# The hydrogeology of Gabriola groundwater

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*Note: There is a glossary at the end of this paper.*

## *Introduction*

The Gabriola Community is currently reviewing its Official Community Plan (OCP) and so this is an opportune time to review the nature of the island's groundwater and to consider its sensitivity to overuse, contamination, and climate change.

The purpose of this paper is to explain the hydrogeology of the aquifers on Gabriola in relatively simple terms, so that decisions on groundwater usage can be more soundly based. It is a background paper, not a contribution to discussions on groundwater management issues and policies.

## *Gabriola's groundwater*

Gabriola does not have just one aquifer from which we all draw as though it were one big sponge. The individual and, to a degree, independent aquifers on Gabriola are very small compared to aquifers on the Mainland and Vancouver Island, and it is not safe to assume that what is true for these larger aquifers is also true of those on the island.

Groundwater on Gabriola flows through, and is stored in, fractures in the bedrock. There are no large deposits of water-bearing sand or gravel as there are in many continental aquifers. In winter, rain and meltwater flows down through the fractures and replenishes our groundwater supply. Excess precipitation fills ponds and saturates wetlands, or runs off in ephemeral creeks, usually from October to March. For the remainder of the year, the demand for groundwater by vegetation (mainly trees) and residents, and the loss through leakage (downward movement, seepage, and evaporation) exceeds supply, and consequently the water level in the aquifers steadily falls. In some aquifers, but not all, the drop in water level increases sharply as the aquifer approaches exhaustion, and this can result in wells suddenly running dry.

Fracture systems are complex, and the horizontal connectivity, or lack thereof, is impossible to predict. The sensitivity of a local water source to overuse depends primarily on the total volume of the aquifer, but also on the speed with which the water moves through the rock. These critical properties can only be determined by detailed hydrogeological studies. It is seldom possible to generalize the results of such studies from one part of the island to another, so much so, that the idea of an "aquifer map" *may* not even be a useful concept on Gabriola in other than a very general sense (see Figure 7).

## *Contamination*

While water travels only slowly through tight fractures in the bedrock, some fractures are more open. There is usually only a two or three week delay between the onset of the rainy season and a rise in the static water levels in wells. The implication of this is that surface contamination can very quickly pollute groundwater if care is not taken to ensure that surface water has to percolate through soil before reaching bedrock.

## *Gabriola Island geology*

Gabriola is made up of late-Cretaceous sedimentary rocks of the Nanaimo Group. The four uppermost formations of this group are, from youngest to oldest:

—Gabriola Formation (primarily sandstone)

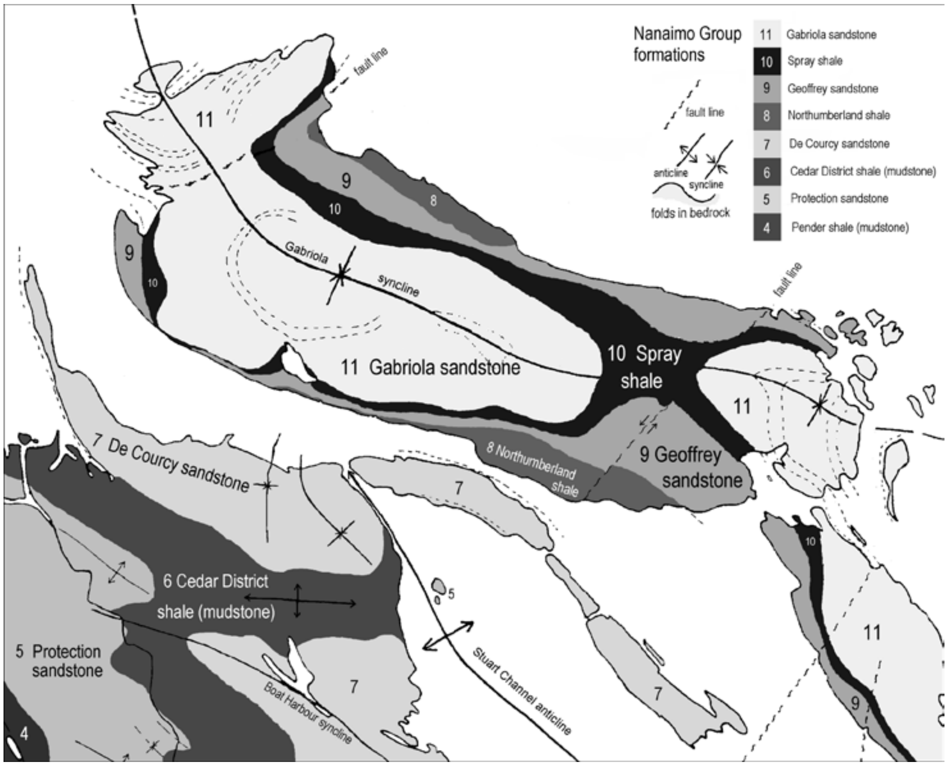


Figure 1: Gabriola's bedrock, showing the outcrop pattern on the island of the four uppermost formations of the Nanaimo Group (labelled here 11, 10, 9, & 8).

Doe, p. 15, 2004. Adapted from England & Hiscott, 1992, and Mackie, 2002.

—Spray Formation (primarily mudrock, usually known on Gabriola as shale)

—Geoffrey Formation (primarily gritty sandstone with locally abundant conglomerate), and

—Northumberland Formation (primarily shale).

These particular formations range in age from about 65 to 75 million years. Older formations of the same sedimentary group exist on Mudge Island (the DeCourcy Formation) and along the southeast coast of Vancouver Island, including Nanaimo (see Figure 1).

The sediments were laid down in the ocean between Vancouver Island and the BC Mainland near the estuary of a large river (or rivers). The grain size, which ranges from cobble-sized gravel in conglomerate, to clay-sized particles in shale, reflects the distance of the deposition site from the mouth of the river.
Finer particles are carried further out to sea than coarser ones.

The lithified sediments were subsequently uplifted and folded by compression as Vancouver Island was pushed against the Mainland in the middle Eocene (about 55 to 42 million years ago) in events associated with the formation of the Olympic Peninsula in Washington State. This folding was accompanied by extensive fracturing of the bedrock. Further uplift and fracturing occurred in the Neogene (about 24 million years ago). The current topography of Gabriola and the Strait of Georgia is the result of repeated glaciations that took place during the two-million-year-long Pleistocene, which ended only twelve thousand years ago.

Although each geological formation has one dominant type of sedimentary rock—sandstone in the case of the Gabriola Formation—they also have thin interbeds of other types of rock. Thin interbeds of fine sandstone and siltstone occur in shale, and thin interbeds of shale occur in sandstone. Although these interbeds represent minor events geologically—earthquakes or the collapse of unstable submarine banks of sediment in the river delta—they can have an important effect locally on the way that groundwater percolates through the rock because their permeability is usually different from that of the dominant type of rock (see Figure 3).

Structurally, Gabriola is a syncline—the ∪-shaped part of a large fold, now heavily eroded—with the axis of the fold running more or less east-west along the centre of the island from Gabriola Passage at the east end, to the Twin Beaches peninsula at the west end (see Figure 2), although the syncline is poorly expressed west of the major fault between Leboeuf Bay and Descanso Bay.

The sandstone of the Gabriola Formation, which is relatively resistant to erosion, is thickest in the centre of the island and so forms the crest of the island. The north-south ∩-shaped surface profile is thus the opposite of the subsurface structural profile. Because the rocks on Gabriola have been folded into a ∪-shape, the oldest rocks, the shale of the Northumberland Formation, are exposed along both the north and south "upturned edges" of the island (Whalebone, Spring Beach, and False Narrows). These shales dip toward the centre of the island at roughly ten to fifteen degrees.

There are only two major faults on Gabriola; both are hybrid types with both strike-slip and dip-slip components. Various interpretations have been made of Gabriola's structure showing more than these two faults, but little consensus has been reached as to the location of these other faults, or of their nature (Doe, 2009). Faults

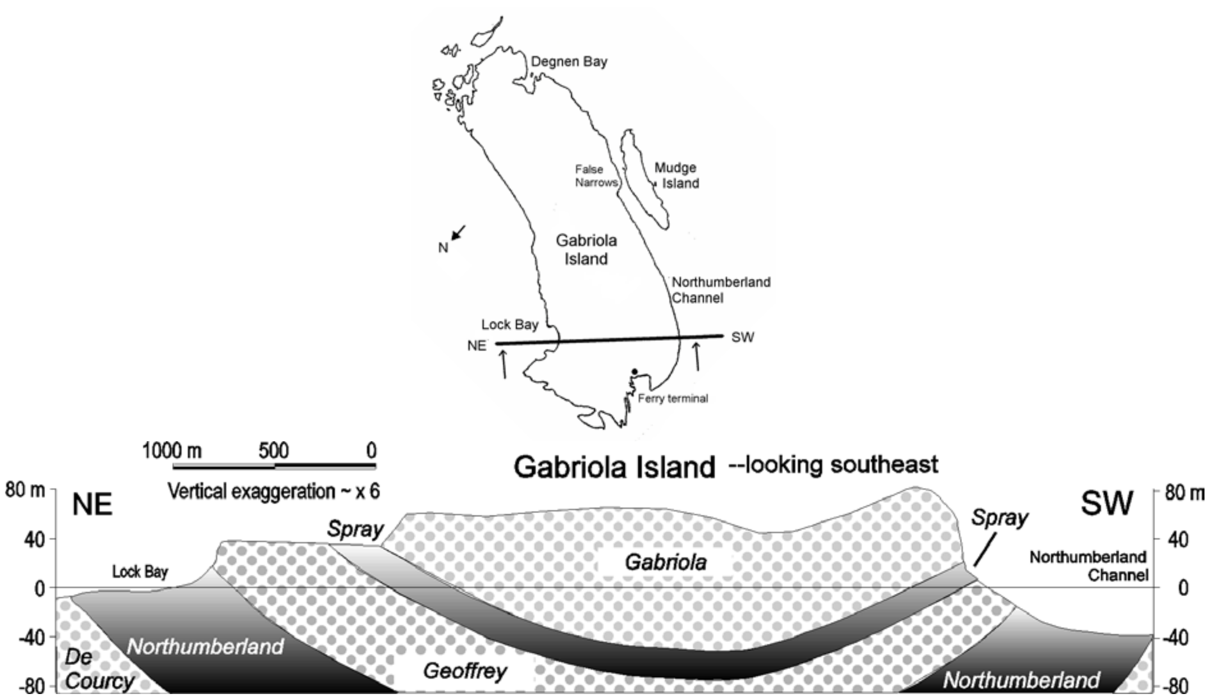


Figure 2: Cross-section of Gabriola Island, from Lock Bay to the Northumberland Channel, showing its Nanaimo-Group geological formations—*Gabriola*, *Spray*, *Geoffrey*, and *Northumberland*.

Earle & Krogh, p.35, 2004.

and erosional contacts have a strong influence on the flow of groundwater locally because large masses of rocks with differing permeabilities abut one another. These contacts can often provide concentrations of groundwater, but they can also hinder access to groundwater and leave the rock dry.

Although bedrock on Gabriola is not heavily faulted, it is heavily fractured everywhere. Fractures, which are intimately associated with the folding, are cracks in the rock with no discernible offset either side of the crack.

Soil on Gabriola is often sparse. It is derived from surface weathering of the bedrock since the end of the ice age, from glacial till, or from very small areas of sand and gravel deposited by copious flows of glacial meltwater. The soil is rarely thick enough to retain significant amounts of groundwater though it may in places support sub-surface flows of water, sometimes identified as springs.

### *Groundwater movement*

Fractures in the sandstone, usually spaced several metres apart, are major conduits for groundwater flow. The shale is also heavily fractured, but the fractures in shale are tighter and far more numerous than in the sandstone. Groundwater can flow both horizontally and vertically through the fractures, and horizontally (more or less) along the weathered bedding planes of the interbeds mentioned above. Because the island's bedrock is so heavily fractured, most groundwater moves through, and is stored in the fractures, rather than in the rock itself.

An important hydrological characteristic of the Gabriola bedrock is that water flows more rapidly through the sandstone fractures than through the maze-like tight microfractures in shale, with the result that flowing water often backs up in the sandstone at the sandstone-shale interfaces. The contacts between the Gabriola and Spray Formations, and the Geoffrey and Northumberland Formations are commonly good places to look for groundwater. Exposures of such contacts in cliff faces are often associated with springs and groundwater seepages.

In terms of water table, at the most simplistic level, the entire island stores water in fractures that accumulate water during the winter rains. Water generally flows slowly through the fractures from the high centre of the island downwards and out to the edges of the island. In the winter, this flow is intense. The flow tapers off in the

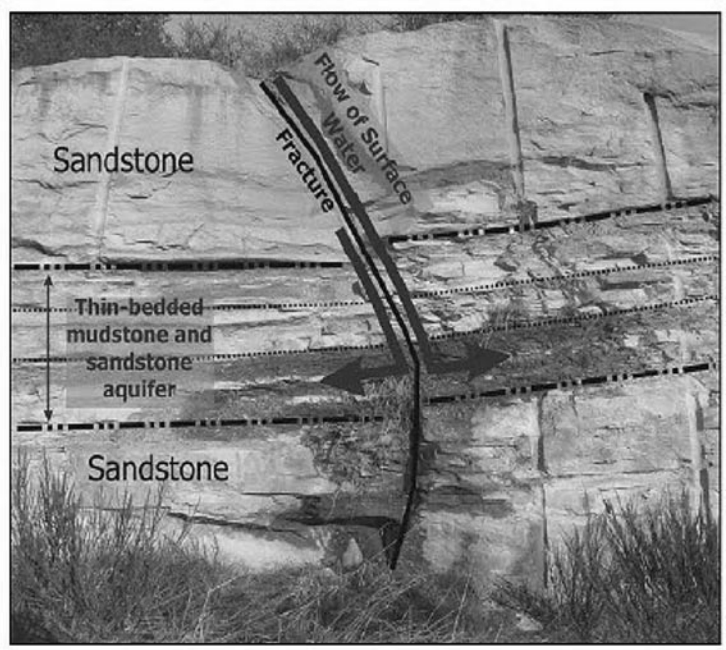


Figure 3: An excellent illustration of the role of fractures and interbeds in the hydrology of the Nanaimo Group rocks.

From Denny & et al, 1999.

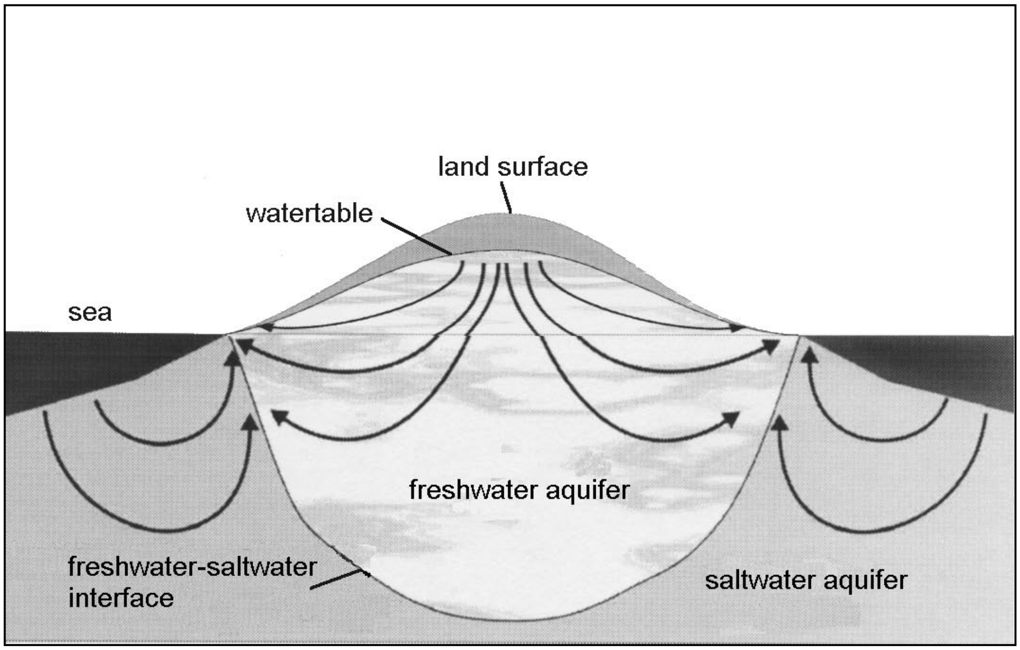


Figure 4: A very idealized model of an aquifer beneath an oceanic island. It has the form of a lens of freshwater maintained by a delicate balance of water pressures. At all points on the freshwater-saltwater interface, the column of freshwater (measured from the interface up to the watertable) is slightly 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. An aquifer in fractured and heterogeneous bedrock of the kind that Gabriola has makes for a far more complicated picture than is implied here.

Doe, p.39, 2008. Adapted from Allen & Matsuo, 2002.

spring as precipitation diminishes, and becomes minimal in the summer dry periods.

All of the groundwater of Gabriola is derived solely from precipitation on the island; there are no underground conduits to locations on Vancouver Island or the Mainland, or even to Mudge Island. It is thus more useful to think of the groundwater, not as a vast underground lake, but as a slowly trickling, braided, mostly-vertical river that depends on precipitation to maintain its flow.

Groundwater very deep beneath the island likely forms a lens of freshwater bounded by saltwater (see Figure 4). The salt-freshwater interface below the shoreline is steep, dipping towards the centre of the island. In summer, when there is less precipitation, the water table drops, and the pressure that is maintaining the lens of freshwater lessens, and so the volume of the lens shrinks. As the salt-freshwater interface moves upward and inland, saltwater can intrude into the deeper wells near the shore. Once saltwater intrusion has occurred, it is difficult to displace the saltwater later. Well-owners need to be aware that saltwater intrusion is not always easy to detect by taste alone. The simplest reliable way to monitor changes in salinity is to use an electrical conductivity meter designed for the purpose.

The volume of the lens is quite sensitive to the amount of precipitation. In the early-Holocene, ten to seven thousand years ago, the climate was warmer and drier than it is now, and although studies on Gabriola have not been done, we can infer from regional paleoclimate studies on Vancouver Island and in the Fraser Valley that the summer water table was so low that there was no rainforest here, only Garry Oak and Douglas-fir savannah with perhaps sagebrush and grass communities resembling today's interior steppe (Hebda 2007, Mathewes, 2002). Lack of soil development, and hints of a lack of peat development in wetlands on Gabriola in this period support this conjecture.

### *The role of clay*

One other important hydrological characteristic of the Gabriola bedrock is the presence of clay both on and below the surface (see Figure 5). This clay is likely the result of chemical weathering of very fine glacial flour, or of the feldspars in the bedrock.

Clay is almost impermeable compared to the bedrock and so can plug fractures and gather in depressions to form the beds of wetlands and, in one case, a lake. Underground beds of clay or sandstone choked with clay can form "perched aquifers". A perched aquifer has dry rock beneath the impermeable layer that supports it, and the water is not in contact with the sea as implied by the diagram in Figure 4.

Probably many or most aquifers on Gabriola supporting relatively shallow wells are perched, and the amount of water in them depends heavily on the amount of summer precipitation, how much evaporation is taking place, and the demands of vegetation for soil moisture. In the winter, perched aquifers fill rapidly and overflow. They then support seasonal creeks. Not all of these seasonal creeks on the island are at the surface, especially when the bedrock is sandstone as it is in the centre of the island.

### *Mapping aquifers*

In practice, local variations in the geology and the connectivity of different rock units horizontally and vertically will mean that any local situation can, and usually is, very complex. Any map of Gabriola's aquifers would have to be three-dimensional and

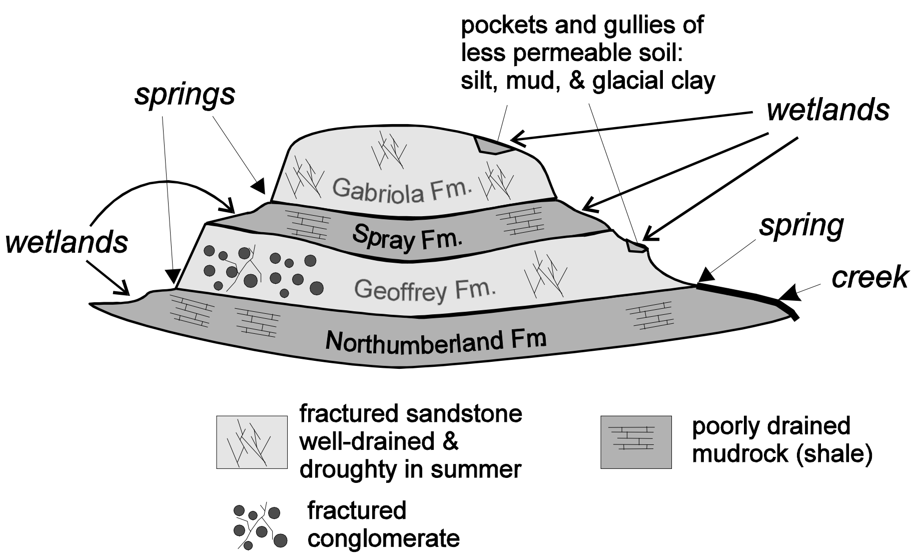


Figure 5: Gabriola's varied bedrock, together with clay soils, (gleysols) lead to the formation of creeks, springs, and wetlands.

Doe, p.18, 2006.

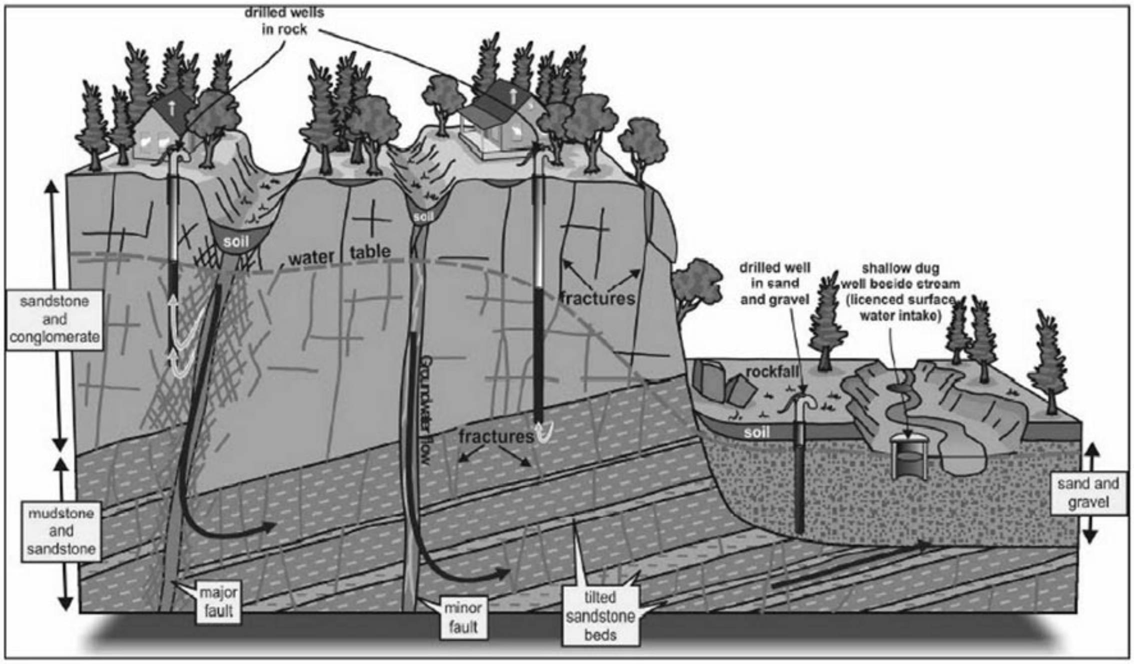


Figure 6: Illustration of some, but not all, of the complexities of groundwater flow in fractured rock. On Gabriola, “sand & gravel” is more likely to be “till and clay (gleysol)” and very few wells are not in the bedrock. Not shown are springs where the water table reaches the surface, commonly at the sandstone-shale interfaces. On Gabriola, some groundwater flows down towards the centre of the island (left on this diagram) and this may play an important role in maintaining the “core” water deep beneath the island.

From Denny & et al, 1999.

have a very large scale; wells just tens of metres apart can have very different yields and need to go down to very different depths to find water (see Figure 7). In places, aquifers can become confined or semi-confined and water can flow up as well as down under pressure. In these situations, the interconnectedness of the networks of fractures, or lack thereof, cannot be established without extensive testing locally for at least a full seasonal cycle.

Perched aquifers will occur where the downward flow of water is impeded by clay, as already mentioned, or by unfractured sand- or siltstone interbeds. Even when major sources of groundwater are being tapped by wells, there can be dry layers between water-bearing layers at different depths. The ability of water to flow through sandstone will depend on the nature and density of the local fractures. Some fractures may be cemented shut by weathering or clogged with fine material known as “gouge” which creates a barrier to the flow of water.

### *Mineral content*

The mineral content of Gabriola groundwater is largely determined by how long the water has been in contact with the bedrock. Although well drillers occasionally come across isolated pockets of stagnant (connate) water, most potable groundwater from wells of normal depths will only be a few years old at the most. Groundwater contains relatively high concentrations of calcium, magnesium, and bicarbonate ions, which are actively stored

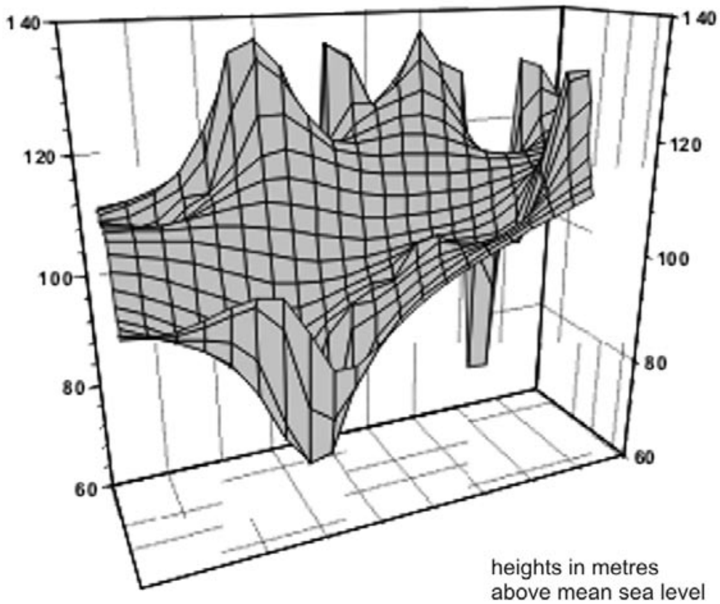


Figure 7: The chart, left, illustrates the problem of mapping aquifers. It shows standing-water levels in a cluster of twenty wells in an area of about 600 × 300 m. The "water table" in the wells shows a height variation of over 70 metres, indicating that the interconnectivity of the water-filled fractures in this area is either very directional along fractures or largely non-existent. Some of the local aquifers here are perched.

Doe, p.41, 2008.

and re-cycled by vegetation. As the water matures in the rock, positively charged ions (cations) will be replaced by sodium ions, which are possible remnants of seawater left over from the late Pleistocene when sea level was some 100 metres higher than it is at present. Sodium together with chloride ions is a strong indication of modern saltwater intrusion.

Sodium raises the pH of the water from the near-neutral or very mildly acidic surface levels, and an increase in pH may be accompanied by a rise in the concentration of fluoride and boron in the water, which can become a health concern. Selenium is another trace element that may occur in elevated concentrations close to, or slightly above, recommended limits. There is also some arsenic in the local groundwater, but natural levels are usually below those deemed a hazard.

Other concerns are the possible concentrations of aluminum leached from soil. In general, high concentrations of aluminum are found in turbid water—the bedrock of Gabriola has high concentrations of aluminosilicates. The concentration in some wells on Gabriola exceeds Health Canada operational guidelines. Also of concern, although for aesthetic reasons rather than health reasons, are high concentrations of iron from weathering of ferromagnesian minerals in the bedrock, and high levels of manganese deposited during oxidation of anaerobic meltwater during de-glaciation.

Hydrogen sulphide gas, which smells like rotten eggs, and methane may come from fossil vegetation in the bedrock. This material would have originally been carried down the rivers in floods, as a tree for example, and buried in the sand, eventually to become a small lens of coal in the sandstone. Hydrogen sulphide may also be generated by modern vegetation when water in a well is not regularly replenished and its oxygen content is depleted by microbes.

## *Climate change*

The coming changes in Gabriola's climate will probably not greatly alter the amount of precipitation Gabriola receives, but most climate models predict that the rainfall will become more seasonal—more rain in winter and less in summer. So far however, there is no evidence that this is happening. The most certain prediction of the likely effect of climate change is a reduction of groundwater due to increased evaporation and transpiration by plants because of warmer temperatures.

Often overlooked in groundwater studies is the possibility of multi-year droughts. A study of tree-ring data in the watershed of the Columbia River has correlated low-growth rates with lower flow levels in the river (Gedalof, 2004). The study has shown that there have been six multi-year droughts in the past 250 years, but none since 1950. The two longest droughts, almost a decade long, were in the 1840s and 1930s. Maybe significantly, it was around 1830–40 that the large Snunéymux$^{w}$ village at False Narrows was abandoned; and it was during the most recent multi-year drought in 1938 that Gabriola experienced a large wildfire. Aerial photographs of Gabriola taken at the time show dried-up swamps. The data in the Columbia paper correlates well with tree-ring data obtained from a large Douglas fir along El Verano Drive—the effects of the 1840s and 1930s droughts are clearly shown. The authors of the study conclude that there is no reason to think that multi-year droughts won't occur again despite the fact that we have not had one recently.

## *Concluding remarks*

In summary, Gabriola's aquifers are complex. Most aquifers contain relatively "young" water that is recharged by winter rain flowing downward through fracture systems every year. Most water is contained within fractures because the sandstone on Gabriola has very little space between the sand grains and is packed with clay and comminuted (crushed) rock fragments. The horizontal connectivity of the aquifers is controlled by the fracture systems, which are complex. The sensitivity of a particular area to overuse of water will be controlled by the volume contained in the particular aquifer being tapped and by fractures of high connectivity within the aquifer. In some cases wells that are close together (a few hundred meters) may be tapping different water sources and have very little effect on each other. In other cases, where there is a larger volume being tapped by wells, the zone of influence of one well on others nearby may be much greater. The use of explosives in an attempt to increase fracture density can easily have adverse effects on near-by wells. Mapping the sensitivity of the water table to overuse requires testing as part of a detailed hydrogeologic study. It is unlikely however that such detailed mapping could be accomplished for the whole island at reasonable cost. Because Gabriola's aquifers are being recharged solely by rainfall, any change in precipitation patterns because of climate change will significantly affect the productivity of our aquifers. ◊

## *Glossary*

**aquifer**: rock, or unconsolidated sediment such as sand or gravel, that contains groundwater and which is sufficiently permeable for the groundwater to be extracted in useable quantities

**basement rock**: the rock formation, invariably igneous or metamorphic, underlying any sedimentary formations. The basement rock is commonly very deep and seldom of interest in groundwater studies

**bedrock**: the first solid rock encountered just below any soil that is present and extending down to the basement rock

**bicarbonate:** an ion of $HCO_3^-$. Calcium carbonate ($CaCO_3$) partially dissolves in groundwater and the bicarbonate ion is one of the components produced

**catchment**: an area bounded by a divide across which surface water does not flow

**clastic**: made up of an accumulation of particles of transported weathering debris

**confined aquifer**: aquifer in which the water is under pressure contained by an overlay of relatively impermeable rock. The pressure is generated by gravity, that is, the water in the aquifer is coming from somewhere uphill of the site

**connate water**: in the context of groundwater, connate water is water trapped in a void or fissure that is not regularly refreshed or replenished. Such water is not potable

**dip-slip**: motion on a fault along the vertical direction of the plane of the fault

**discharge:** the movement of groundwater to the land surface or into the sea

**divide:** a vertical or near-vertical boundary separating groundwater flow systems

**fault**: a fracture or fracture zone in rock along which movement has occurred

**fracture**: any kind of crack in a rock including joints and all kinds of faults

**groundwater:** water that exists in the soil and rocks below the water table in a zone of saturation

**hydraulic conductivity:** a measure of permeability

**hydrological cycle**: the never-ending global circulation of water involving oceans, rivers, and the atmosphere

**hydrostatic:** pressure caused by the height of a column of water. Freshwater is lighter than saltwater and therefore floats on saltwater

**impermeable:** unable to transmit water. Impermeable rock, or impermeable unconsolidated sediment such as clay, may contain water, but there are no easy passageways through which the water can flow

**interbed**: a thin bed of sedimentary rock different from the host sedimentary rock. Rock with no interbeds or fractures is called "massive"

**lithified:** lithification is the process by which sediments are converted into sedimentary rock by compaction, de-watering, and cementation over long periods

**meteoric water**: the technical term for water that is precipitated as rain, snow, hail, or dew. It is understood that the precipitation is fairly recent, that is, the water is not "fossil" water of great age

**mudrock:** "Mudrock" is a general term for rock with particles finer than sand and includes siltstone (mostly silt), claystone (mostly clay, laminated or not), and mudstone (silt & clay). Most "shale" on Gabriola is claystone, sometimes only vaguely laminated, with interbeds of siltstone or mudstone, and commonly with dykes of fine-grained sandstone

**perched aquifer**: an aquifer that is prevented from draining downward by a layer of impermeable rock or sediment such as clay

**permeable:** able to transmit water. Permeability is a measure of the degree to which water-containing voids and fissures in the rock are interconnected

**porous:** containing voids that may contain water. The degree to which the voids are interconnected determines the permeability; a porous rock or sediment is not necessarily permeable

**recharge:** the refilling of an aquifer with meteoric water

**sandstone:** a clastic sedimentary rock made up mainly of sand-size (1/16 to 2 millimetre diameter) weathering debris. Environments where large amounts of sand can accumulate include beaches, deserts, flood plains, and deltas. On Gabriola, the sandstone is usually medium-grained, rich in feldspars, and cemented with clay except very locally in often-abundant concretions where the cement is calcite. The surfaces of the rocks including the fracture faces are commonly “case-hardened” with limonite derived from modern weathering of the iron and manganese minerals

**sedimentary rock**: technically clastic sedimentary rock. Rocks formed from sediment, the grains of which have been cemented together by one or more of several kinds of mineral. Sedimentary rocks are classified according to the predominant grain size and are commonly called conglomerates, sandstones, siltstones, or claystones. Although sedimentary rocks are to a degree porous and permeable, they usually only make good aquifers if they are fractured

**shale:** a clastic sedimentary rock that is made up of clay-size (less then 1/256 millimetre in diameter) weathering debris. It typically is fissile, meaning that it breaks into thin flat pieces. The term “shale” is widely used on Gabriola to refer to any “mudrock” regardless of whether it is laminated and fissile, or not. Although not strictly accurate, this is also the usage here

**semi-confined aquifer**: aquifer in which the water is under low pressure contained by an overlay of rock that is not as permeable as that in the aquifer itself. Semi-confined aquifers are sometimes described as being “leaky”

**surface water:** water running on top of the ground or in the top few feet of soil

**syncline:** a trough-shaped fold, concave up, with youngest strata in the centre

**strike-slip:** motion along a fault along the horizontal direction of the plane of the fault

**till:** an unsorted sediment deposited directly by a glacier and not reworked by streams

**transmissivity:** a measure of permeability

**unconfined aquifer**: aquifer in which the contained water is not under any pressure

**water table**: the level below which the rock or soil is saturated with water. Some water tables are perched, that is, the water is not continuously present with depth.

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Note: The geology of several other Gulf Islands is very similar to that of Gabriola's and so pertinent references to groundwater studies on those islands have been included.

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