I calculated the proportion later as it is a bit complicated, but the end result was that the best match, on average, with the observed proportion was obtained when the hydraulic conductivities of the sandstone-dominant and shale-dominant formations (they need to be different) were taken to be roughly 3.0×10^{-5} and 1.3×10^{-5} m/s respectively.

Rather surprisingly,[17] given the difference between the two calculation methods, the answer for shale is almost exactly as predicted by the Hoggan Lake calculation.

Flooding in coal mines

It's an interesting thought that, in principle, it might also be possible to estimate hydraulic conductivity from the capacity of the pumps that the old Nanaimo coal mining companies used. Many of the workings were below sea level and water constantly dripped from the roof. Abandoned mines used to fill with water, and it took a couple of months to pump out them out again before they could be re-opened.

From descriptions of flooding disasters, it seems likely that even the emergency pumps could only draw down the water a few inches per hour. I think we can deduce from this is that the hydraulic conductivity of the rocks above couldn't have been more than a inch or two per hour, otherwise the everyday pumps couldn't have kept up, but it could of course have been a lot less. This is very comfortably within our estimated range of values—10^{-5} m/s is 1.4 inches per hour.

Nature of the aquifers

Now although the results of these calculations might not look very useful, knowing something—anything—about the porosity and the hydraulic conductivity of the rock can tell us something about the nature of an aquifer.

For example, textbook figures for the hydraulic conductivity, K, range from:[18]

forest soil:	1×10^{-3} to 4×10^{-5} m/s
sandstone:	6×10^{-6} to 3×10^{-10} m/s
shale:	2×10^{-9} to 1×10^{-13} m/s.

Figures for saturated soil are:[19]

gravelly sand:	1×10^{-4} m/s
top soil (loamy sand overburden):	1×10^{-5} m/s
glacial till:	1×10^{-6} m/s
clay:	2×10^{-9} m/s

That the observed conductivity, 10^{-5} m/s, is significantly higher than that of solid rock, especially for shale, supports the familiar notion that groundwater on Gabriola travels through fractures, not through the rock itself.

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[16] *SHALE* 14, p.30.

[17] Even suspiciously perhaps, but I did come by the answer completely honestly.

[18] Harr, 1977, and Domenico, p.65–7.

[19] Appiah-Adjei, p.64.

Groundwater—the coal miners' rather different perspective

> "We worked in about a three-foot space. You had to lie on your side. Work shoulder to shoulder. You're always dripping in water. You go down and the first thing you know you're dripping wet. You stay that way and work that way, never getting dried out. It would be dripping from the roof and you'd be lying in the water."
>
> "I've worked in the wet quite a few times. Some places, if you had swamp on top of the ground, well it seems to come right through into the mine. Even very deep under the ground, the water seems to come through. And some places even if there is no water on top, there is different streams in the ground. It might be dry on the surface and then down so many feet it might be a stream."
>
> "Each time the seam ignited, management closed the area off and allowed it to flood. Even then it was a cause for wonder. Sometimes the water flooding these subterranean tunnels would recede as if it was independent of the forces that affected the ocean above it."
>
> "In 1927, the company sank a second shaft to dewater the mine. Other mines pumped the water out, but Reserve hoisted it with two four-tonne cast iron buckets."
>
> "I was up to my waist in water lots of times. And we didn't get extra for that. One place was on fire and another place was flooded."
>
> "The only thing I was afraid of was tapping an old mine and having a flood. I didn't want to drown. Wasn't afraid of cave-ins, just water."

Just a few extracts from Lynne Bowen's *Boss Whistle—the Coal Miners of Vancouver Island remember*, published by the Nanaimo and District Museum Society & Rocky Point Books, Nanaimo BC, 2002.

It's also rather interesting to note that the observed hydraulic conductivity falls within the range measured for soil on mature forested slopes. Although, from the point of view of groundwater retention, we may bemoan the lack of old-growth forest cover on the island, the shale formations appear to be very good backups, groundwater-wise.

Here's another reality check. Applying D'Arcy's Law[20] with a hydraulic head per path length of 1 (that is the downward pressure is simply generated by the weight of the water) means that bedrock with the calculated conductivity can sustain a flow of:

$$10^{-5} \times (60 \times 60 \times 24) = 0.9\ \mathrm{m}^3/\mathrm{day.m}^2$$

This is many hundreds of times greater than the volume of precipitation that actually sinks into the ground in upland areas (0.44 cubic metres per square metre of surface *in the entire six months of winter*), which indicates that, as observed, the fractured bedrock can quite easily absorb all the precipitation.

The similarity of the conductivity with that of typical Gulf Island soils is in line with the observation that standing pools of water on

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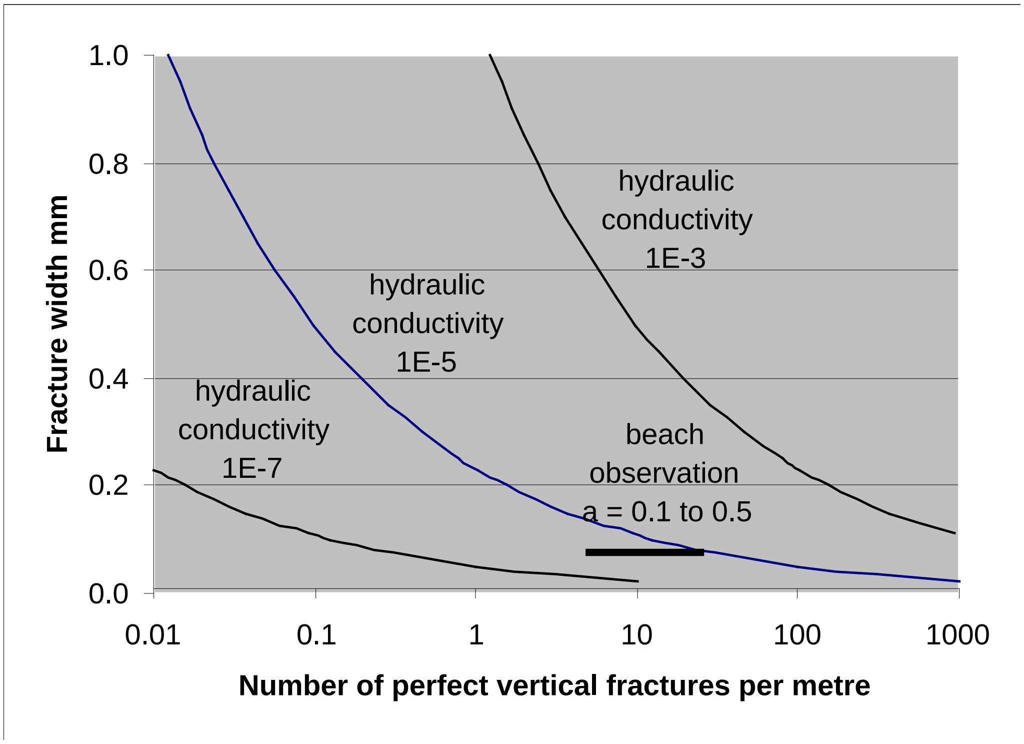
[20] The volumetric flow (in cubic metres per second) of a specific fluid (in this case, freshwater) per unit cross sectional area (in square metres) through a permeable medium is directly proportional to the hydraulic gradient. The proportionality constant is the hydraulic conductivity (in metres per second).



The graph above shows the many possible relationships between fracture density (the horizontal axis) and fracture width (the vertical axis). “Fracture density” is not the count of real fractures per metre (N), but is the lesser number (αN) of equivalent perfectly vertical, straight-sided, smooth-sided fractures per metre.

It’s interesting to note that no matter what the fracture density, so long as it is greater than about ten per metre, the width of the fractures is significantly less than 0.5 mm (500 μm or .020 in.) for hydraulic conductivities in the range 10^{-3} to 10^{-7} m/s. So, no matter how we view it, we’re dealing here with small cracks, many perhaps clearly visible but not much more than the thickness of a sheet of paper wide (0.1 mm or .004 in.).

the island do not form unless lined with clay.

For the bedrock to fail to be able to absorb the precipitation, the hydraulic conductivity would need to be below 2.9×10^{-8} metres per second (m/s). The hydraulic conductivity of clay is between 4.7×10^{-9} and 1×10^{-11} m/s.[21] Clay therefore, be it marine clay left by glaciers or clay resulting from bedrock weathering, can, and likely does, make an effective barrier to the sinking groundwater, thereby forming the perched aquifers we talked about earlier.[22]

Width of the fractures

While the hydraulic conductivity of rock varies over several orders of magnitude

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[21] Domenico, p.65.

[22] Appiah-Adjei, p.66, reports that a model used to estimate vertical hydraulic conductivities for the southern Gulf Islands gave 1.1×10^{-7} m/s for “interbedded mudstones and sandstones” (IBMS-SS). This seems low, perhaps because microfracturing not due to major tectonic events (weathering) is underestimated, or perhaps Gabriola is different.

depending on the nature of the rock, the hydraulic conductivity of fractures does not—a crack is a crack is a crack. Detailed figures for the hydraulic conductivity of fractures have been worked out.[23]

The hydraulic conductivity "K" in metres per second (20°C) is:

$$K = 0.81 \times 10^{6} \times \alpha N \times w^{3}$$

where there are "N" fractures per metre of surface, each of width "w" metres. I have introduced the factor α to take into account that in reality not all fractures are perfectly smooth and vertical; that not all are interconnected; and that some meander.[24, 25]

Given that we think that K is around 10^{-5} m/s, we can then deduce that:

$$\alpha N \times w^{3} \approx 10^{-11}$$

Now at this point when I was writing this, I had no idea as to the values of "N" or "w", so I went for a walk on the beach armed with a set of feeler gauges to look at some seepages from cracks in shale in the cliffs. The ones that were leaking water seemed to be, on average, about 0.003 in.(75 μm) wide, and there were, very roughly, 50 of them per metre.[26] Substituting gives us:

$$N \times w^{3} \approx 2 \times 10^{-11}$$

Not too bad at all. Although the shale I saw was weathered, localized surface-like weathering in aquifers is very likely as the weathering is primarily due to oxygen and water.

These numbers however would seem to make no sense in relation to sandstone. The fractures in it appear both far wider (0.5–2 mm), straighter, and far less numerous. Presumably, when we look at mixed shale/sandstone strata hydrographically, we see only the shale because the shale is less conductive.

Wells

Although I'm trying to avoid focussing on wells, most of which don't go down very far into the underground, they can provide us here with one more reality check. The theoretical flow of water into a well penetrating aquifers has of course been calculated[27]. Let's use simple forms of the Dupuit (unconfined) and Thiem (confined) equations, which predict the hydraulic conductivity K given Q the pumping rate (m^3/s); r_0 the radius of influence (m); r_w the radius of the well shaft (m); h_0 the height of the static water level; and h_w the height of the water when the well is being pumped. For confined aquifers we also need b (m) the thickness of the water bearing strata.

I'll just give one example calculation for a well in sandstone (Geoffrey Fm.) and finishing in shale (Northumberland Fm.). The well had several small sources but the largest one was encountered only 25 feet from the bottom, so the aquifer is at least partially confined. At a pumping rate of 2.5 imperial gallons per minute (0.3 L/s); r_0 = 1000 ft. (this value is not critical); $2r_w$ = 6 in.; h_0 = 100 ft.; a stable drawdown

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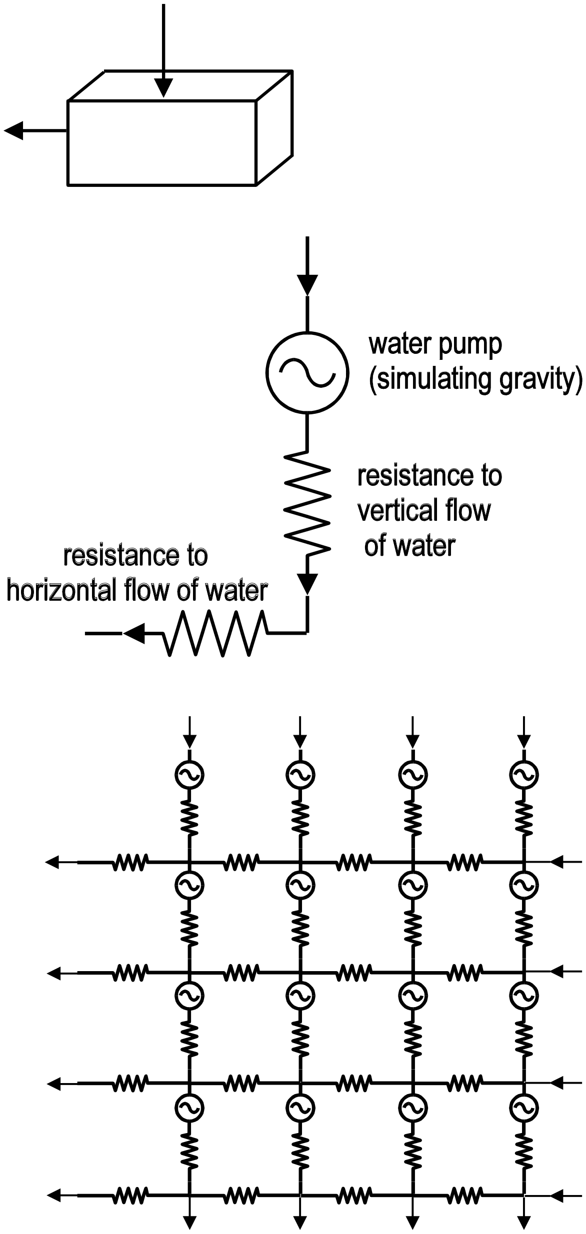
[23] Hoek & Bray, 1981.

[24] Meandering is common in Nanaimo Group mudrock because it has often been lightly concreted and fractures form around concretions rather than passing through them, *SHALE* 13, pp.39–44.

[25] My own guess (nothing more) was that α would be in the range 0.1–0.5. Megan Surrette however uses a carefully calculated value of 0.06 in her modelling of mudrock (IBMS-SS, deduced from her Fig. 4.4 & 4.6). Her figure for sandstone is even less at 0.03.

[26] It was also clear that horizontal (bedding-plane) fractures were more numerous than vertical ones. Surrette, 2006, adopted a fracture aperture of 100μm for all kinds of rock in her work.

[27] Todd, p.84 (eq. 4.15) and p.82 (eq. 4.11).



We can represent the flow of water through a small prism-shaped sample of rock as a pump (simulating gravity) and resistances to the top-to-bottom flow and right-to-left flow representing friction. Collections of these small samples can then be assembled to form a model of the complex flow of water through a mass of rock of unlimited size.

(h_0–h_w) of 38 ft.; and a confined aquifer thickness of 25 ft.; the inferred value of K is 3.2×10^{-5} m/s (T = 2.5×10^{-4} m^2/s).[28]

My own well, which is entirely in Northumberland Fm. shale, and considered as unconfined, though the drilling log doesn't make it absolutely clear that it is, gives a value for K of 4.6×10^{-6} m/s (T = 2.1×10^{-5} m^2/s).

These equations assume homogeneous and isotropic aquifers, which keeps things simple, but doesn't reflect the reality of aquifers on Gabriola. As drilling logs show, the water is often sourced from particular "water-bearing zones" (wbz's) interleaved with almost dry impermeable zones that the shafts penetrate, and the aquifers are far from being homogeneous. My contention would be therefore, given the uncertainties, the values of K obtained from well data are perfectly consistent with the other estimates.

A groundwater model

So we're ready now to think of a computer model for Gabriola's groundwater. It is going to be a very crude model—many models are, and this one is especially so—but at least it's a start and something to test against other people's models.

The purpose of the model was simply to see if it is possible to predict the proportion of the groundwater that flows back to the sea below sea level, and the proportion of the groundwater that flows back to the sea in creeks fed by springs. The variables allowed were the different hydraulic conductivities of the sandstone-dominant and shale-dominant formations, the dip of the formations due to Gabriola being in a

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[28] T is the transmissivity. Brown & Dakin (1972) measured 1.6–4.0 × 10^{-4} m^2/s (Northumberland Fm. nr. fracture) and 2.9–5.0 × 10^{-5} m^2/s (Spray Fm.). Brown & Erdman (1975) report 3.3×10^{-6} to 3.2×10^{-4} m^2/s for various test wells on Gabriola.

geological syncline, and the height of the watertable in the centre of the island. I'm not talking now about the perched watertables, only the surface of the "core" aquifer of the island that extends beneath it.

Because I'm likely to lose a few readers here, let me jump ahead and say that the model could not come up with the same division between above-sea-level flow and below-sea-level flow as observed without introduction of a different hydraulic conductivity for the sandstone and shale. Moreover, much to my surprise given the simplicity of the model, it was easier to accurately predict the ratio using the model if I gave the sandstone and shale formations a dip of 10º towards the centre of the island along the long sides of the island, which is very close to what the dip actually is. In other words, the model seems to show that you cannot hope to predict what happens to groundwater beneath Gabriola if you don't take into account some of the detail of the island's geological structure.

Modelling the rock

The most important task in creating a computer model is to divide what may be one very complex task into a multiplicity of many, much simpler tasks. Computers are very good at doing millions of simple calculations quickly, so by breaking a complex task down into simpler ones, you reduce the time required for a simulation to something that is reasonable—a few minutes rather than a few days.

The simplest basic unit of an island of rock is just a rectangular prism (a cuboid or simply a "brick"). This unit of rock can be combined with many thousands (millions) of others to form any sized three-dimensional shape we like. Obviously, the smaller the unit, the greater the precision of the model, but the more units we will need for any given sized shape, the greater the number of calculations we will have to do, and the longer we will be kept waiting for a result.

Neglecting for a moment the flow of water between the front and back of the cuboid, we can model it hydrographically as shown in the middle diagram on the previous page.

Water can flow from right to left (a negative flow is vice-versa), and from top to bottom (a negative flow is vice-versa), and the only thing forcing the water to move is the force of gravity, which we can model as a small pump generating pressure proportional to the vertical thickness of the unit.[29]

For the basic unit, water can flow only in the up-and-down and left-and-right directions, but if we put lots and lots of these units together, a path sloping at any angle can be approximated by a zigzag path through the network, a small portion of which is shown in the bottom diagram on the previous page.

Given values for all the pressures generated by the pumps, and values for all the resistances that the rock offers to the flow of water, we can get the computer to calculate the flow of water through each branch of the network. This is a routine task that computers (and first-year undergraduate students) are often asked to do.

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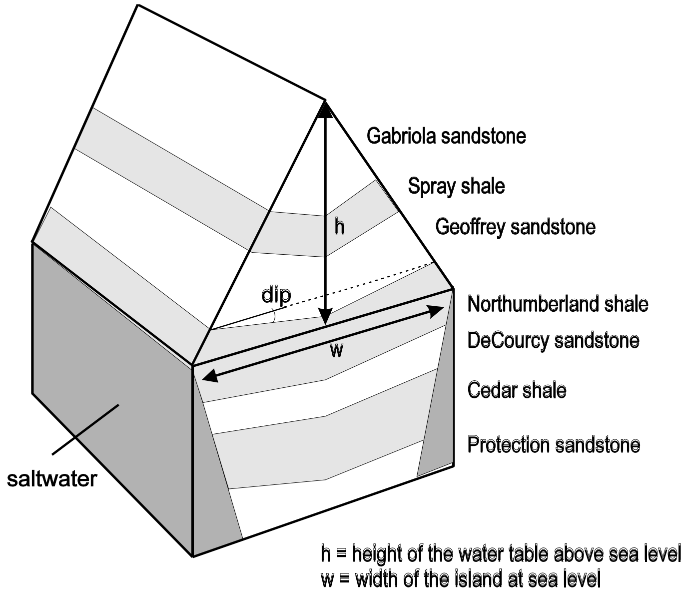
[29] Electrical engineers will recognize this as being the analog of a voltage generator. The flow of water is then analogous to the flow of electrical current. Resistance to the flow of water is inversely proportional to the hydraulic conductivity of the rock and proportional to its thickness.



To keep things simple, the shape of the island above sea level was modelled as a TOBLERONE bar. The geological strata were taken to dip down uniformly toward the long central axis of the island.

Modelling the island

A simple model of the island is a tent-shape, a bit like a TOBLERONE© chocolate bar. If you think that this is too crude, remember, we are not attempting to model the surface topography of the island, just the topography of the "core" aquifer, that is the aquifer that extends down below the level of the sea. Surface topography would be important if we were modelling the perched aquifers on the island, but we're not. It is very unlikely at this stage of the game that modelling the surface topography accurately would be worthwhile when one considers the added complication and the "roughness" of the model in other respects.

Another simplification I made—OK, OK, my computer is pretty feeble—was to ignore the "ends" of the island. Ignoring the ends—Descanso Bay to Clark Bay at the north end, and Degnen Bay to Law Point at the south end—has a couple of advantages.

The main one is that we don't have to consider flow parallel to the island's long axis; every cross-section or vertical slice has the same flow pattern. This enormously reduces the amount of computation to be done, and it's why I neglected the flow of water between front and back of the basic cuboid just a moment ago.

A second advantage is that it avoids what could be difficult modelling complications. For example, the dip of the island's strata northeast of the fault that runs between Leboeuf Bay and Descanso Bay is different from the rest of the island—the central syncline axis running through the Twin Beaches area is not horizontal but actually plunges gently northward into the sea. Investigating the hydrological significance of this is a task for another time.

We can note here too, that because of the symmetry of the problem as formulated—what happens on one side of the vertical centre line exactly matches what happens on the other—we only need do half of the calculations.[30]

Modelling the saltwater interface

To model the interface between the sea and the freshwater, I just calculated the pressure of the sea- and freshwater at each depth, and if the seawater pressure exceeded the

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[30] I took the half-width of the island to be 1820 metres, and took ten horizontal slices above sea level and ten below, calculating to a maximum depth below sea level of just over a kilometre (1160 m). The height of the watertable at the island centre was variable, and I assumed the island was 150 metes high, though there are hillocks up to around 170 metres.

freshwater pressure, I took that particular unit to contain seawater.[31]

Modelling the geology

Gabriola's bedrock is gently folded with the fold axis running more or less longitudinally down the centre of the island. Although, in principle, this should be modelled as a shallow ∪-shape deformation of the strata (it's a syncline), for ease of computation I just assumed the dip observed on the coasts continued right through to the central axis of the fold (a shallow ∨-shape deformation). I don't imagine this simplification makes any significant difference to the results.

The strata, I modelled as being alternating formations dominated by sandstone, including conglomerate, and shale. Because the model was going to be asked to say what goes on deep underground, I ended up modelling eight formations instead of the usual four, with four of these below sea level on Gabriola.[32]

Criteria for success

In an earlier *SHALE*,[33] I derived a freshwater budget for Gabriola showing where all the precipitation eventually ends up.

The 900 mm of annual precipitation we get is equivalent to a sustained supply of freshwater flowing at around 1440 litres per second (L/s). Of this flow, about 44%, is returned directly to the atmosphere and so is of no concern to us at the moment. Also, of the total inflow, about 12% was measured as flowing across the surface of the island, or close to it, and entering the sea without ever being part of the groundwater cycle. Again this is of no concern to us at the moment. This leaves us with a flow of 44% of the total precipitation into the ground (393 mm, or 628 L/s).[34]

According to the budget, of this remaining 628 L/s, 360 L/s (57%) emerges from the ground in springs and flows into the sea overland, while the remaining 268 L/s (43%) flows, unseen, into the sea beneath the island. The job of the model was to reproduce these numbers.

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[31] This assumption of hydrostatic equilibrium is another simplification, but again, not likely one that makes a difference.

[32] They were, starting from the top, with assumed nominal thickness at the centre of the island:

Gabriola Fm.	280 m	s/s
Spray Fm.	88 m	shale
Geoffrey Fm.	120 m	s/s
Northumberland Fm.	200 m	shale
De Courcy Fm.	240 m	s/s
Cedar Fm.	320 m	shale
Protection Fm.	160 m	s/s
Pender Fm.	400 m	shale
	1808 m	

The thicknesses were adjusted for various dips so as to maintain the positions of the contacts of the formations on the surface the same as for a 15° dip; hence, the bottom of each formation present, at the surface or, where below sea level, on the beach, relative to sea level was:

Gabriola Fm.	88 m
Spray Fm.	67 m
Geoffrey Fm.	27 m
Northumberland Fm.	–50 m
De Courcy Fm.	–290 m
Cedar Fm.	–770 m
Protection Fm.	–610 m
Pender Fm.	–1170 m

This isn't exactly how it is in reality, but it is a fair approximation if you take "the beach" to be Whalebone or False Narrows. A hole drilled 600 metres (1970 feet) to explore for coal at the back of Brickyard Beach (1887–9) reached only as far as Cedar Fm. shale.

[33] *SHALE* 14, pp.18–32, September 2006.

[34] Appiah-Adjei, p.74, gives a Gulf-Island-wide average of 45% for "recharge", but his figure includes springwater runoff.

The results

Springs?

The first task was to establish that the model did predict that some of the rainwater soaking into the ground re-emerges as springs. It did. When runs were made with no differentiation between the sandstone and shale strata,[35] no matter what the height of the (core) watertable in the centre of the island was taken to be, there was springwater runoff. Underground, the old maxim that water *always* flows downhill is not true; however, what the model did not predict when the sandstone and shale were not distinguished is the correct division between springwater and groundwater. In every case, the flow of springwater was too low.

Impermeable shale?

The next task was to establish how impermeable the shale strata had to be compared with the sandstone strata before the correct proportion of springwater could be predicted, at any height of watertable.

Ratios of sandstone to shale hydraulic conductivities in the range 1.8; 4; 16; 64; and 100 were tested[36] over a range of watertable heights (70–150 m),[37] and for three values of dip at beach level (10°, 15°, and 20°). The results were shown in the three tables on the next page.

The figures are the mismatch between simulation and field measurements in litres/sec. The lower the figure, the better the match. Dark shading indicates groundwater flow too high in the model; no shading indicates springwater flow too high in the model; light shading indicates a good match. Columns are for different sandstone/shale hydraulic conductivity ratios. Rows are for different heights of watertable on the island's central axis.

Although the results for the 70-m high watertable are shown, all modelling results for watertable heights below 88 m have to be regarded as being unrealistic because they imply no springwater flows from the Gabriola/Spray Formation contact, contrary to what is observed.

Trade offs

A good match between the model's predictions and the field observations is obtained under a variety of circumstances. The first table, for a dip of 20°, shows good matches, but only for the right combinations of watertable height and ratios of sandstone to shale hydraulic conductivity. These results have to be judged as being moderately poor because a good match is critically dependent on the precise parameters used (only two light-shaded units).

The second table, for a dip of 15°, shows a similar pattern. These results also have to be judged as marginally satisfactory (only one light-shaded unit above 88 metres).

The third table, for a dip of 10°, show that a good match can be obtained under a greater variety of circumstances than in the other cases.

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[35] Treating the sandstone and shale as homogeneous makes the dip of the strata irrelevant.

[36] I also checked a case where the sandstone hydraulic conductivity was taken to be *less* than that of the shale. Although the model could be made to predict the correct rate of springwater flow, the water was clearly coming from points on the surface where, in practice, none exist, at the top of the sandstone formations. However, Appiah-Adjei, p.66, suggests that "less-fractured sandstone" (LFSS) has only half the conductivity of mudstone (IBMS-SS).

[37] A series of 20 wells, 150 m above sea level, show watertable heights in the range 63–139 m with an average of 107 m.

In the three adjacent tables, the figures are the mismatch between simulation and field measurements in litres/sec of the annual flow of water to the sea below sea level and of water to the sea as springwater runoff. The lower the figure, the better the match.

Dark shading indicates groundwater flow too high in the model; no shading indicates springwater flow too high in the model; light shading indicates a good match.

Columns are for different sandstone/shale hydraulic conductivity ratios. Rows are for different conjectured heights of watertable (ignoring perched aquifers) on the island's central axis. The tables are for three values of dip along the north and south coasts toward the island's central (syncline) axis.

Although the results for the 70-m high watertable are shown, all results for watertable heights below 88 m are unrealistic because they imply no springwater flows from the Gabriola/Spray Fm. contact.

dip 20°	1.8	4	16	64	100
150m	21	43	86	135	
130m	6	28	82	150	
100m	47	9	11	129	
70m	65	36	21	119	

dip 15°	1.8	4	16	64	100
150m	20	42	94	117	182
130m	2	23	76	120	172
100m	37	15	37	31	168
70m	79	7	11	4	142

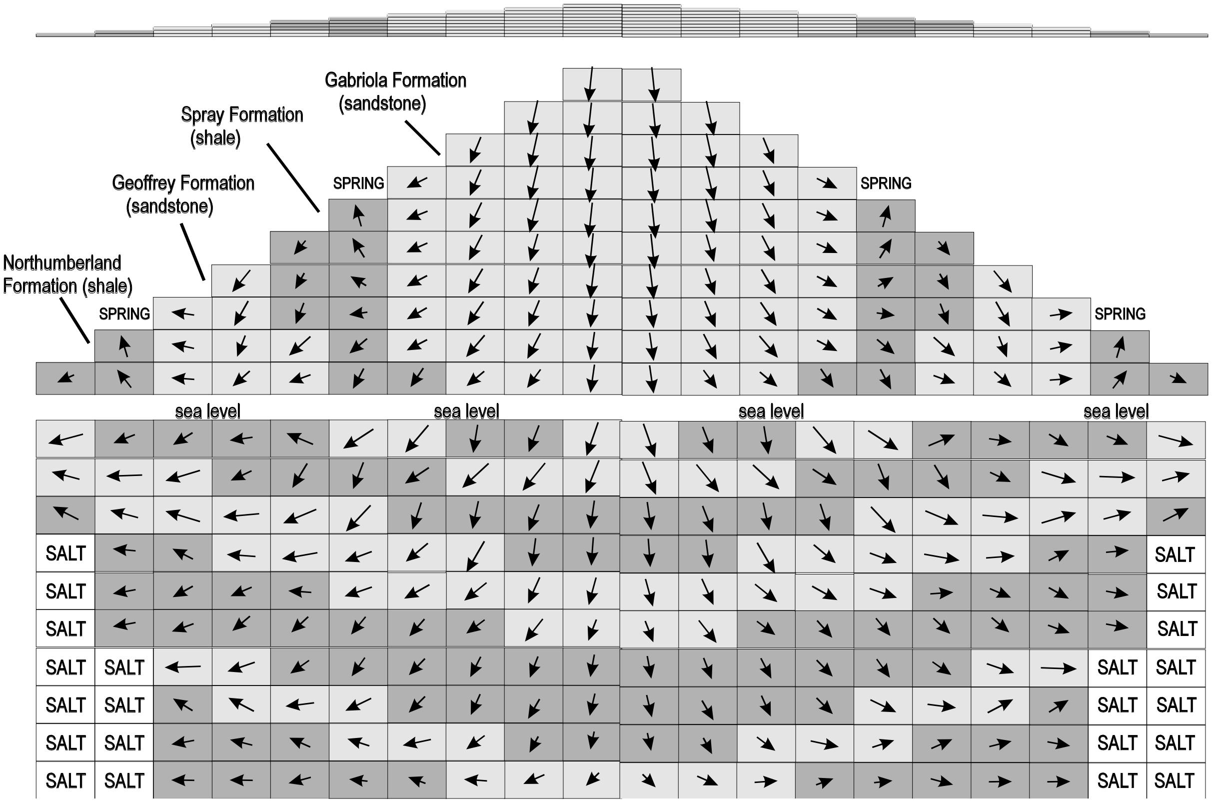
dip 10°	1.8	4	16	64	100
150m	11	28	91	137	133
130m	5	57	97	130	182
100m	9	1	16	86	165
70m	42	32	10	56	163

In general, there is a trade off between height and conductivity ratio; the more impermeable the shale relative to the sandstone, the lower the watertable has to be to get a sufficient flow of groundwater. None of the tables shows a good result for permeability ratios of 16:1 or greater.

That such good results are obtained with a dip of 10° is very gratifying, because that's close to what it actually is.

Hydraulic conductivity

Taking all of the "best" matches (those with the light shading in the tables), we get a one-sigma range for the hydraulic conductivity of sandstone $2.2–3.7 \times 10^{-5}$ m/s, and for shale, $1.0–1.5 \times 10^{-5}$ m/s. As noted, this is remarkably similar to other estimates made completely independently and given earlier.



An example of how water moves through the rock according to the simple model described in the article. The light shaded areas are sandstone, the darker ones shale. Note springs at sandstone:shale contacts and the associated upward movement of water—water does not always flow downhill when underground.

The vertical scale and horizontal scales are different. All the “bricks” are 182 metres wide, but above sea level, they are only about 13 metres high, and below sea level, they are 116 metres high. The thin diagram at the top shows the above-sea-level bricks on the same vertical scale as the below-sea-level bricks.

How long would it last?

Given the rate at which water passes through the underground system, we can get the model to estimate how much water would be lost in a year of drought. The answer is around 11 (±6) %. In other word, if we were to have a decade of drought—an extremely unlikely scenario but nevertheless conceivable if the climate were different as it probably has been in the past—then Gabriola’s aquifers would disappear and the island would become a desert.

Conclusions

The main lessons learnt are that:

- the hydrology and geology of the island are closely linked. Studying the former without considering the latter won’t give you any idea of what goes on
- even a simple model can give some insight to the underground movement of water. A more comprehensive 3-D model might tell us more, particularly if it took into account that the hydraulic conductivity of fractured rock is anisotropic (it’s directional)

- because of the different types of aquifer on the island, particularly perched aquifers, concepts like the “zone of influence” have to be used with care and may not be that useful. Deep wells tapping the core aquifer, for example, may have influence on every well on the island that is close to the shoreline
- the volume of subterranean water is a delicate dynamic balance between the retention capacity of the rock and precipitation. Several years of drought would disrupt this balance, and the result would be very different ecosystems and landscapes from those we are used to seeing today.

Finally, let me add that in 1962, a hydrogeologist working for the Department of Lands, Forests, and Water Resources observed that, “…there is no clue as to where water will be encountered on these islands [Gabriola, Valdes, and DeCourcy]; whether by drilling in low or high areas; along beaches, the fracture zones cannot be predicted from surface examination… …drillers’ logs indicate no common depth at which fracture zones are encountered but that the deeper holes are either dry or poor producers”. Consultants are still being paid forty-six years later to say the same thing. ◊

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