The nature of the fractures in Gabriola Formation sandstone as it pertains to groundwater movement and storage

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There are some common themes in almost all reports and studies on groundwater supply on Gabriola Island that indicate an incomplete understanding of the nature of the island's fractured bedrock as it pertains to the island's groundwater supply.

Looking just at the groundwater within the sandstone of the Gabriola Formation, [ref.1] these are:

—that static-water levels in unpumped wells tend to correspond to their height above sea level and often show relatively little seasonal variation; [ref.2, p.15]

—that some wells in large catchment areas nevertheless run dry in summer despite there being high-quality wells in the vicinity;

—that the quality of the water in some wells drilled in the sandstone is poor, namely, the water has a high pH and is over-rich in fluoride and boron [ref.3] or is reported to be undrinkable fossil water;

—that there are mixed reports of interference between wells drilled in close proximity, some showing drawdown, some none at all.

I want to argue in this article that all of these themes are related, and that they are a consequence of the fact that not only is the hydraulic conductivity of the fractures in Gabriola Formation sandstone highly anisotropic, but that this anisotropy varies considerably with depth.

Recognizing the very heterogeneous nature of the fractures in the sandstone, quickly leads to an appreciation that some concepts commonly used by hydrogeologists, such as "cone of influence", "water table", "catchment area", and "aquifer" are not always useful concepts when attempting to explain the behavior and nature of the groundwater in particular wells within the formation.

Geological background

There are general background articles on Gabriola's groundwater hydrogeology here. [ref. 4 and ref. 4a]

The Gabriola Formation is the uppermost formation of the Nanaimo Group and is of Maastrichtian age. [ref.5] It is predominately thick-bedded coarse- to medium-grained sandstone with a high feldspar content, sometimes being so arkosic as to be a feldspathic wacke. [ref.6, p.10] [ref.7, p.31] On Gabriola, some of the formation is locally gritty, but not so much as to make it conglomerate, an indication that the original sediments were deposited in relatively deep water some distance off-shore. [ref. 8]

More significantly from the groundwater perspective are the occasional small interbeds, usually of silty mudstone. [ref. 9, pp.418–9] When these are fractured or foliated by surface weathering, they conduct water, but some are well-cemented, fine-grained sandstone and act as aquitards.

Also present in the Gabriola Formation sandstone are seldom-mentioned partings [ref. 10] between strata and these can often be seen in cliff faces to be conductors of groundwater along bedding planes.[1]

Interbeds and partings thereby add complexity to determinations of the lack of isotropy of the hydraulic conductivity of the sandstone.

[1] Drawn to my attention by Steven Earle.

Thin sectioning of Gabriola Formation sandstone reveals that there are very few interstices of significant size between grains, the matrix being a fairly even mix of comminuted grains (micro-gouge), and clay, the clay acting as the cement. This is a common characteristic of sandstone rich in feldspars.

Case-hardening of the surfaces of sandstone is common and occurs wherever the rock is exposed to oxygen-rich water. This mostly occurs at the surface and along the planes of fractures that are conducting groundwater. The hardening is due to oxidation of mafic minerals (hornblende and biotite) in the sandstone, which creates "rust" (limonite) that strengthens the cement. [ref.7]

Sometimes case-hardening improves the hydraulic conductivity of fractures by sealing the walls or by spalling, [ref.7a] but it can also "heal" the thinner fractures so that they no longer transmit water.

Fractures

Tectonic fractures

All of the formations on Gabriola were subject to folding in the Eocene and are as a result heavily fractured. [ref.11] Most of these fractures are bedding-plane perpendicular. Since the Gabriola Formation on Gabriola is part of a synclinal fold with an axis running roughly east-west along the centre of the island,[2] for the most part, and for present purposes, these bedding-plane-perpendicular fractures of tectonic origin can be regarded as being close to vertical.

According to a 3-D model of this type of fracture on Gabriola, they play no role in the storage and transmission of groundwater below a depth of approximately 200 metres. [ref. 12] One can envisage that at depth, apart from the natural termination and closure of fractures, they become clogged with clay and other fine-grained material.

The orientation of sets of tectonic fractures is a significant factor in determining the degree of interference between wells in close proximity. [ref. 13] The largest set of fractures in the Gabriola Formation runs N29ºE±15º, [ref. 14, A-set] roughly orthogonal to the syncline, with a clockwise rotation as one moves from west to east; however, they are not present at all locations and there are several other major sets with different orientations and likely different ages. It is common for more than one set to be present at any particular location.

Glacigenic fractures

Much less-often discussed in the academic literature are fractures in the Gabriola sandstone that are a result of glacigenic deformation during the Pleistocene and subsequent post-glacial relaxation. These form sets, seldom more than five metres below the surface, and are predominately horizontal fractures (photos next page).

The surface zone often weathers to Saturna soil containing many channery fragments, while in the lower zone approaching the interface with the tectonic-fractured rock, the fractures reduce to just tension gashes.

Weathered glacigenic-fractured rock also frequently forms large boulders. These were originally rectangular blocks in shape, but have been spheroidally weathered. [ref. 15, pp.39–40] These, together with ablation till or its lag-gravel remnants, often form the regolith below the post-glacial soil.

Faults

There are two major faults on the island. I will comment only on the north end fault as only this one runs through the Gabriola Formation. The two faults probably have a common origin. [ref.16, pp.34–5]

[2] At the limbs of the syncline along the north and south shores, the dip toward the central axis is up to a maximum of around 15º.

Fractures in the Gabriola Formation (bluffs above Lock Bay and False Narrows). There are two sets.

The lower set of Eocene age consists of wide bedding-plane-perpendicular fractures in rock that is sometimes unfractured. Any horizontal fracturing in this set is either occasional joints between two vertical fractures, or a thin interbed of silty-mudstone, which may intersect many vertical fractures.

The upper set are likely of Pleistocene age and occur within about five metres of the present-day surface. These are bedding-plane-parallel fractures, most likely tension fractures resulting from post-glacial stress relief. Less likely is that they are partings; there is no reason for partings to cluster at the surface

Note the tension gashes below the vegetation in the picture on the left and how the interface zone between the two sets is an obvious source of subsurface water flow..

An exposed tectonic vertical fracture (Bluff overlooking Lock Bay). Obviously a groundwater conduit. Note the lack of horizontal fracturing—possibly only one small joint—in stark contrast to the facturing in the rock capping it near the surface.

Above: Gabriola Formation cliff on Valdes Island. What was probably once a vertical fracture plane showing a horizontally fractured zone at the top, with only occasional bedding-plane fractures (joints) and interbeds lower down. The black streaks are lichen indicating freshwater flows.

Below left: Bedding-plane parallel fractures at the top of this cliff.

Below right: Two small interbeds in otherwise unfractured Gabriola sandstone (Galiano Gallery). Probably silty mudrock. The brown weathering and the algae staining below the interbeds indicate that they carry groundwater, and this was darkening the sandstone below the lower interbed.

Subsurface features at Berry Point, Gabriola Formation. A mix of mudstone interbeds, weathered-out interbeds, spalling, and partings with a few vertical joints here and there.

Cliffs, 20 m high, leading out to Schooner Point, Gabriola Formation.

Interbeds or partings between sandstone of differing lithologies? Chemical weathering by oxygen-rich groundwater indicated by the brown staining (limonite from hornblende and biotite) complicates interpretation without thin-film sectioning. Both however provide some horizontal connectivity at depth.

Gabriola Formation at Malaspina Point.

The north end fault runs from Cox Bay to Leboeuf Bay and is a dextral strike-slip fault modified by clockwise rotation of the block to the northwest that has produced additional extension fractures (Mode I) sub-parallel to the fault at the Cox Bay end, and minor thrusting, once thought to be an anticline, at the Leboeuf Bay end. [ref.17] [ref.18] The parallel extension fractures near Cox Bay underlie the valleys of Winthuysen Creek, Columbia Creek, and Mallett Creek. [ref.19]

The fault plane is a shear zone containing mylonite, zeolite, and calcite and is likely an aquitard, but whether this has a significant effect on groundwater movement in the area is a matter of conjecture. For the most part, the fault does not bring rock formations with differing hydraulic conductivities into contact in the way that a dip-slip fault might; however, it has probably introduced a difference in the dips of the rock on either side of the fault.

Soils

Soils on Gabriola play no role in groundwater storage—they are too immature and too thin. The exception is areas of gleysol with a high concentration of montmorillonite,[3] a clay that is a product of the post-glacial chemical weathering of silty glacial flour rich in feldspars accumulated by meltwater after the sea had retreated, or of marine undermelt till. [ref.20]. Gleysol commonly maintains perched aquifers on Gabriola and underlies all of the island's static surface water and most of its wetlands.

Hydraulic conductivity

Some reports assign a single value to the hydraulic conductivity of the Gabriola Formation sandstone, in the range 10^{-5} to 10^{-7} m/s is usual.[4] This is compared to "textbook" values for unfractured sandstone generally between 10^{-6} to 10^{-10} m/s. [ref.23, p.130]

However, these values are only for the horizontal hydraulic conductivity [bedding-plane parallel]. A common statement in hydrological textbooks is that "within an anisotropic geological formation, the vertical component [meaning the bedding-plane perpendicular component] of the saturated

[3] Parksville, Fairbridge, and Tolmie soils, often existing beneath organic-rich Metchosin soil. [ref.21]

[4] My own evaluations [ref.22] suggests the higher end of this range, 10^{-5} to 10^{-6}, m/s, but the estimates would probably not stand up to peer-reviewed scrutiny.

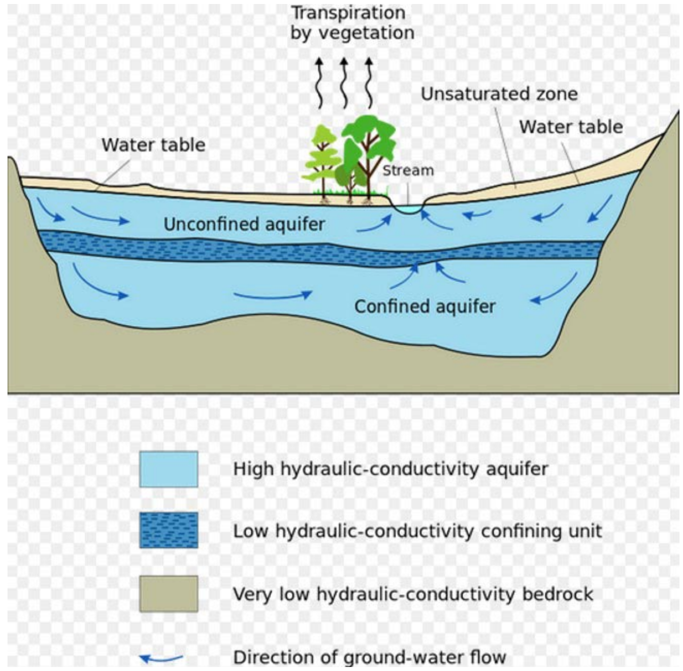
hydraulic conductivity is usually smaller (one to two orders of magnitude) than the horizontal component". While this assertion may be true in general for bedded sedimentary rocks, it clearly does not always apply to those that are fractured.

Hydraulic conductivity parallel to the bedding planes in the tectonic-fractured zone in Gabriola sandstone is provided by joints along bedding planes, partings, interbeds of much higher conductivity than the host rock, and to a much lesser extent, slight variations in the conductivity of stratified beds.[5]

It is important to remember here too that hydraulic conductivity is an averaged value over an area of rock. A conductivity of say, 10^{-5} m/s, does not mean that water only travels through fractures at 10^{-5} m/s or 26 metres per month. If the fractures only constitute, say 5% of the area in the travel direction, and there is virtually no flow in the confining rock, then the water is travelling through the fractures at an average rate of 0.2 mm per second, or around 500 metres per month.

Concepts in hydrogeology that do not apply to Gabriola Formation sandstone

Here are several concepts that are common themes in hydrogeological studies that are either not applicable to Gabriola's fractured bedrock, or have to be interpreted somewhat differently than in "textbook fashion".



Wikapedia. Courtesy Hans Hillewaert.

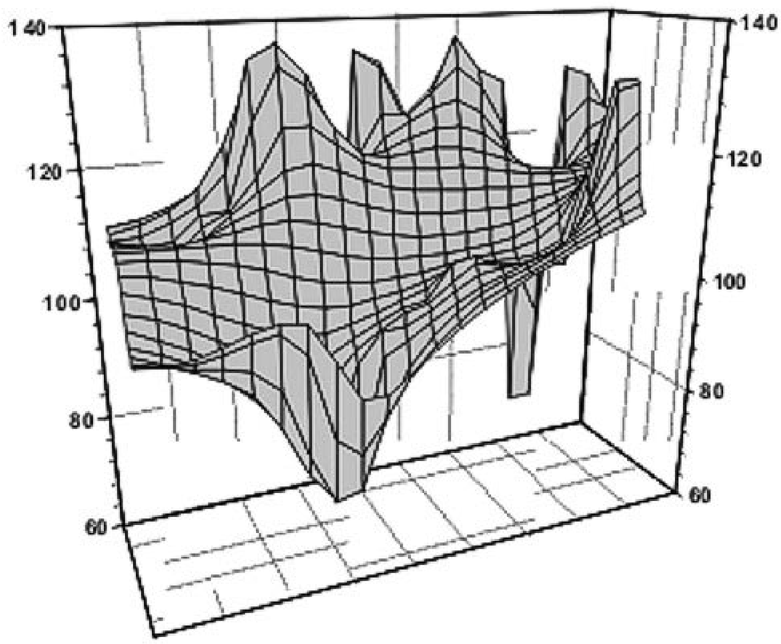
Aquifers

Aquifers are "permeable bodies of rock capable of yielding quantities of groundwater to wells and springs". Quite clearly then, there are aquifers within the Gabriola sandstone. The issue is then how big are they and how many are there?

The idea that there is a single aquifer beneath the island, an underwater lake sourced from far-off sources, is a widely discredited idea. We need to expand the definition of an aquifer to include a description of its boundaries.

The excellent diagram above from Wikipedia (Hans Hillewaert) gives a good solution, "…an aquifer is bounded by bedrock of very low hydraulic conductivity". Given that the hydraulic conductivity of unfractured sandstone bedrock can be orders of magnitude less than fractured rock, we would be then entitled to regard, as an example of an aquifer, a single fracture that just happened to have little to no conductivity in the

[5] Slight differences in the conductivity of sandstone strata within seemingly homogeneous units can result in easily observable differences in the way the strata salt-weather. Salt-weathering (honeycombing) depends on the flow of brackish moisture from the interior of the rock to an evaporation surface. Finer grains produce lower conductivity; higher quartz content produces better conductivity; higher feldspar content may result in lower porosity and permeablity.



It is tempting to think of a "water table" 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 "water table" 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.

horizontal direction below the subsurface zone. Gabriola has not just one aquifer, it probably has thousands of them.

Water tables

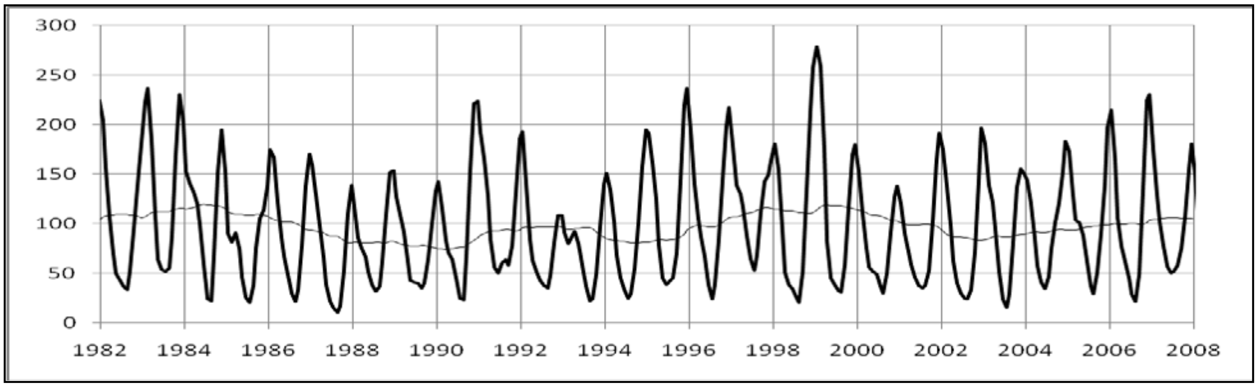
Closely allied to the concept of an aquifer is the idea of a water table. Just as some commentators are happy with the idea of there only being a relatively small number of aquifers on the island, so are they happy with the idea that over correspondingly reasonably limited regions of the island, catchment areas, there are water tables.

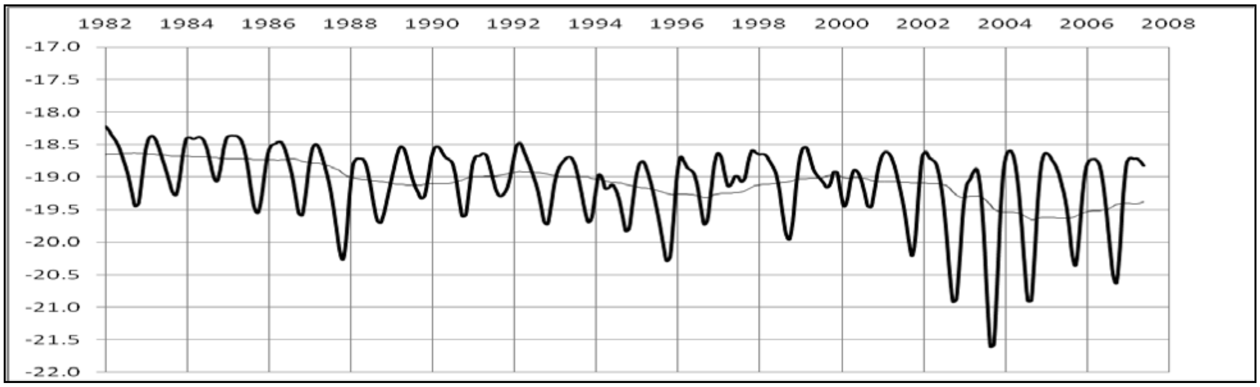
What proponents of this notion do not explain so well is, if indeed there is a fair amount of horizontal connectivity between wells, why is this not always reflected in the unpumped standing water levels in them. An example of how much standing water levels in wells can vary on Gabriola is shown in the diagram above. This data is from a cluster of wells on the Legends development on the False Narrows bluff.

Another problem with the water-table concept as applied to fractured Gabriola Formation sandstone, is, given that it is commonly observed that the postulated water table is a subdued replica of the land surface topography,[6] why is it that during periods of very heavy precipitation in winter, this water table does not rise to the surface and cause either flooding or visible surface run-off? The records of unpumped observation wells sometimes show an apparent cap in standing water level that is below ground surface level. An example is shown on the next page. [ref.24]

A simple explanation for these observations is that the hydraulic conductivity in the fractured rock is greatest in the vertical direction when the standing water level is at or slightly below the boundary between the tectonic-fractured rock and the overlying glacigenic-fractured rock. When the standing water level rises above this level, as it does in winter, the direction of greatest

[6] This is a natural outcome of the solution to the equations for the flow of groundwater through a homogeneous isotropic medium, and is often proffered as an explanation for standing water levels following the topography, even when the medium is far from homogeneous and far from being isotropic.





Top: Monthly precipitation for 26 years for Nanaimo Airport. The record has been filtered to smooth out short-term changes. The thin line is the 3-year running average.

Bottom: Variation in water-table height m at Hydrographic Observation Well 194 (Emcon yard). The trend lines are three-year running averages. Note the apparent "cap" on height and that a small decrease in precipitation can sometimes lead to a disproportionate drop in standing water level.

hydraulic conductivity rapidly switches from being vertical to being horizontal, and the excess water runs off, albeit unseen below the surface of the ground. As soon as the rain eases off in late-spring, the standing water level declines until the direction of greatest conductivity switches back from being horizontal to vertical.

The drop in standing water level in late summer is a consequence of their being continuous seepage into the deeper bedrock. The whole bulk of the rock is not a source as implied in the homogeneous medium water-table model.

Water tables and porosity

A secondary, but important, effect of neglecting subsurface run-off through the glacigenic-fracture zone when estimating the porosity of the sandstone by comparing seasonal fluctuations in standing water level in unpumped observational wells with precipitation, is that leads to an overestimate of the porosity. It assigns to the rock a propensity to absorb precipitation that it does not in fact have.

Cones of influence

Nobody expects the drawdown in the water table of wells neighbouring a pumped well to follow the textbook conical pattern when the bedrock is not homogeneous. If, in the simplest case, the pumping well intersects a single high-yielding fracture or highly-interconnected fracture set, the "cone"

Left: Possibly what a water-bearing-zone (an interbed) looks like. The green algae show the presence of water as does the light brown staining above and below the interbed marking where water has penetrated the sandstone through capillary action and chemically weathered it.

Right: Not all interbeds conduct water. This one shows no sign of it. The black streaks are coalified vegetation. (Galiano Gallery, Gabriola Island)

Above: Minor dip-slip faults in sandstone like this may be one reason why interbeds are sometimes only effective over a limited range, though here water is seeping from both sides of the fault.

Above: Horizontal sandstone fractures are often finer-grained material that has been foliated by weathering thereby increasing its horizontal conductivity.

would be expected to be greatly elongated in the strike direction of the fractures.[7]

Unfortunately, it is not possible in advance of drilling to say which factures will be encountered,[8] and if a single well does not show drawdown in the expected elongated direction, pumping tests on that single well cannot be used to generalize the results to areas beyond the tested area. [ref. 13] [ref. 25]

Catchment areas

The conventional notion of a catchment area is a fixed geographical area defined by local topography. Catchment areas on Gabriola are more dynamic than this. At the start of the rainy season, the level of water in the fractured rock is low; consequently, relatively little of the precipitation runs off. Some areas within a catchment area may even be isolated from the rest of that area.

Conversely, at the end of the rainy season, the soil is saturated and the fractures are full to overflowing. Practically all of the

7 I'm only aware of anecdotal evidence of this.

8 Well drillers habitually drill only as far down as is necessary to provide sufficient water leaving open the possibility that there might be even better supplies further down.

precipitation runs off in ephemeral creeks and subsurface flows.

Fractures are also leaky, and their leakiness depends on the level of the water in them, so a few days of heavy rain can result in more run off than when the same volume of rain falls steadily over a longer period. [ref. 27]

For these reasons, the fraction of the precipitation that flows into lakes, creeks, and wetlands varies considerably throughout the year, as does the effective areas of the supposedly fixed catchment areas.

Horizontal (bedding-plane) connectivity in the tectonic-fractured zone

Studies of the hydraulic conductivity of fractured rock often conclude that while it is possible to make statements regarding its nature on a regional averaged basis, it is much more difficult, some would say impossible, to make statements universally applicable to smaller areas containing only a few meshes of the regional network of fractures. [ref. 12] The only way to find out what is down there for certain is by drilling.

Probably the most significant transmitters parallel to the bedding planes in the Gabriola sandstone are thin interbeds. These sheets occur at random depths and are noted in well-drillers' logs as "WBZ's" or water bearing zones. It is commonly necessary when drilling a well to continue down through several such zones before the yield is judged to be sufficient. Yields of water between WBZ's is commonly completely absent.

Partings, where present, may be the providers of exceptional strong radial flows of groundwater, but they are probably not often encountered as, judging from cliffs, their vertical separation is usually large.

Because of their thinness, it is unlikely that the interbeds themselves have the storage capacity necessary to qualify them as aquifers. They just provide the local connectivity between the more productive sub-parallel vertical fractures.

Joints between adjacent vertical fracture planes are also unlikely to be useful repositories of water; their range is limited and there is no reason to suppose that they have been subjected to tensile stress that would widen them and improve both their conductivity and their storage capacity. All of the bedding-plane perpendicular sets of fractures visible at the surface of the sandstone bedrock on the island are accompanied by minor sets of joints with strikes 90º offset to the main set. Some fracture sets are conjugate pairs, which complicates any calculation of the shape of possible cones of influence. [ref. 14]

The sandstone in the tectonic-fractured zone that is not in close contact with underlying shale units is thus probably fairly characterized as being providing high-storage vertical fractures with low-storage but high-conductivity horizontal connectors, in a host rock that is essentially impermeable.

One consequence of this is that the commonly used parameter for judging the quality of a well, its pumping rate in gpm,[9] is not necessarily sufficient. This parameter is appropriate when the capacity of the aquifer is virtually unlimited, but not in the special case of a fractured rock aquifer where the long-term volume of the aquifer may be more significant than the short-term rate that it can be pumped. Reports on well quality on Gabriola never mention volumes of local aquifers despite their importance.

Some anecdotal evidence

As part of the Gabriola Streamkeepers goal of measuring the baseline characteristics of

[9] gpm = gallons per minute, all too often not specified as Imperial or US gallons.

creeks on the island, measurements of the quality of the water have been made over the years. Practically all creeks on the island are either ephemeral or intermittent, but some are described by old-timers and in older literature as being sourced by "springs". Investigations have shown that with just one exception[10] these springs respond quickly to short-term changes in precipitation; they do not maintain any flow in summer regardless of what they may have done in the past; and their pH, electrical conductivity, and dissolved-oxygen content is very close to that of surface run-off.

These observations are consistent with the idea that the springs are examples of subsurface runoff reaching the actual surface, not that they are sourced deep in the bedrock as the conventional notion of a spring might imply.

Some of the best observations by people who live on the island that support the notion that there there is substantial subsurface run-off in glacigenic-fractured zones comes from, appropriately enough, the communally-owned Commons. Their well is just across the road from the Gabriola Elementary School and from the nearby Hydrographic Observation Well 194 in the Emcon yard.

Despite the fact that the school makes substantial withdrawals of water from their well—more than the average domestic user—the quality of the water at the Commons is always good, showing little sign of the mineralization that would be present if the water had been stored underground for a long time, and its quantity is always adequate; it has never run dry. It dates from the 1980s. However, another well on the property dating back to the 1960s, about 25 metres away from the main well, often runs dry after very limited use.

An insight as to what was going on was provided when it came to installing a septic system at the Commons. This was done in July 2015, a very dry summer. Much to the surprise of everyone, flowing water was discovered below a boulder field[11] and above the unfractured bedrock below it. It appeared to be coming from a slightly confined aquifer. The water was a mere 2.5 metres below the surface.

This discovery suggested that there is a subsurface flow year round, that the flow does not extend laterally very far, and that it is why the school well has such a high yield. It is also suspected that the presence of this subsurface run-off is the reason why the standing water in the Observational Well 194 shows so little seasonal variation, and why the water extracted at the Commons has the characteristics of being water that has had only modest contact with the local bedrock including fairly neutral pH and low chloride. [12]

Clearly if this interpretation is correct, the Observational Well 194 cannot be taken as a typical well in this catchment area.

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[10] Upper Jenkins Creek [ref. 26] known to be sourced from a perched aquifer supported by a substantial layer of gleysol of marine origin. Investigations included Mallett, Columbia, and Winthuysen creeks.

[11] Boulder fields are common periglacial features, but there is no definitive evidence this is what this was.

[12] Obs.194 (May 1981): pH 7.5, hardness 16.8 mg/L as $CaCO_3$; Na 82 mg/L; Ca 6.2 mg/L; Mg 0.31 mg/L; Cl 12.5 mg/L
Commons (Feb. 2016): pH 6.7, hardness 17.2 mg/L as $CaCO_3$; Na 79 mg/L; Ca 5.3 mg/L; Mg 1.0 mg/L; Cl 31.3 mg/L.

Another example, of which there are many, is of a well producing a good supply of water from the Gabriola Formation becoming contaminated with bad smelling and bad tasting, presumably fossil water, when a neighbouring well was drilled 25 metres away in the direction of the island's most significant fracture sets [ref. 14, A-set].

While a rule-of-thumb on the island is that wells should be 100 metres apart to provide almost certain insurance that they won't interfere with each other,[13] there are no guarantees that this will always be adequate.

Fracture fields are complicated places, everyone says so, and there may be no way to get to fully understand them on a local individual-well scale short of drilling down to explore them. ◊

An A-set fracture in Gabriola Formation sandstone. They are bedding-plane perpendicular extension fractures with minor irregular strike slip, and likely important repositories of groundwater. This one is in Drumbeg Park, but they are common elsewhere on the island.

[13] An observation of John Peirce.

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"Parting" should not be confused with "parting lamination" or "parting lineation". The latter are grain-sized structures on bedding plane surfaces, sometimes used to determine paleocurrent directions. Some "planes of parting" in the Gabriola Formation are probably weathered-out planar interbeds of mudstone.

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