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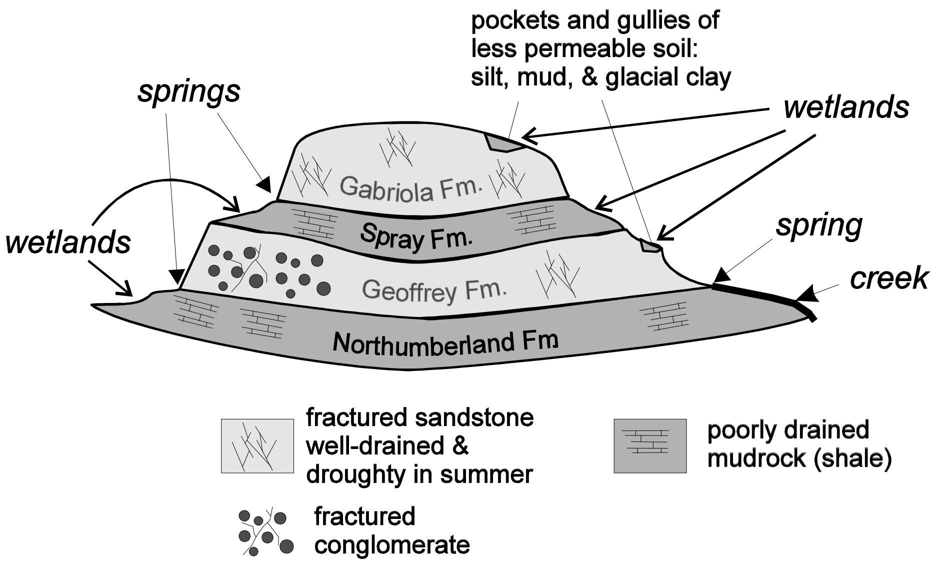
Groundwater budgets

by Nick Doe

That it sometimes rains here is something we all know.[1] We all know too where the rain eventually ends up, at least as far as Gabriola is concerned. It either evaporates, or, one way or another, it flows down to the sea. The less-easy-to-answer questions are: how much evaporates? how much is used by plants, especially forests? how much runs off in creeks and rivulets? and how much soaks into the soil to become groundwater?

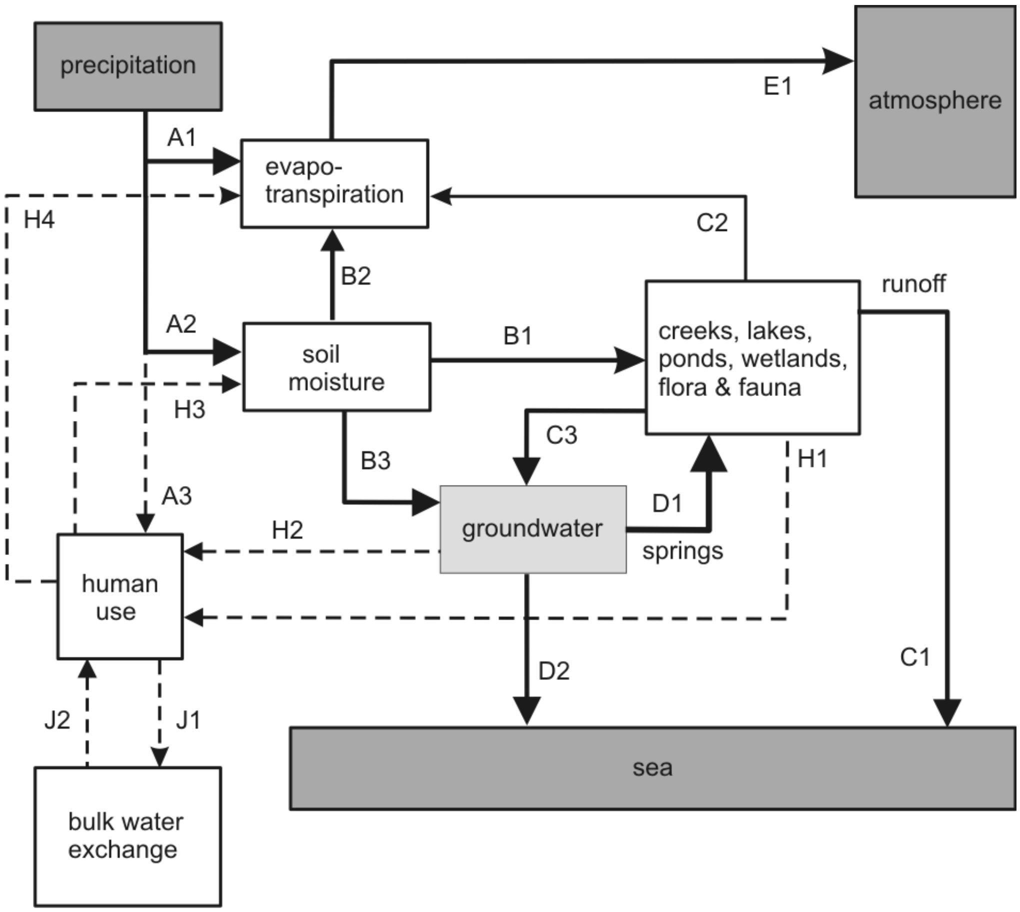
In an earlier note,[2] I surmised that 60% of the precipitation returned to the air; 25% ran off; and 15% became groundwater, but here's an attempt at improving the accuracy of these numbers. Lest you're wondering, why bother? I'm going to show in follow-up articles that, with the help of good water budgets, you can figure out what must go on deep underground in some surprising detail.



Gabriola's hydrogeology: The island's bedrock is fractured and most water travels through, and is stored in, fissures in the rock rather than the rock itself. There are four geological formations (Fm.); two of sandstone (with minor conglomerate) and two of mudrock (shale). In general, sandstone fractures are open—water moves freely through them—while mudrock fractures are far more numerous, but tighter—water moves through the hairline cracks only slowly; consequently, water sinking down through sandstone backs up and sometimes emerges as springs whenever it meets up with mudrock. Although many productive wells on the island terminate in mudrock, wells in sandstone are not uncommon. These exist where fractures are clogged with mud. Sandstone also contains thin interlayers of mudrock that cause water to move laterally along bedding planes.

[1] By "rain", I mean all precipitation, of which we get, on average, 900 mm a year. We should note that in some ecosystems, rain and snow are not the most important contributors of water. Dew, for example, can be vital to the survival of seedlings in dry areas. Fog drip and hoarfrost also contribute moisture.

[2] Nick Doe with Norm Windecker, *Groundwater notes*, *SHALE* 11, pp.37–44, May 2005.



Gabriola's water account: Just as it is possible for a 20-dollar bill to spend a long time circulating in the economy, so it's possible for a molecule of water to spend a long time circulating above and below Gabriola, even though eventually it will end up in the atmosphere or in the sea. A plausible, if unlikely, route would be: fall as rain onto the soil (A2), percolate into the ground (B3), emerge as a spring from the Spray Formation and flow into a pond (D1), be extracted for human use (H1)—*several intimate steps missing here*—soak back into the ground (H3), become groundwater again (B3), emerge again as a spring from the Northumberland Formation (D1), join surface water (B1), and flow in a creek down to the sea (C1).

Once in the sea, it will, on average, be three thousand years before any particular molecule returns to the atmosphere, but having done so, it will usually precipitate within a few days—not necessarily on Gabriola though! Back-of-an-envelope calculations show that the groundwater phase of any particular molecule could last a few years on Gabriola, but not a lot more. On Mudge, which has its own groundwater system quite separate from Gabriola's, it might last no more than a single season.

Water is always on the move and it is a mistake to neglect this and to think of groundwater as an underground lake.

Runoff

Runoff—water that reaches the sea above sealevel—has two major components:

surface runoff, which is water that travels directly from the topsoil or over the bedrock without going underground, at least not to any great depth (it may infiltrate, but it doesn't percolate); and

s*pringwater runoff*, which is essentially groundwater that just happens to be making the final stage of its journey back to the sea as a creek.

In doing a budget, we have to be careful not to count the water from springs twice, once as groundwater (in aquifer *recharge* areas) and again as runoff (in aquifer *discharge* areas).[3]

As you might expect, surface runoff depends very much on the amount of rain we've had in the past few days, while springwater runoff is slower to respond to changes in daily precipitation because water travels more slowly through the ground than over it, and also because groundwater that feeds springs comes from transient storage underground, which buffers the flow.[4]

Runoff, both kinds, is not substantial—there are no whitewater-kayaking opportunities on Gabriola—though there are many seepages of freshwater to be seen on the beaches in winter. There is virtually no runoff anywhere from July to October. What little there is from springs feeding Hoggan Lake can't keep up with evaporation, which we'll get to in a minute.

Surface runoff

A fair proportion of Gabriola's surface is fractured sandstone, with minor amounts of equally-fractured conglomerate, and these fractures keep the surface well drained.[5] In sandstone areas, creeks that are more than just seasonal trickles usually only exist in gullies where the bedrock is overlain with clay or compacted glacial till. These creeks often follow meltwater channels left over from the ice age. So-called "springs" found in areas where the bedrock is sandstone or conglomerate are usually more accurately described as *subsurface flows* carrying surface runoff, springwater runoff, or a mix of both.

Quite a few of the swamps on the island likely feed subsurface flows because although there are no visible outlets to be found, without an outlet somewhere, the swamps would turn into huge lakes in winter.

The impact of development on true surface runoff is likely not that great. The construction of ditches, storm sewers, and paved surfaces increases runoff in urban environments by increasing the speed at which the runoff travels, and by reducing infiltration; however, in rural environments, especially ones like ours where culverts leading directly to the sea are rare and water from gutters and drains soaks into the ground with relatively few signs of flooding,

[3] For historical reasons, the two "kinds" of water are currently managed by two separate groups in Victoria who are not always 100% aware of what the other is doing. Both acknowledge however that surface and groundwater interact and should be managed as one.

[4] We should take care not to exaggerate this however, nearly all springs on Gabriola are seasonal and some only flow when there's flooding.

[5] See *SHALE* 7, p.15 for a map of the geological formations. About 78% of Gabriola is classified as being covered with shallow soil and rock (Agriculture Canada, *Soils of the Gulf Islands*, vol. 4, p.89).

Springwater runoff feeding into Hoggan Lake. The flow here is about 60 L/s. Creeks like these support wetlands, in this case on the south side of South Road both east and west of the lake, and are an indispensable source of moisture for these ecosystems in summer. The "surplus" water entering the lake is used to keep the golf course green, a good example of making as much use of the water as possible before it inevitably returns to the air or sea.

it wouldn't surprise me if infiltration was actually slightly increased by development.[6]

Springwater runoff

"Real" springs, those that come from the bedrock, mostly occur where a contact between sandstone and underlying mudrock is exposed. These contacts are typically found at the foot of steep sandstone slopes overlooking lowland that is underlain by mudrock. Mudrock weathers a lot faster than sandstone, so mudrock landscapes are typically deep-soil farmland, as found on the south end of the island, while sandstone landscapes are shallow-soil uplands, as found in the large new park in the north-central area of the island.

Springs are found where the two types of landscape meet because groundwater travels more rapidly through fractured sandstone than it does through mudrock, so the mudrock underlying the sandstone causes downward-flowing groundwater to back up, pool, and move laterally along bedding planes or through a maze of fissures.[7]

As you can see in the sketch on page 18, the four geological formations that make up Gabriola's bedrock alternate between being sandstone dominant and mudrock (shale) dominant, and so offer two major sandstone-to-mudrock contacts where groundwater tends to gather (Gabriola-above-Spray, and Geoffrey-above-Northumberland).

Mudrock formations may also be a good source of groundwater for a second reason, and although this is still only a conjecture on my part, it is confirmed by a simple groundwater model that I'll describe in another article.

The layered bedrock of Gabriola is gently folded into a ∪-shape trough (a syncline) with an axis that runs the length of the island from close to Silva Bay in the south to Twin Beaches in the north. This trough stores groundwater, and as a result water overflows in the form of springs from the exposed edges of the trough. The highest-volume springs on the island drain throughout the

[6] Checkerauer, pp.107–8. Also to be remembered is that we're talking primarily of runoff from discharge (lowland) areas where, even without development, there would be runoff on account of the poor natural drainage. Urban-style runoff is critical only in recharge areas.

[7] See *SHALE* 11, pp.37–44 for a detailed discussion.

year into wetlands on both the long northeast- and long southwest-facing sides of the island, especially into Lock Bay (Tim Brown's lands) and into wetlands connecting into Hoggan Lake (Clyde Coats' lands). It's no coincidence of course that both named gentlemen belong to long-established local farming families who needed a reliable source of water.

Measuring the runoff

In an effort to determine what percentage of Gabriola's precipitation does run off into the sea (above the surface), I recently measured how much water was flowing into the sea from every creek I could find.[8]
I also measured the flow from dozens of trickles on various beaches, enough to make an estimate of the total flow from such sources along Gabriola's entire shoreline. Many trickles flow at not much more than a litre per minute so individually they amount to practically nothing, but there are hundreds of them in the wet season.

My measurement technique varied according to the flow. I used a stopwatch and a beer glass for the really small stuff; a stopwatch and a bucket for the bigger stuff and for culverts; and a stopwatch, a pair of Wellington boots, a measuring stick, and small leaves and twigs for gauging the flow for the bigger creeks.[9] It was interesting that after a bit of practice, I found I could often make a reasonable estimate of the flow of a creek just from the sound it made—though this didn't stop me from buying a portable flowmeter for measuring the most vigorous flows in mid-winter. Most of the sources I looked at were flowing at less than 10 litres per second (L/s).[10]

I made all the measurements twice. Once in the fall at the start of the rainy season, and once in mid-winter when precipitation was high.

Early in November 2005, over a period of three days during which there was fairly light intermittent rain, I measured a grand total of 287 L/s from 34 creeks plus 12 more that were estimated,[11] and from an estimated 700 very minor sources. For you old-fashioned folk, that's about 3800 imperial gallons per minute (gpm), which isn't an awful lot.

At the end of December 2005, after a week of steady rain, flows were everywhere much higher and I measured 1710 L/s from the same sources plus a few more that were

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[8] There are 18 that run off into the sea for which running, *lotic* rather than *lentic* water licences have been issued: Castell Brook (incl. McClay Brook), Chapple Spring, Claude Spring, Dick Brook, Easthom Spring, Francesco Brook (incl. Harold Spring), Hoggan Creek (incl. Goodhue Creek, Eppler Spring), Ike Brook (incl. Pam Brook, Pam Spring, Darling Spring, McCall Spring), Jacqueline Brook (incl. Windecker Spring), Jenkins Creek, Lobo Spring, Lucas Spring, Mallett Creek (incl. Fiddlehead Spring), Martin Brook, McCormack Creek, Stoney Creek, Vicki Spring, and Wagg Spring. About half of these are minor or seasonal.

[9] The average velocity of water in a creek is roughly the same as the velocity at the surface a third and two thirds of the way across. The peak velocity is below the surface at the centre. Breed, p.542.

[10] One litre per second corresponds roughly to the flow along a gutter during a torrential downpour. Household buckets hold 10 litres (2.6 US gallons). There are a thousand litres (L) in a cubic metre (m^3); 4.546 litres in an imperial gallon; and 3.785 litres in a US gallon. One litre per second is 13.2 imperial gallons per minute (gpm) and 15.9 US gallons per minute (US-gpm).

[11] The runoff from Hoggan Lake is not directly observable because a dam controls the flow so instead I measured the flow of the three springs feeding into it, thereby ignoring evaporation and groundflow losses from the lake. In an island-wide budget, this will generate only a minor error.

previously dry. That's about 22 500 gpm or 1.7 tonnes of water every second!

I also did my best to sort out what was surface runoff and what was runoff from spring-fed creeks, though this was seldom obvious and some creeks carry a mix of water, so I'm not very confident that the results mean very much.

In the fall, I reckoned that only about 25 L/s (9%) was surface stuff, the remaining 262 L/s (91%) being attributable to springs.

At the end of the year, I reckoned that about 659 L/s (39%) was surface runoff, the remaining 1051 L/s (61%) being runoff attributable to springs.

As you can see, the flow of water from springs is quite seasonal, which adds to the difficulty of distinguishing it from surface runoff. It also confirms that groundwater travels fairly rapidly through the fractured bedrock.

litres per second (all units)	Water Allocation Plan	Observed (Plan selections only)	Observed (whole island)
<u>All sources:</u>			
October	8	-	-
November	474	267	287
December	1852	1259	1710
<u>Two major springs:</u>			
October	4	-	
November	215	254	
December	840	796	
<u>Spring runoff:</u>			
October	6		-
November	320		262
December	1249		1051
<u>Surface runoff:</u>			
October	2		-
November	154		25
December	603		659

Table showing a comparison of observed runoff (2005) and figures for average runoff in the BC Government's (Surface) Water Allocation Plan for Gabriola (1994). The observed figures for sources listed in the Plan are, in general, less than those in the Plan, particularly in the summer-to-winter transition month of November. I may also have missed one or two sources. There is however a good match between the December figures in the Plan and the observed flows for the whole island (making up for what I may have missed). Because of this good match, the Plan figures were used as a basis for drawing up the budgets.

Runoff analysis

The first thing I did to sort this out was determine how the total precipitation for the twelve months November 2004–October 2005 compared with the long-term average annual rainfall. Turns out it was slightly above average at 108% but with very little difference in the distribution throughout the year. I just took this to mean that my measurements were made in a fairly average year.

Because surface runoff on any particular day is not so dependent on long-term average precipitation as springwater runoff, the 25 L/s (9%) I measured was probably just a consequence of the rain being fairly light at the time I did the measurements. Several creeks I looked at that normally run freely in winter were totally dry.

Supporting evidence for this came from an examination of the Province's Water Allocation Plan for Gabriola.[12] It lists for November, a combined flow from twelve sources (not all gauged) of 474 L/s compared to my 267 L/s for the same sources, and from the two major springs alone 215 L/s compared to my 254 L/s. In other words, my observed flow of selected sources all over the island was only 56% of that listed in the Plan for November, but for the two major springwater runoffs, it was 118% of that listed in the Plan.

The bottom line here, before we get lost in a maze of figures, is that the surface runoff I observed, although perfectly reasonable for a typical October to November transition period, doesn't tell us a whole lot about average flows either for the month or the rest of the year. However, the springwater runoff I observed is probably typical for an October to November transition period given that the Plan estimates the average October figure to be 6 L/s increasing to 320 L/s for November.

My total observed flow for the Plan's sources scattered over the whole island at the end of the year was 1259 L/s which is 68% of the 1852 L/s listed in the Plan for December, and for the two major springwater runoffs, it was 796 L/s or 95% of the 840 L/s listed in the Plan.

So the Plan's figures are, I think, pretty reliable. In summary, although some of my measurements of runoff from specific sources were lower than those in the Plan (56% and 68%), the results for the major sources agreed well (118% and 95%), as did my total for all sources on the island (61% in a period of light precipitation and 92% in a period of seasonally normal precipitation).

Runoff—the bottom line

How does runoff compare with the total rainfall? Well I reckon we get enough rain to sustain a flow throughout the year of about 1440 L/s (19 000 gpm).[13] So if we accept the Plan figures as being accurate, which the measurement results suggest they are, the total average runoff rate for the year is 533 L/s, or 37% of the total.

However, of this 533 L/s, about 360 L/s comes from springs, and is better regarded as groundwater. It becomes a moot point

[12] Welyk, p.41.

[13] *SHALE* 11, p.37. An annual average of 900 millimetres (mm) over 5075 hectares (ha). Mudge Island is about 220 ha, so its equivalent rate is 62 L/s or 824 gpm. A flow of 1440 L/s (1.44 m^3/s) is about that of a small river; the summer-time flow of the Englishman River on Vancouver Island for example is maintained at not less than 1600 L/s.

as to why we should draw a sharp distinction between runoff that enters the sea above sealevel, and groundwater that enters the sea below it. Both may be a source of water for wells.

Accepting this line of reasoning leaves us with 173 L/s to allocate to surface runoff, or 12% of the total precipitation.

Now about those heavy-breathing trees….

Evaporation and transpiration

In British Columbia, evaporation and transpiration (breathing by plants) are the ways most precipitation returns to the global hydrological cycle. Okanagan Lake, for example, only receives about 21% of the annual precipitation in its entire watershed. The remainder has, one way or another, returned to the atmosphere before reaching the lake. Of this 21%, about half evaporates from the lake's surface, leaving only 11% to flow on down into the Okanogan River.

Evaporation and transpiration from "green" landscapes are often treated together for budgetary purposes, if only because it's difficult to figure out the difference on wet leaves and blades of grass.

Estimating exactly how much precipitation returns to the atmosphere by evaporation or transpiration in any particular locale is an interesting exercise because so many of the factors are inter-related, sometimes in unexpected ways. One study, for example, has shown that the transpiration of birch leaves (alder is more relevant to Gabriola, but figures are not available) is 7.3 times the rate of transpiration from the same weight of Douglas-fir leaves.[14] However, if one looks at the overall rate of transpiration of mature stands of birch and Douglas-fir, the rates are about the same (a stand of birch transpires at 0.9 times the rate for a stand of Douglas-fir). In other words, Douglas-fir leaves transpire much less than the same weight of birch leaves (and presumably alder leaves too), and this allows Douglas-firs to produce many more leaves per unit area of forest than alder in similar circumstances.

Another interesting topic is the effect of logging. On one hand, mature trees pump a lot of water into the air as they transpire; they also intercept rainfall, allowing it to evaporate before it ever reaches the ground (which is why taking shelter under a tree during an unexpected shower works).[15] On the other hand, they provide shade, which reduces evaporation, and they also carpet the forest floor with rotting leaves and other organic matter, which greatly increases the retention of moisture.[16] This effect is particularly obvious in places like the new Nature Reserve on Gabriola—the old-growth forest understory remains green and damp throughout the year, much to the delight of the amphibians there, in stark contrast to the fire-hazardous clearcut areas.

The conventional wisdom is that clearcuts lower the proportion of the precipitation that becomes groundwater because they encourage evaporation and runoff, but on

[14] The numbers in this paragraph come from Kimmins, p.266. Transpiration rates from leaves are measured in kilograms of water per day per kilogram of leaf.

[15] Interception "losses" in BC forests are around 20% of the precipitation. Kimmins, p.261.

[16] I've seen an estimate that the litter alone can store 25 mm (an inch) of rain.

Gabriola it's not obvious to me that this is the case. Most rain falls in winter when evaporation is low, and because the surface is so permeable, surface runoff, as we have seen, is not that great. Although clearcuts do change the seasonality of surface and subsurface flows compared to forests (higher flows in winter and lower flows in summer), it could well be that overall, clearcuts raise the proportion of precipitation that becomes groundwater. Certainly the anecdotal evidence from old-timers is that the flow of water from the major springs on the island, which reflect averaged *annual* rates of groundwater generation, has not been greatly impacted by clearcutting if we leave aside the increased drying up in summer.

Evaporation

Although evaporation alone isn't at the core of our interest here because lakes only amount to 0.5% of the island's surface, it's an entertaining diversion. I managed to get three estimates for the evaporation from a free surface (a pond or lake) in the Gulf Islands. Two of the estimates agree perfectly, but the third was higher.[17] Given that the discordant estimate was obtained from a model used to estimate the evapotranspiration from forests rather than a lake, I think we can happily abandon it.

Lake evaporation is about 730 mm or 81% of the annual precipitation which is why open-water retention areas (ponds) on Gabriola that do not have significant inflow from a larger catchment area dry out. Despite its inflow, golfers can attest to drops of more than a foot in the level of Hoggan Lake in summer, even when it's not being used for watering the greens.

Evapotranspiration

For figures on evapotranspiration, I first consulted the literature and found the following table.[18]

type of forest (deciduous conifer)	summer moisture	annual precip. (mm)	evapotr. %
ponderosa pine, USA	severe lack	1260	46
Coulter pine, USA	severe lack	1230	52
mixed, Switzerland	no lack	1650	52
N taiga, Russia	no lack	525	54
S taiga, Russia	no lack	600	55
spruce, UK	no lack	1350	59
evergreen rain forest, Kenya	modest lack only	1950	81

Evapotranspiration is least when summers are dry (ponderosa pine 46%, Coulter pine in southern California 52%) for although there's lots of warm sunshine, it's to no avail if there isn't any water. We might guess that this also the situation on Gabriola.

The taiga of Russia has a very severe continental climate, so nothing much happens in winter, and there's no shortage of water in summer but not much heat either (North 54%, South 55%).

Lots of water and lots of heat (tropical rainforest, 81%) means, of course, lots of evapotranspiration.

[17] The two sources that agree were the Water Allocation Plan referred to earlier (for Hoggan Lake, the total loss was 700mm) and a map developed for lake evaporation in the US (for the southern Gulf Islands it estimates 760 mm ± 15%. The high estimate was 1000 mm.

[18] Kimmins, p.267.

A closer-to-home analysis was kindly provided by the UBC forestry department. Although they had no model set up specifically for the Gulf Islands, they did have a tested model for the Slocan Lake area in the Kootenays for three different years, one of which, for them a drought year (800 mm of precipitation), fairly closely matched the long-term average conditions on Gabriola (900 mm of precipitation).

For a stand of mature Douglas-fir,[19] the evapotranspiration was 49% with a significant portion of that occurring in winter. When the area was clearcut (simulated) and the trees replaced with a 50% coverage of shrubs and herbs, the evapotranspiration dropped to 33%.

As suspected, although evapotranspiration in a clearcut area on Gabriola is potentially very high, it in fact isn't, and this is because of the lack of surface moisture in summer. This relatively low level of evapotranspiration is compounded by the rapidity with which water infiltrates into the ground through the shallow soil and into fissures.

The lower the evapotranspiration, the greater the amount of precipitation that goes into groundwater, so it's an interesting point that, as our clearcuts revert to forest, groundwater will diminish—surprise! Big trees need water too.

Farmland? In general evaporation from grassland is lower than for a forest because there is no interception from a canopy. On the other hand, transpiration will be higher than for a typical shallow-soil clearcut because farm soil is deep and rich in organic material, and so retains moisture that leafy crops can use in the summer. A typical figure for evapotranspiration is around 40%.[20]

Evapotranspiration—the bottom line

I'd say that about 60% of the island is treed (if not all forested), about 15% is currently clearcut, and the remaining 25%, ignoring houses and so on, is grass- or farmland.[21] This makes the island-wide annual evapotranspiration around 44%, or about 400 mm.

The reckoning

We can only figure out the amount of precipitation that goes into groundwater and returns to the sea below sealevel by seeing what's left after subtracting runoff and evapotranspiration.

The results are shown in the tables at the end of this article. You'll see that I have assumed that in the recharge areas (the uplands) water that eventually emerges as springs in discharge areas (the lowlands) is counted as groundwater; but in those discharge areas it is counted as runoff.

For me, one of the surprises in these numbers is that the total amount of runoff—surface and spring—533 L/s is about twice as much as the 269 L/s that disappears into the ground, something I would never have guessed. Walking around the island in winter knowing this and watching the creeks full to the brim doing their thing, gives one a real feel for the magnitude of our groundwater supply.

[19] The forests of the Gulf Islands are mostly in the Coastal Douglas-Fir Zone (CDF), while those on neighbouring eastern Vancouver Island are in the Coastal Western Hemlock Zone (CWH).

[20] Ministry of Environment website.

[21] Oswald, pp.14–15.

Seasonal conditions

Annual budgets such as the one just constructed are relatively simple to draw up because, on average, there is no change in the quantity of the water stored in the island's aquifers over the course of a year; however, this is decidedly not true over a six-month period. During summer, the aquifers are drawn down by a combination of evapotranspiration (water drawn to the surface) and outflows to the sea (below sealevel) that exceed inflows from precipitation. In winter, they are replenished.[22]

We can make an estimate of how much water is involved in the semi-annual discharging and charging of the aquifers by drawing up two separate budgets, one for summer, one for winter. The sum of the groundwater flows in the two budgets then corresponds to the average annual flow, while the difference between them corresponds to the seasonal change in water stored in the aquifers.

Conclusion

I'll conclude this article with the budgets, but as I said at the beginning, given reliable budgets, there's more that one can discover about Gabriola's groundwater, so please stay tuned.

Acknowledgements

I should like to thank Brad Seely and Rob Guy in the UBC forestry department for their data and helpful discussion.

[22] I count winter as being October to March, though runoff is highest December to March (1400 L/s); average during November, April, and May (250 L/s), and lowest June to October (5 L/s).

References

Agriculture Canada, *Soils of the Gulf Islands of British Columbia—Soils of Gabriola and lesser islands*, Report 43, vol. 4, British Columbia Soil Survey, 1990.

Charles B. Breed & George L. Hosmer, *Hydrographic surveying and stream gaging*, in *The Principles and Practice of Surveying*, vol. II, 7th Edition, Wiley and Sons, 1953.

Douglas S. Checkerauer & Sajjid A. Ansari, *Estimating Ground Water Recharge from Topography, Hydrogeology, and Land Cover*, Ground Water, pp.102–112, Jan/Feb. 2005.

Nick Doe & Norm Windecker, *Groundwater notes, SHALE* 11, pp.37–44, 2005.

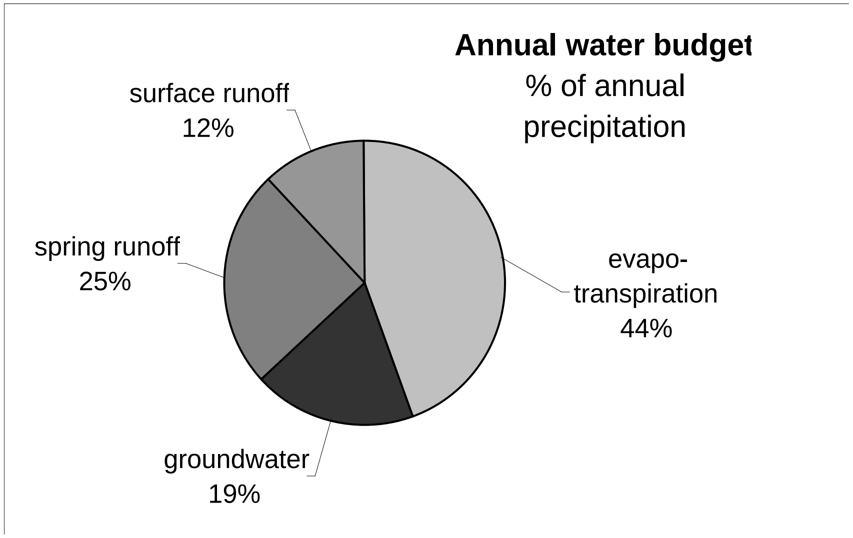
Patrick A. Domenico & Franklin W. Schwartz, *Physical and Chemical Hydrogeology*, Wiley and Sons, 1990.

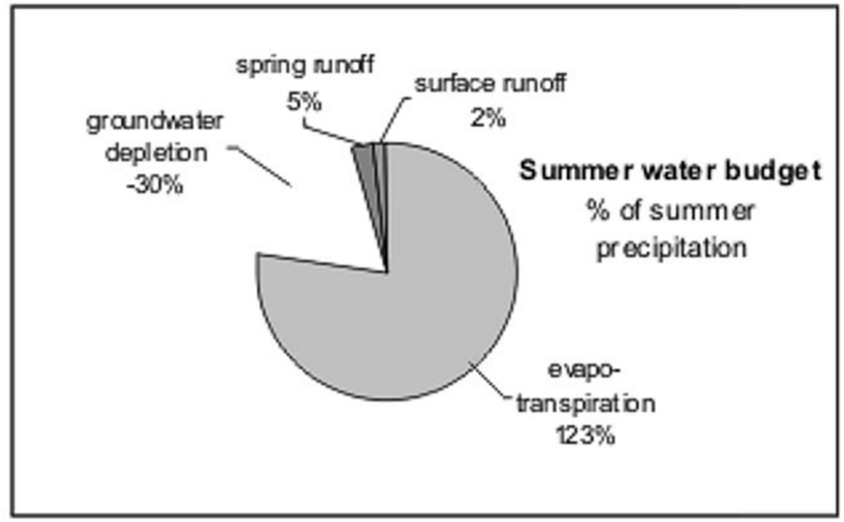
George M. Hornberger, J.P. Raffensperger, P.L. Wiberg, & K.N. Eshleman, *Elements of Physical Hydrology*, John Hopkins University Press, 1998.

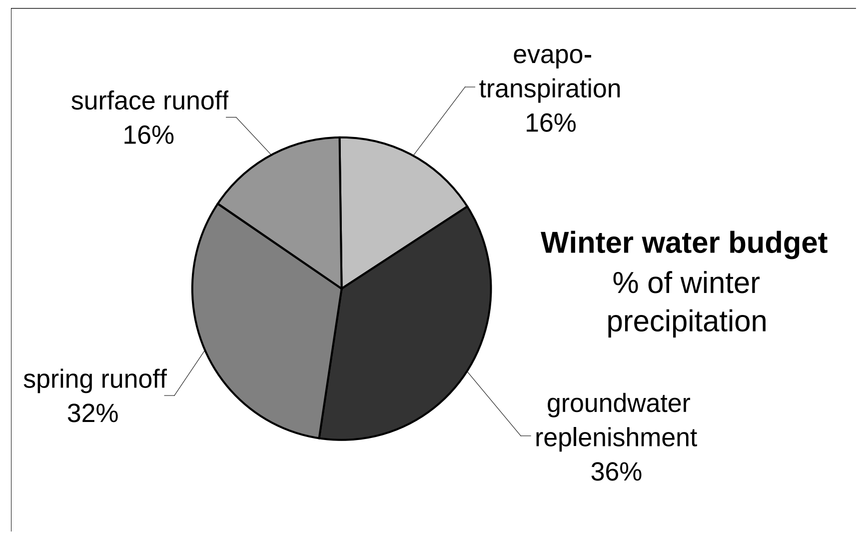
J.P.Kimmins, *Forest Ecology—a Foundation for Sustainable Forest Management and Environmental Ethics in Forestry*, edition 3, Prentice Hall, 2004.

E.T. Oswald, *Gabriola Island and neighbouring islands—a landscape analysis*, Environment Canada, 1977.

Tammy-Jo Welyk & John Baldwin, *Gabriola, Valdes, Thetis, and Kuper Islands, Water Allocation Plan*; Ministry of Environment, Lands, and Parks; March 1994.







Annual, summer, and winter water budgets (island-wide flows).

The depletion of the aquifers in summer and replenishment in winter is an indication of how dynamic Gabriola's groundwater is. Given a few winters with no rainfall, the watertable would rapidly sink below the point at which forests could survive. An interesting speculation is that during the hypsithermal period which lasted from about 9000 BC to 3500 BC (*SHALE* 2, p.29–30) such arid conditions prevailed and Gabriola was indeed without forests. This might account in part for the present-day lack of topsoil in the interior of the island.

Forested uplands (60% of island):

Annual	%	mm	L/s	L/s runoff
evapotranspiration	49	441	423	
groundwater[1]	39	351	337	
surface runoff[2]	12	108	104	104
	100	900	864	104

1. Including water that re-emerges in springs.

2. Surface runoff from upland (recharge) areas is likely slightly less than quoted here because the water has further to travel and thus has more opportunity to become either groundwater or water vapour.

Clearcut uplands (15% of island):

Annual	%	mm	L/s	L/s runoff
evapotranspiration	33	297	71	
groundwater[1]	55	495	119	
surface runoff[2]	12	108	26	26
	100	900	216	26

1. Including water that re-emerges in springs.

2. Surface runoff from upland (recharge) areas is likely slightly less than quoted here because the water has further to travel and thus has more opportunity to become either groundwater or water vapour.

Lowlands (25% of island):

Annual	%	mm	L/s	L/s runoff
evapotranspiration	40	360	144	
groundwater[1]	48	432	173	
spring runoff				360
surface runoff[2]	12	108	43	43
	100	900	360	403

1. Excluding water that re-emerges in springs.

2. Surface runoff from lowland (discharge) areas is likely slightly more than quoted here because the water has less further to travel and drainage is poorer.

Island wide:

Annual	%	mm	L/s	L/s runoff
evapotranspiration	44	399	638	
groundwater	19	168	269	
spring runoff	25	225	360	360
surface runoff	12	108	173	173
	100	900	1440	533

An annual water budget for Gabriola. Figures for runoff (spring and surface) were obtained from the Water Allocation Plan; figures for evapotranspiration from the UBC forestry department; and figures for groundwater inferred from the need to balance water loss with precipitation. Numbers are %, millimetres (mm) of precipitation, or average annual flow rates in litres per second (L/s). 1 L/s = 13.2 gpm (imperial).

Forested uplands (60% of island):

Winter	%	mm	L/s	L/s runoff
evapotranspiration	18	119	229	
groundwater	67	442	848	
surface runoff	15	103	198	198
	100	664	1275	198

Clearcut uplands (15% of island):

Winter	%	mm	L/s	L/s runoff
evapotranspiration[1]	12	80	38	
groundwater	72	481	231	
surface runoff	16	103	50	50
	100	664	319	50

1. This assumes that the winter loss is as for forests, 27% of the annual loss. In fact, it might be a little less because there is little evaporation from bare ground in winter.

Lowlands (25% of island):

Winter	%	mm	L/s	L/s runoff
evapotranspiration[1]	15	97	78	
groundwater	70	464	371	
spring runoff				685
surface runoff	15	103	82	82
	100	664	531	767

1. Assuming the same seasonal variation as for forests.

Island wide:

Winter	%	mm	L/s	L/s runoff
evapotranspiration	16	108	345	
groundwater[1]	36	239	765	
spring runoff	32	214	685	685
surface runoff	16	103	330	330
	100	664	2125	1015

1. The increase in groundwater (+765 L/s) is made up of the average annual flow to the sea (+269 L/s) plus replenishment of the aquifers (+496 L/s).

A winter (October to March) water budget for Gabriola. Figures for runoff (spring and surface) were obtained from the Water Allocation Plan; figures for evapotranspiration were on the basis of 27% annual, which strictly is only known to be true of forests; and figures for groundwater inferred from the need to balance water loss with precipitation. The data in these tables is less “robust” than the annual figures because it is not known directly how much replenishment of aquifers there is in winter. I have assumed that the flow of groundwater to the sea below sealevel is not seasonal.

Forested uplands (60% of island):

Summer	%	mm	L/s	L/s runoff
evapotranspiration	136	322	618	
groundwater[1]	–38	–91	–175	
surface runoff	2	5	10	10
	100	236	453	10

1. Water is lost to trees, evaporation, and drainage to the sea.

Clearcut uplands (15% of island):

Summer	%	mm	L/s	L/s runoff
evapotranspiration[1]	92	217	104	
groundwater	6	14	7	
surface runoff	2	5	2	2
	100	236	113	2

1. This assumes that the summer loss is as for forests, 73% of the annual loss. In fact, it might be a little more because there is little evaporation from bare ground in winter.

Lowlands (25% of island):

Summer	%	mm	L/s	L/s runoff
evapotranspiration[1]	111	263	210	
groundwater[2]	–13	–32	–25	
spring runoff				34
surface runoff	2	5	4	4
	100	236	189	38

1. Assuming the same seasonal variation as for forests.
2. Water is lost to shrubs , grasses, evaporation, and drainage to the sea..

Island wide:

Summer	%	mm	L/s	L/s runoff
evapotranspiration	123	291	932	
groundwater[1]	–30	–71	–227	
spring runoff	5	11	34	34
surface runoff	2	5	16	16
	100	236	755	50

1. The loss of groundwater (–227 L/s) is made up of the average annual flow to the sea (+269 L/s) less depletion of the aquifers (–496 L/s).

A summer (April to September) water budget for Gabriola. Figures for runoff (spring and surface) were obtained from the Water Allocation Plan; figures for evapotranspiration were on the basis of 73% annual, which strictly is only known to be true of forests; and figures for groundwater inferred from the need to balance water loss with precipitation. The data in these tables is less "robust" than the annual figures because it is not known directly how depleted aquifers are in summer. I have assumed that the flow of groundwater to the sea below sealevel is not seasonal.

APPENDIX (not in the print published version)

Budget figures

In the article, a flow chart appears on page 19, and a set of values for some of the variables in the flow chart on page 29. For example, evapotranspiration, E1, has a value of 44%. However, not all of the variables are so readily evaluated, and because there are more variables in the flow chart than observed values on page 29, there is no unique solution for the values of all the variables. We can however deduce some restrictions to the ranges of values that the variables can have.

Neglecting completely the human use components (dotted lines), the fixed values are:

A (precipitation) = A1 + A2 = 100%

B3 (groundwater) = 19%

C1 (surface runoff) = 12%

D1 (spring runoff) = 25%

E1 (evapotranspiration) = 44%

The algebra intrinsic to the flow chart then requires that:

A1 + C2 < 44%; C3 = 50%; and D2 = 44%

Some solutions are:

A1	A2	B1	B2	B3	C1	C2	C3	D1	D2	E1
0	100	38	43	19	12	1	50	25	44	44
10	90	38	33	19	12	1	50	25	44	44
20	80	38	23	19	12	1	50	25	44	44
30	70	38	13	19	12	1	50	25	44	44
40	60	38	3	19	12	1	50	25	44	44
20	80	42	19	19	12	5	50	25	44	44
0	100	47	34	19	12	10	50	25	44	44
10	90	47	24	19	12	10	50	25	44	44
20	80	47	14	19	12	10	50	25	44	44
30	70	47	4	19	12	10	50	25	44	44

Very little weight should be attached to these numbers without further ground-truthing, but they do indicate that wetlands may play a more significant role than one might expect given their small surface area. These numbers assume that there is no net increase or decrease in internal storage of water in any of the elements (soil moisture for example). They are thus annual averages only.