Memorandum

Ministry of Forests, Lands, Natural Resource Operations and Rural Development
Water Protection, Nanaimo

November 30, 2020

To: Sarah Hardy, Water Authorizations Specialist

File: 58000-38-21/20013567 Gabriola Housing Society

On request, a review was completed of the hydrogeologic assessments and data submitted in support of the application for a groundwater licence for a water supply system for an affordable housing development on Paisley Place, Gabriola Island.

The review consisted of evaluating available documentation related to this application (File 20013567) and the subject aquifer (AQ709) and undertaking additional analysis to assess the primary aspects of concern including: long-term well capacity, potential adverse impacts to adjacent groundwater users, potential hydraulic connection between the aquifer and adjacent surface water bodies in the area of the subject well(s), and well susceptibility to intrusion of saline water or sea water. No field assessment component was completed.

The following information was provided:

- Average daily volume (15.55 m^3/day); and
- Purpose use (waterworks for 24-unit housing complex, 3.24 ha land area);
- Period of use (year-round);
- Well Tag Number (WTN) of the primary production well (WTN 104473; ID 33795).

To formulate my recommendations, I reviewed:

- Available information regarding the application, including technical assessments completed by the applicant's hydrogeologic consultant (listed at the end of this document);
- Hydrogeologic data for the area from Groundwater Wells and Aquifers (GWELLS) database;
- DataBC spatial files in ArcGIS including: Wells, Aquifers, Stream Networks, Water Allocation Restrictions, and Water Rights;
- Preliminary analyses completed by Sarah Hardy, including cross-sections, safe available drawdown calculations, distance-drawdown estimations; and
- Literature including hydrogeologic studies completed for the subject area (aquifer characterization and water budget reports).

1. Site description

The subject property is located at on Paisley Place, Gabriola Island, Lot 1 (PID 028-580-095), lot 2 (PID 028-580-109), and lot 4 (028-580-125), SECTION 19 GABRIOLA ISLAND NANAIMO DISTRICT PLAN EPP11544. The 3.24 ha (8 acre) property is within an area of mixed rural residential, institutional and commercial land use near the Gabriola Island Village, where each lot is supplied by an individual well. A map of the subject site and elements discussed in this review is included in Figure 1.

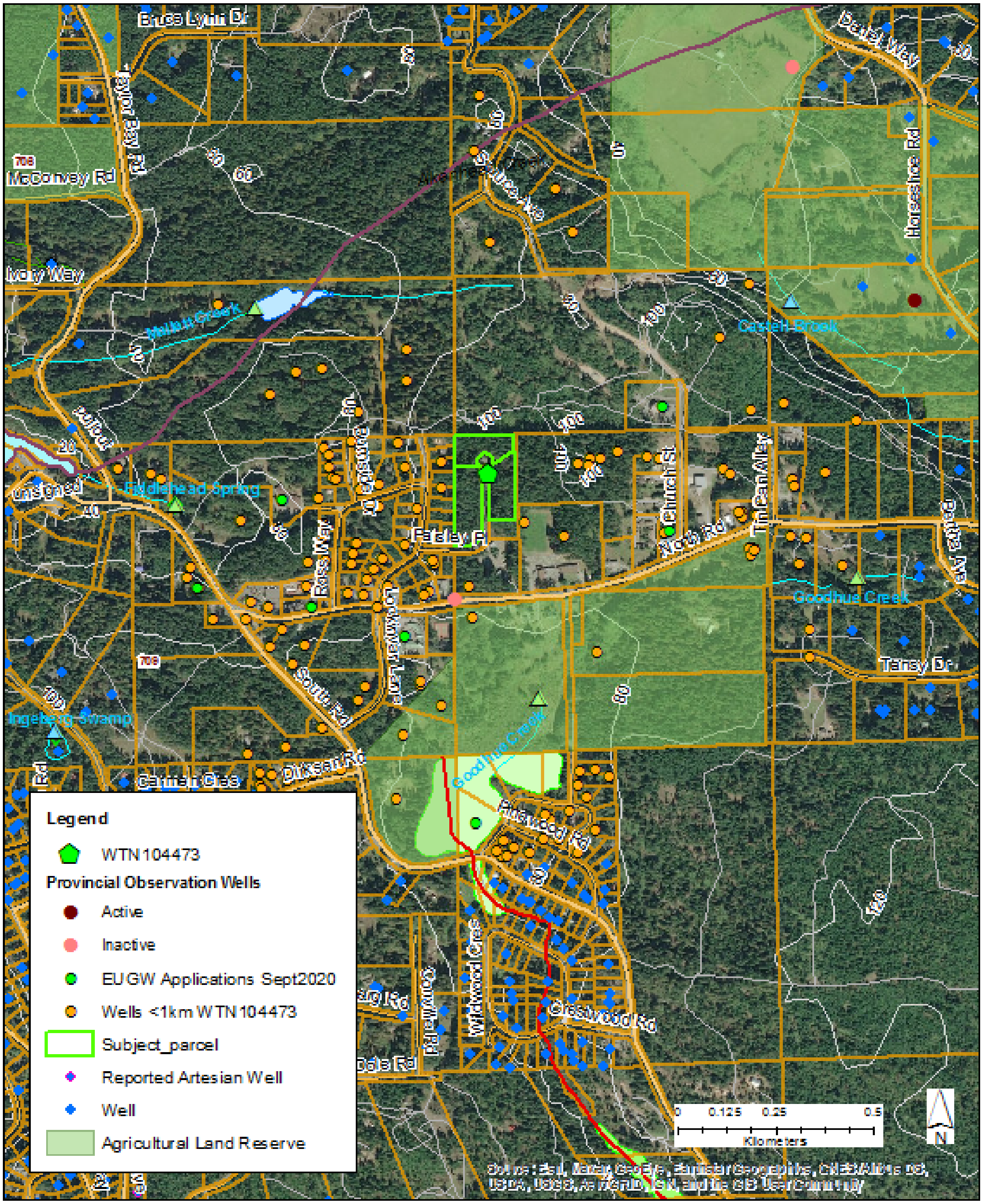


Figure 1: Map of subject area

2. Well and aquifer description

Four wells were drilled to service potential development of the subject properties, initially with the intent to establish one well per parcel, but due to low water-bearing fracture density of aquifer in this area, only one well was determined to be viable to provide water through a shared system. This primary production well is WTN 104473 (ID33728), referred to as Well 73. The well is constructed in sandstone with shale seams, and the principal water-bearing fracture is at 54.86 meters below ground surface (mbgs).

The subject well is constructed in Aquifer 709 (AQ709), a fractured sedimentary bedrock (5a) aquifer composed of sandstone, shale and minor conglomerate of the Nanaimo Group, with a total mapped areal extent of 46.8 km^2 (Province of B.C., 2020). Soil and sedimentary overburden is generally shallow therefore the aquifer has a high vulnerability to infiltration of contaminants from the land surface, geometric mean overburden thickness is 2.4 m for reported wells in the aquifer summarized in the aquifer worksheet (Province of B.C., 2004), and the median depth to bedrock was 1.9 m for wells in the area of the subject parcel as reported in Elanco, 2019. Aquifer productivity is considered low and there is an overall moderate level of well density, with localized areas of higher development.

3. Long-term well capacity

Assessment of Well 73 included completion of a 90-minute step test on September 18, 2019, followed by a 3.9 day (5655 minute) long-term pumping test beginning on September 19, 2019, and sampling of the well for geochemical quality near the end of the long-term test. During the pumping test, three additional wells were monitored, including the three other onsite wells, and a former provincial observation well located at the adjacent road maintenance yard (OW194, WTN26710).

The long-term well capacity of Well 73 was estimated as 2.9 USgpm (11.0 L/min, 15.8 m^3/d), based on the curve of drawdown response during the test period from 400 to 1440 minutes (during period of pumping at a constant rate of approximately 4.75 USgpm) projected to 100-days. I independently calculated the weighted average pumping test rate, safe available drawdown, and long-term well capacity, and obtained results that were consistent with values reported by Elanco (2019). Characteristics of the wells used for the pumping test are included in Appendix A, Table A1, and the well capacity assessment for WTN 104473 is summarized in Table 1 below.

Table 1: Long-term well capacity rating for WTN 104473

	Estimated long-term well capacity*, Q (FLNFR)		**Elanco reported long-term well capacity, Q**			
	L/min	USgpm	L/s	L/min	USgpm	m^3/d
Q_{calc}	11.8	3.1	0.18	11.0	2.9	15.8
$Q_{pump\ (average)}$	19.8	5.2				

There were two different phases of pumping response in Well 73, based on the semi-log plot of drawdown versus time, Elanco (2019, Figure 13). Elanco calculated transmissivity of the aquifer for two three test periods, phase 1 and 2 during well pumping, well recovery. I have verified the calculated transmissivity, both manually using well response interpreted from Figure 13, and using commercially available software Aqtesolv (v. 4.5, HydroSOLVE, Inc.) and drawdown data included in Elanco, 2019, Appendix A2, and obtain consistent values. Storativity was not calculated (not valid) for the pumping well, and continuous drawdown data for Well 72 (observation well) were not provided in the hydrogeologic report. An empirical value of storativity, S=0.0003 is reported from other tests in fractured sedimentary bedrock (Lepitre & Beebe, 2019). Properties of AQ709 determined from the 2019 pumping test, and other sources indicated are summarized in Table 2.

Table 2: Aquifer 709 properties based on pumping test of WTN 104473 and literature values obtained from testing of other wells in Nanaimo Group sedimentary bedrock (5a) aquifers

	Well	WTN	Transmissivity T (m2/s)	T (m2/d)		S (no units)	Comment	Reference
Study well								
Sandstone	73	104473	3.8E-05	3.28		nc	First leg (pumping)	1
	73	104473	2.3E-05	1.99		nc	First leg (recovery)	1
	73	104473	5.2E-06	0.45		nc	Second leg (pumping)	1
	73	104473	2.0E-06	0.17		nc	Second leg (recovery)	1
			9.8E-06	0.84		nc		
Nanaimo Group studies								
			Transmissivity T (m2/s)	T (m2/d)		S (no units)	Specific storage (m^{-1})	
Sandstone -dominant	Geometric mean		1.30E-05	1.12	Min	2.8E-09	3E-06	2,3,4
					Max	1.8E+01		2,3,4
Mudstone-dominant	Geometric mean		9.50E-06	0.82			2E-06	2,3,4
Average compiled sedimentary bedrock (5a aquifer) well tests						0.0003		5
Geometric mean (literature and 2019 test)				*0.92 (6)*				
Literature value (used for analyses)						*1.00E-03*		*7*

Notes and references
nc=not calculated
[1](Elanco, 2019)
[2] (Burgess & Allen, 2016)
[3] (Laroque, Allen, & Kirste, 2015)
[4] (Allen, Liteanu, Bishop, & Mackie, 2003)
[5] (Lepitre & Beebe, 2019)
[6]Geometric mean from Elanco (2019) and Nanaimo Group studies listed.
[7] (Freeze & Cherry, 1979)

4. Groundwater availability and potential impacts to adjacent groundwater users

Elanco (2019) estimated the potential recharge within a 40,000 m^2 elongate capture zone extending upslope from a NW/SE oriented fault that intersects the subject parcel in the vicinity of the subject well (Elanco, Fig 2 & 3, shown in Figure 2 below). He concluded that available storage in the soil and aquifer fractures (1568 m^3) is greater than water use at a rate of 15.21 m^3/day for 100 days (total water demand for 100 days, 1521 m^3, and assuming no additional recharge occurs during that period). I have reviewed the assumptions used for estimation of recharge and water storage in overburden materials, and bedrock fractures, and find the methods consistent with existing literature for Gabriola Island and Nanaimo Group aquifers (Burgess & Allen, 2016; SRK Consulting (Canada)

Inc., 2013). Present estimate of use for application is 15.55 m^3/d (Sarah Hardy, personal communication, November 4, 2020); estimated storage indicated is greater than higher demand level. One possible addition to the water balance methodology could have been to consider current and future climate change related impacts, for example evaluating the water balance with a longer duration of the period with low precipitation (e.g. 180 days).

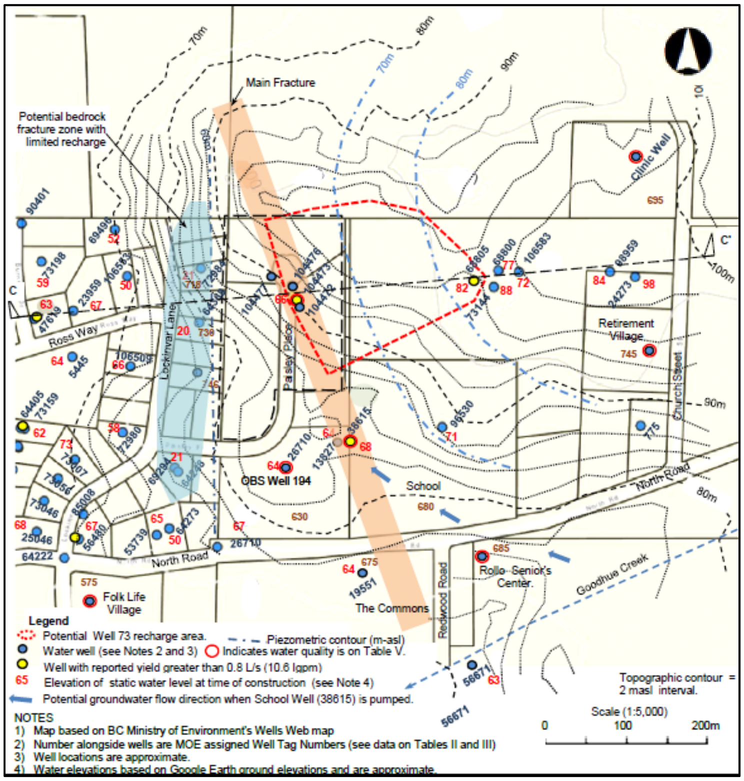


Figure 2: Inferred recharge zone for subject well (from Elanco, 2019, Fig. 3)

There is no active observation well in the Gabriola Village area. Historical conditions in comparison to groundwater development in the village during the period when OW194 was in operation (1973-2007) were evaluated in Elanco, 2019, Fig. 8 and 9, reproduced in Figure 3, below. I concur with Elanco's assertion that the long-term trends in groundwater levels in OW194 are linked to patterns of precipitation and recharge, illustrated by the cumulative deviation from monthly mean, whereby dry season water levels deepen during periods of decreased precipitation (negative departure from the mean), and become shallower during periods of increased precipitation (positive departure from the mean). I note that the overall trend in winter (maximum elevation) water levels appears to be declining over time (green dashed line), and that during latter part of the record starting around 2002, summer groundwater levels are deepening substantially (by approximately 2 m), and that this trend to deeper summer levels continued beyond 2005, despite an interpretation of a wetter phase beginning around that time. A pattern of deepening of summer water levels is being observed in several areas of B.C. and in the Gulf Islands (Allen, Stahl, Whitfield, & Moore, 2014; Lapcevic, Kenny, & Wei, 2006), and may be a result of longer duration dry season, increased rainfall intensity in fall/winter periods or other factors affecting the relative proportions of runoff and infiltration, and due to increases in groundwater demand from new or existing wells.

The closest active provincial observation well is OW385 (Gabriola Island, Horseshoe Road) 1.2 km northeast of the subject site. Groundwater levels in OW385 fluctuate by approximately 3 m annually

(Figure 4) (Province of B.C., 2020). Within the RDN State of Our Aquifers report the long-term trend for this well was rated as declining at a moderate rate -0.045 m per year from 2012-2016, and -0.05 m per year since the well was established in 2010. This decline is attributed primarily to climatic factors (GW Solutions Inc., 2017).

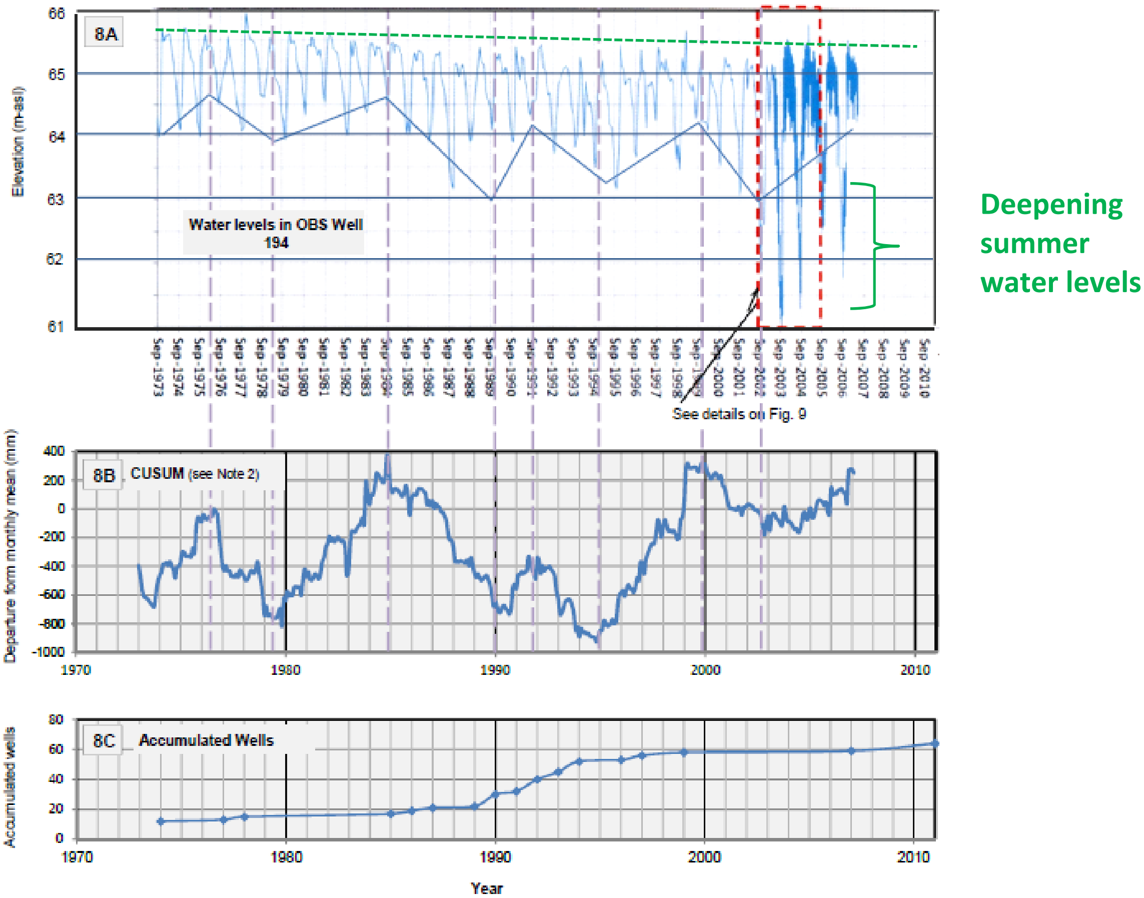


Figure 3: OW194 hydrograph (1973-2010), compared to cumulative deviation from monthly mean (from Elanco, 2019, Fig. 8). Green dashed line illustrates overall downward trend in winter (maximum) water elevation, and highlighted area shows deepening summer water levels.

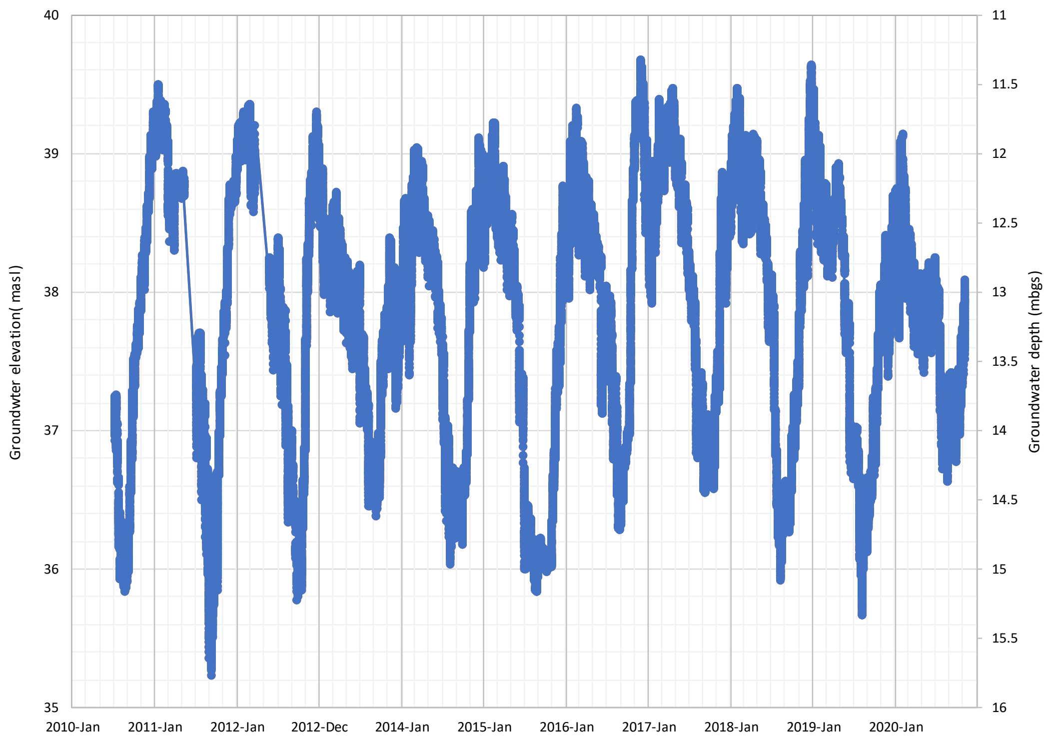


Figure 3: OW385 hydrograph (2010-2020)

A Phase 1 water budget study completed for Gabriola Island in 2013 (SRK Consulting (Canada) Inc., 2013) evaluated the relative seasonal water stress (groundwater demand/recharge) within water sub-regions. The subject parcel is near the eastern boundary within the Descanso Bay water management sub-region, delimited based on the watershed boundary for small (zero- and first-order) streams such as Mallet Creek, which drain toward the Georgia Strait on the northwest end of Gabriola Island. The Phase 1 water budget indicated that water demand in the Descanso Bay sub-region ranged from 1% (winter season) to 9% (summer season) of potential recharge, indicating a low level of water stress. In comparison to the Descanso Bay sub-region as overall, water demand in the Gabriola Village area is likely greater due to the high density of wells and commercial, industrial and domestic groundwater use in that area.

There are 152 registered wells within 1 km of WTN104473, equivalent to a well density of 48 wells/km^2 which is considered high. Well interference and potential for adverse impacts between the subject well and adjacent wells was evaluated within the well testing report (Elanco, 2019), a secondary report (Elanco, 2020), and calculations made by FLNR staff.

The most direct information we have on drawdown with distance from WTN104473 is from the response in adjacent wells during the September 18, 2019 pumping test. The rate of pumping was higher than the projected demand for the proposed water system and ranged from 13.63 to 54.51 m^3/d (2.5 to 10 USgpm), with a weighted average of 28.53 m^3/d, compared to the rate of 15.55 m^3/d (2.9 USgpm) for the application. During the test, drawdown was measured in the pumping well, and three additional wells from 4 m up to approximately 230 m away. The drawdown measured in the pumping and observation wells during the period of maximum pumping rate is tabulated in Appendix A, Table A1. The maximum observed drawdown due to well interference occurred during the period of highest pumping rate, and in wells that were closest to the subject well. The observed maximum drawdown with distance in the observation wells is shown in Figure 4. The observed response at distance from Well 73 is likely indicative of projected interference of pumping between the maximum rate and the weighted average rate, which is significantly higher than the rate being applied for in the application. For this reason, under the design rate for the well, drawdown in adjacent wells in the aquifer is anticipated to be less than observed during the pumping test.

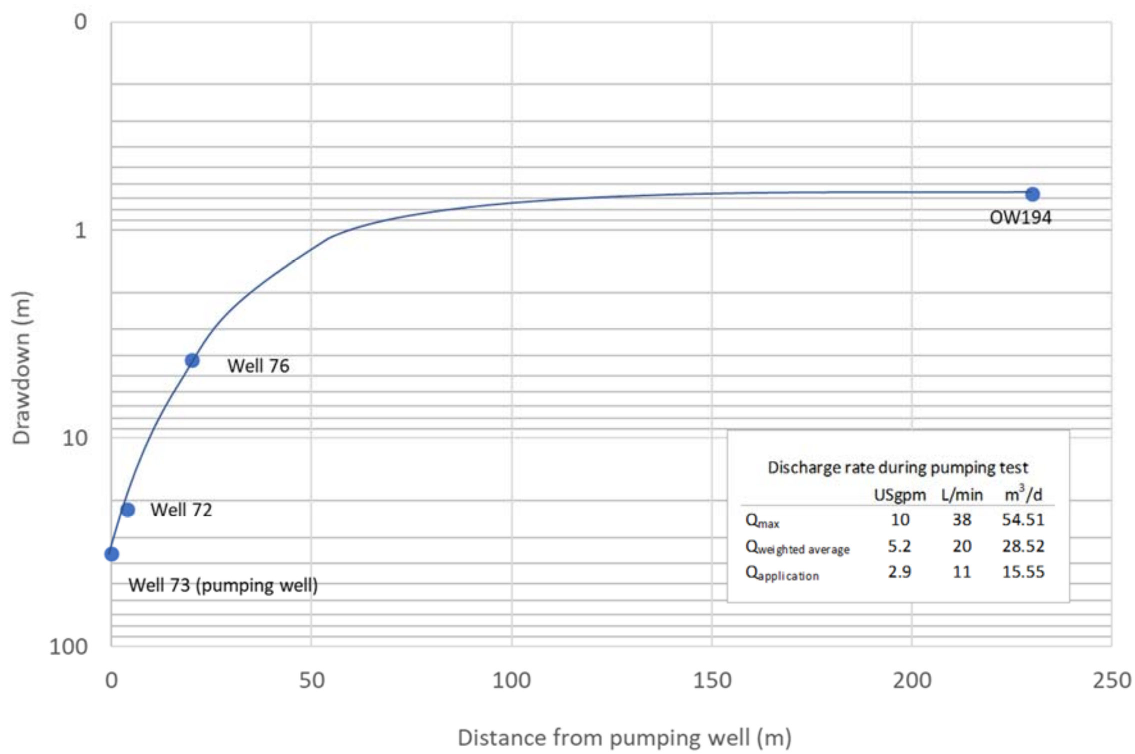


Figure 4: Drawdown with distance from Well 73, based on results of September 19, 2020 pumping test

The degree of potential interference between Well 73 and the well at Gabriola Island School (WTN 96530), reported by Elanco as 200 m to the NNE, was considered by observing the response in Well 73 and Well 72 during a car-wash event at the school in October 2019. Available drawdown in Well 73 and Well 72 was found to decline by approximately 1 m due to pumping of the school well during the car wash event. The rate and duration of the school well pumping during the event was not measured. Under the design pumping scenario total interference from pumping of the School well on Well 73 was estimated by Elanco (2019, Table IV) as 1.5 m, while the potential interference of Well 73 on the School well was estimated as 1.2 m, the latter being equivalent to approximately 3% of estimated safe available drawdown, based on the depth between the historic static water level and the depth of the primary water producing fracture (minus a 30% safety factor). While pumping of Well 73 is not anticipated to adversely affect water availability to the well at Gabriola Island School (WTN96530), monitoring within Well 73, Well 72, and former OW194 (WTN 26710) in comparison to operational information from the school indicates that water levels in these wells are closely linked and that the fracture networks intersected by the wells are interconnected. Well 73 may intersect some deeper fractures, as illustrated by significant difference in water chemistry compared to the school well (see section 6 below). Ongoing monitoring of groundwater levels is recommended understand conditions within the aquifer in this area, to mitigate any adverse impacts as a result of well interference, if they occur, and to evaluate changes over time.

In comparison to unconsolidated (sand and gravel) aquifers, within a fractured rock aquifer the magnitude and direction of interference between adjacent wells can exhibit directionality, dependent on orientation and interconnectivity of heterogenous fracture networks (Allen D. A., 1999). Elanco indicated that the magnitude of drawdown in adjacent wells as a result of Well 73 pumping is likely greatest for wells oriented along the NNW-SSW oriented fault system (red line in Figure 2), whereas wells situated perpendicular to that fault system will likely be less impacted. For example, Well 77, located west of Well 73 which has limited fractures and was hydrofractured to produce a small amount of water, exhibited a dampened response to Well 73 pumping (maximum 3 cm drawdown, approximately 40 m away), compared to Well 76, 20 m from the pumping well which had a maximum drawdown of 4.22 m. OW 194 located approximately 230 m south of Well 73 on the N-S trending fault line, exhibited a maximum of 0.67 m drawdown (Figure 4). Due to the low overall permeability of the bedrock aquifer, the area of drawdown influence around Well 72 is anticipated to be elongated and greater for wells sited directionally along the fault zone, with a lower magnitude of response in wells sited perpendicular to the fault zone.

In response to concerns expressed by residents in the Lockinvar Lane subdivision regarding potential impacts of Well 73 on sustainable water supply in their area, a subsequent technical report was prepared by Elanco (2020). FLNR has received reports from residents within this subdivision of wells with low yields, wells that may go dry seasonally, or that have had to been deepened in response to declining groundwater levels, necessitating use of alternate water sources such as rainwater collection, while other property owners have indicated that they have not experienced problems with water supply but are concerned that increasing groundwater development in this area might cause future problems.

In general wells in fractured sedimentary bedrock aquifers have lower yields in comparison to other aquifer types (Wei, et al., 2009). The productivity of an individual well depends on the number of water-bearing fractures intersected by the well bore, and the connectivity of those fractures with regional fracture networks, through which groundwater is recharged from precipitation events. Groundwater levels tend to be deeper within higher elevation recharge zones and exhibit a greater seasonal range or fluctuation, compared to groundwater levels within discharge zones, which exhibit less seasonal variability, and tend to be closer to the ground surface.

The Lockinvar Lane subdivision, with typical lot sizes in the range of 2000 to 4000 m^2, each with an individual well, is already heavily developed in terms of groundwater use; this area is also at slightly higher elevation and is identified as an aquifer recharge zone in a groundwater flow model that was developed for the island (Burgess & Allen, 2016). Elanco (2019 and 2020) report that wells the elevation of the groundwater table in the wells on the east side of Lochinvar Lane (e.g. WTN72984 and WTN764368) differ significantly from groundwater levels in the wells on the subject parcel(s) and exhibit large seasonal fluctuations (up to 40 m); these Lochinvar wells are believed to intersect a distinct fracture network from Well 73, and therefore are unlikely to be impacted by its pumping.

The Gabriola Village area is an area of high groundwater usage for domestic and non-domestic purposes; for this reason, a preliminary summary of water demand and availability was developed for the 1 km^2 area surrounding the subject well. Annual recharge was estimated as 15% of precipitation over the 1 km^2 area, consistent with previous studies (Burgess & Allen, 2016; SRK Consulting (Canada) Inc., 2013). Precipitation data was based on records from the Gabriola Island (climate normals from 1981-2010) (Environment Canada, 2020). Using zoning maps and BC Assessment Data (B.C. Assessment Authority, 2018a) the land use associated with each parcel was determined. Water demand associated with different land use categories (domestic, industrial & commercial and agriculture) or parcel was estimated based on license applications for existing use groundwater, information on water use on the island from the Phase 1 Water Budget, effluent discharge volume standards from public health, and the BC Agricultural Water Calculator (SRK Consulting (Canada) Inc., 2013; Province of B.C., 2020; Ministry of Health, Health Protection Branch, 2014). Table 3 provides a summary of the water demand analysis. Figure 5 includes the summary of land use categories in the area. Locations of inferred non-domestic water use are shown in blue, domestic parcels in yellow, agricultural parcels cross-hatching. Although it is estimated that there are approximately 51 parcels associated with non-domestic groundwater use, to date FLNR has received 7 applications for existing groundwater use in this area, indicating more education and outreach is needed to ensure these users are able to apply for water rights under the transitioning provisions of the *Water Sustainability Act* (Province of B.C., 2014). Current estimated groundwater demand represents approximately 21% of annual recharge, while the subject application would increase annual demand in the Gabriola Village to approximately 22% of recharge. Based on this preliminary analysis the current water balance (demand vs availability) is considered sustainable.

Table 3: Water demand analysis, Gabriola Island Village

Water Use Type	Number of Parcels	Volume (m^3/d)
Domestic	115	97
Industrial & Commercial	40	102
Agriculture	11	54
TOTAL	166	253

-	Without Application Pumping Demand	With Application Pumping Demand
Total Annual Recharge (m^3/yr)	434906	434906
Total Annual Pumping Demand (m^3/yr)	92401	98077
Demand as % of Recharge	21.2	22.6

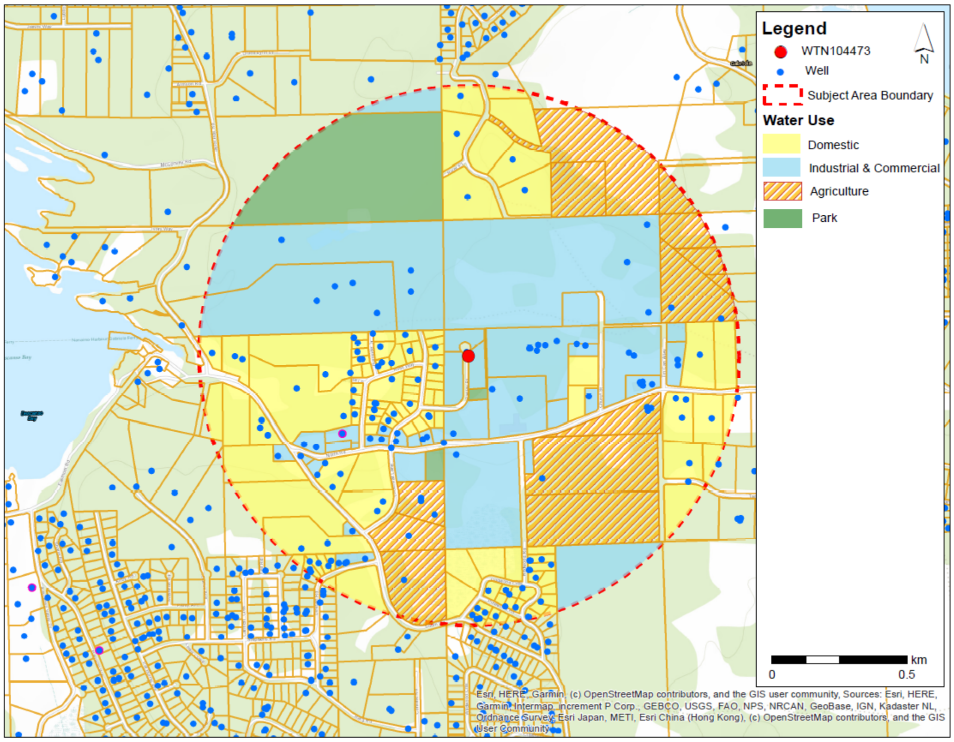


Figure 5: Land-use in the Gabriola Village area, within 1 km of subject well

5. Hydraulic connection to surface water bodies

The guidance document "Determining the Likelihood of Hydraulic Connection" (Province of B.C., 2016), defines hydraulic connection as being: "for the purpose of water allocation and use,… the reasonable likelihood that pumping of groundwater from a well will eventually result in a change in the flow of a stream or spring or change in the level of a lake, pond, wetland that overlies or borders the aquifer, over a time period and to an extent that the decision maker must take into account in considering the environmental flow needs of the stream or whether the rights of other authorized users on the stream are likely to be detrimentally affected."

Aquifers of subtype 5a—made up of fractured sedimentary bedrock—may be hydraulically connected to adjacent surface water bodies if there is no continuous confining layer overlying the aquifer in the area of the stream, or if there is a correlation between water levels in the stream and adjacent wells.

The associated technical assessments and review of wells for this area indicate that overburden sediments are shallow (median <2 m thick) or absent (Elanco, 2019, Province of B.C., 2004). Groundwater levels (static water level at time of drilling) are a median of 6 m bgs within bedrock wells within 1 km of the area. Elanco (2019), Table I and Figure 2, listed surface water licenses associated with streams in proximity to the subject parcel including Castell Brook, Fiddlehead Spring, Goodhue Creek, Ingeberg Swamp, Lucas Spring, and Mallet Creek (Figure 6). Potential hydraulic connection between groundwater and surface water was not explicitly evaluated or described by Elanco. A preliminary determination of the likelihood of hydraulic connection for adjacent surface sources is provided in Table 4, based on information provided in the hydrogeologic reports (Elanco 2019 and 2020), cross-sections of the subject area prepared by Sarah Hardy (Water

Authorization Specialist), and other references as indicated, including surface water mapping available in RDN Map (Regional District of Nanaimo, 2020). Based on the described information, hydraulic connection between the subject well and adjacent streams, and adverse impacts on environmental flows from this application are considered unlikely.

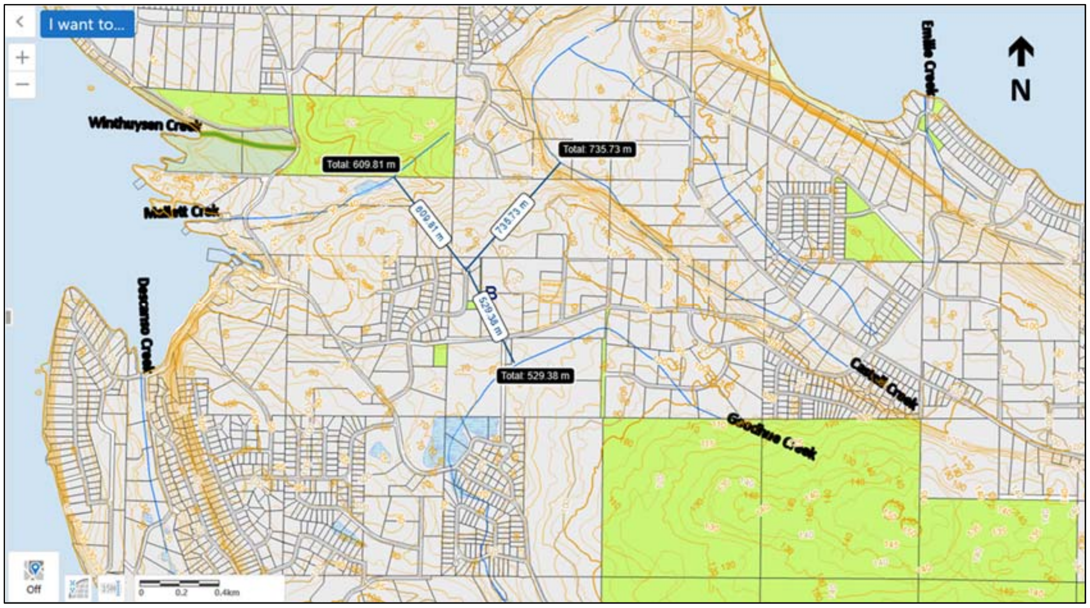


Figure 6: Locations and distance of streams in the vicinity of the subject parcel (excerpted from RDN Map)(Fiddlehead Spring not shown, see Figure 1).

Table 4: Adjacent surface water bodies and preliminary assessment of hydraulic connection

Stream or water body	Minimum distance (direction) from subject well	Likelihood of hydraulic connection to subject wells	Rationale
Castell Brook	736 m (NE)	Hydraulic connection unlikely	Located north of subject property, and flows (direction) into Cox Bay (Descanso Bay). Reported as perennial in lower reaches, while upper reaches are ephemeral and lacking well defined channel. Stream likely perched in comparison to groundwater elevation. Groundwater level in subject wells > 20 m below ground surface.
Fiddlehead Spring	808 m (W)	Unlikely	Sited west and on opposite side of a topographic rise and low permeability zone, away from the subject well. Spring may be present due to topographically driven discharge via shallow soils overlying bedrock which come to the surface at the toe of the slope. Due to distance of well from the spring, deeper groundwater levels in the well and low permeability of the bedrock aquifer, hydraulic connection is considered unlikely.
Goodhue Creek	529 m (SE)	Unlikely	Well 73 is located in a recharge zone for the Goodhue Creek Valley. Provincial mapping suggests creek channel is poorly defined along parts of its course closest to North Road. Due to distance of well from the stream, and low

Stream or water body	Minimum distance (direction) from subject well	Likelihood of hydraulic connection to subject wells	Rationale
			permeability of the bedrock aquifer, hydraulic connection is considered unlikely.
Mallet Creek	610 m (NW)	Unlikely	Well 73 is located in a recharge zone for the Mallet Creek Valley. Due to distance of well from the stream, and low permeability of the bedrock aquifer, hydraulic connection is considered unlikely.

References:
1. Elanco, 2019.
2. BC Freshwater Atlas (2020).
3. Regional District of Nanaimo Public Map Viewer (Regional District of Nanaimo, 2020).
4. Burgess, R., & Allen, D. M. (2016).

6. Groundwater quality and assessment of saltwater intrusion risk

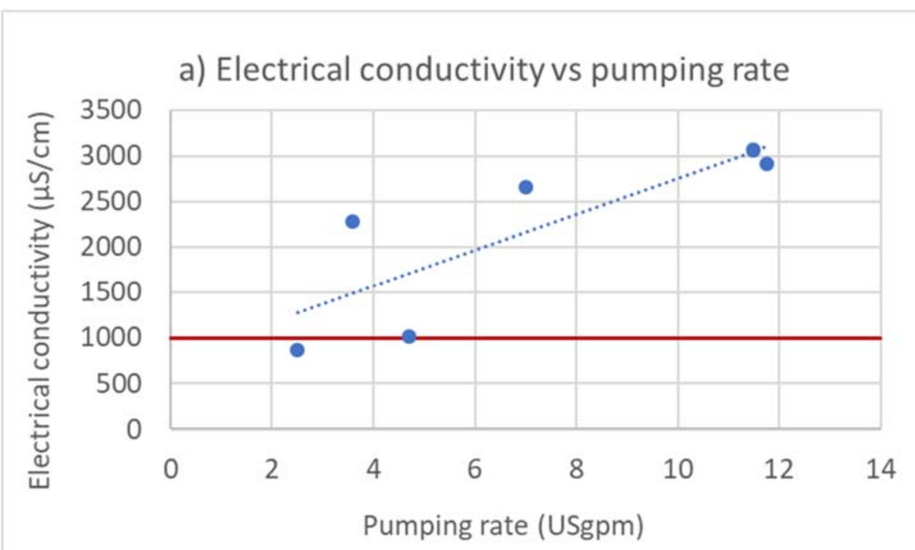
During the step-test of the well, beginning on September18, 2019 specific electrical conductivity (EC) of the discharge measured in the field was as high as 3058 µS/cm indicating that the groundwater from the well was initially brackish. For this reason, a more detailed analysis of aquifer susceptibility and risk of saltwater intrusion at the location was completed using the information provided within Elanco (2019).

Operation of wells while maintaining groundwater quality below established thresholds (EC 1000 µS/cm, TDS 700 mg/L and chloride 150 mg/L) is a best practice promoted by FLNR for protection of fresh groundwater supplies from intrusion of salt water or sea water into fresh aquifers; operation of a well causing intrusion is a violation of the WSA, s. 58, and can cause long-lasting or semi-permanent changes in groundwater quality affecting multiple wells within an aquifer or area. S. 58 applies to saline water that enters the well via fractures interconnected with the brackish transition zone or saline zones of marine water in the subsurface below the island. Mature groundwater with a higher mineral content, or connate, relict sea water from geologic periods of higher sea level may also be present in deeper aquifer formations and produce groundwater with higher salinity. Wells that are constructed in bedrock aquifers are not screened over a specific depth interval but typically intercept multiple fracture zones, therefore the pumping of a well that intersects both fresh and saline fractures may cause mixing and salinization of shallower fracture zones, potentially affecting the quality of water in nearby wells that intersect the same fracture networks. Saline groundwater may also be associated with zones of enhanced weathering and mobilization of minerals such as boron, fluoride and arsenic (SRK Consulting (Canada) Inc., 2013). For these reasons, FLNR evaluates groundwater quality in pumping wells in comparison to the operational thresholds and promotes utilization of best practices to prevent and mitigate the potential effects of intrusion.

A comparison of the well characteristics and physiographic conditions at the site in comparison to saltwater intrusion susceptibility criteria is include in Appendix B, Table B1. From this assessment it is noted that many of the criteria for elevated saltwater intrusion susceptibility are not present at the subject site. For example, the static groundwater level, principle water-bearing fracture and bottom of the wellbore are more than 20 m above sea level, the well is sited inland approximately 1050 m from the coastline.

From the pumping test field parameter measurements and using EC as an indicator of relative salinity within the discharge water, it is noted that the conductivity initially rose during the step test with each increasing pumping rate but diminished toward the end of the long-term test (Figure 7a,b). No correlation was observed between groundwater depth during pumping and electrical conductivity Figure 7c. Chloride and EC exceeded operational thresholds based on laboratory analysis of a sample taken toward the end of the test (4000 minutes). The ionic balance of the groundwater illustrated within a Piper plot (Figure 8), is interpreted to be consistent with mature groundwater.

Elanco (2019) stated that based on the observed decline in EC during the test, and "experience from pumping groundwater in other areas in the Gulf Islands… that the TDS, chloride and the sodium concentrations will decline as fresher water is flushed into the fracture zone." During the test pumping of Well 73, it is estimated that water equivalent to over 100 well volumes was purged from the well prior to sampling. Saline water has a higher well density and stratifies naturally within the well bore but is flushed out during pumping so that following sufficient purging the water quality within the sample is considered representative of water within the aquifer formation. Groundwater quality varies in wells in this area. Water from the Gabriola Island School well is very fresh (median chloride 24 mg/L in samples from 2019-2020), while the well for the Clinic on Church Road which is deeper, has more saline water (median chloride 172 mg/L in samples from 2011-2020, and possibly increasing over time)(data in Elanco, 2019, and obtained from Island Health (Jill Lucko, personal communication, November 22, 2020). Based on this review, while there may be some seasonal variation in groundwater quality, I believe it is unlikely that Well 73 will freshen significantly from the values observed during the end of the long-term test (chloride 176 mg/L) and is likely to continue to have a concentration in the range of the threshold for chloride during well operation.



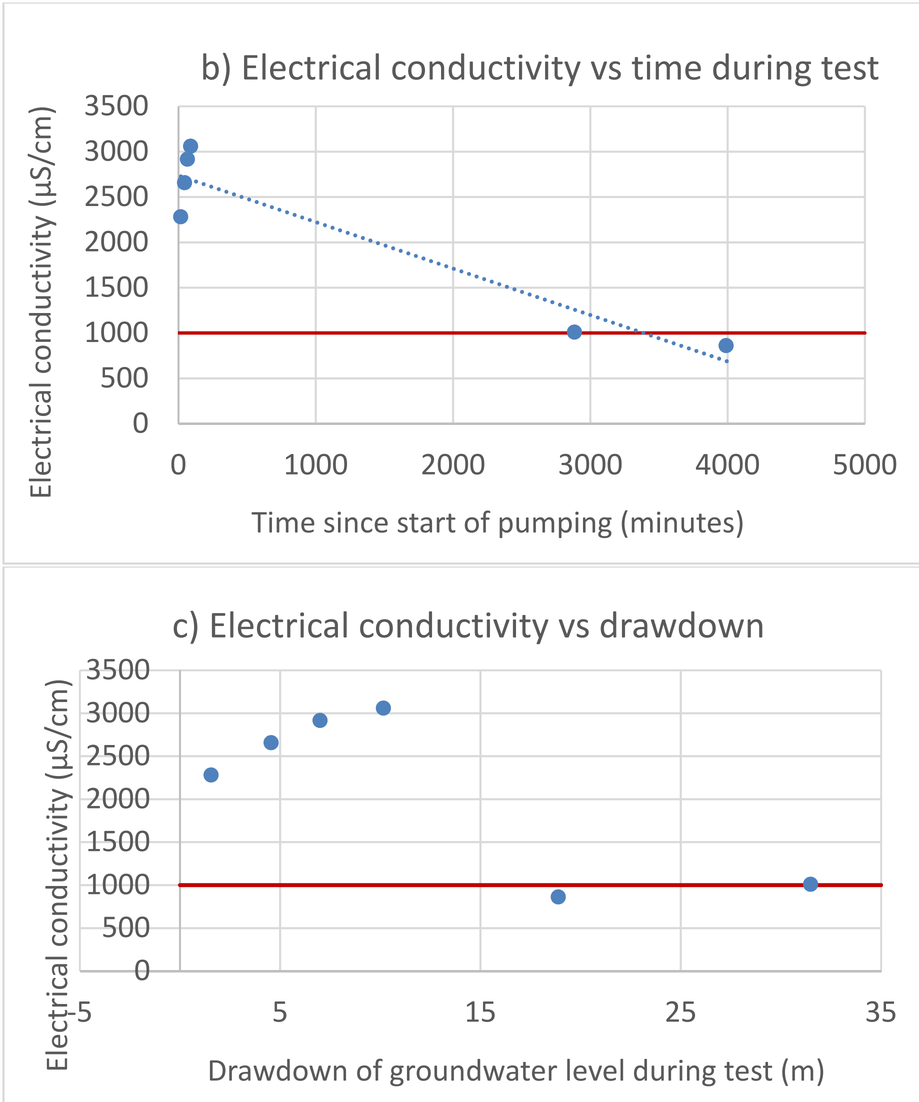


Figure 7: Electrical conductivity vs pumping test conditions (pumping rate, duration, and drawdown)

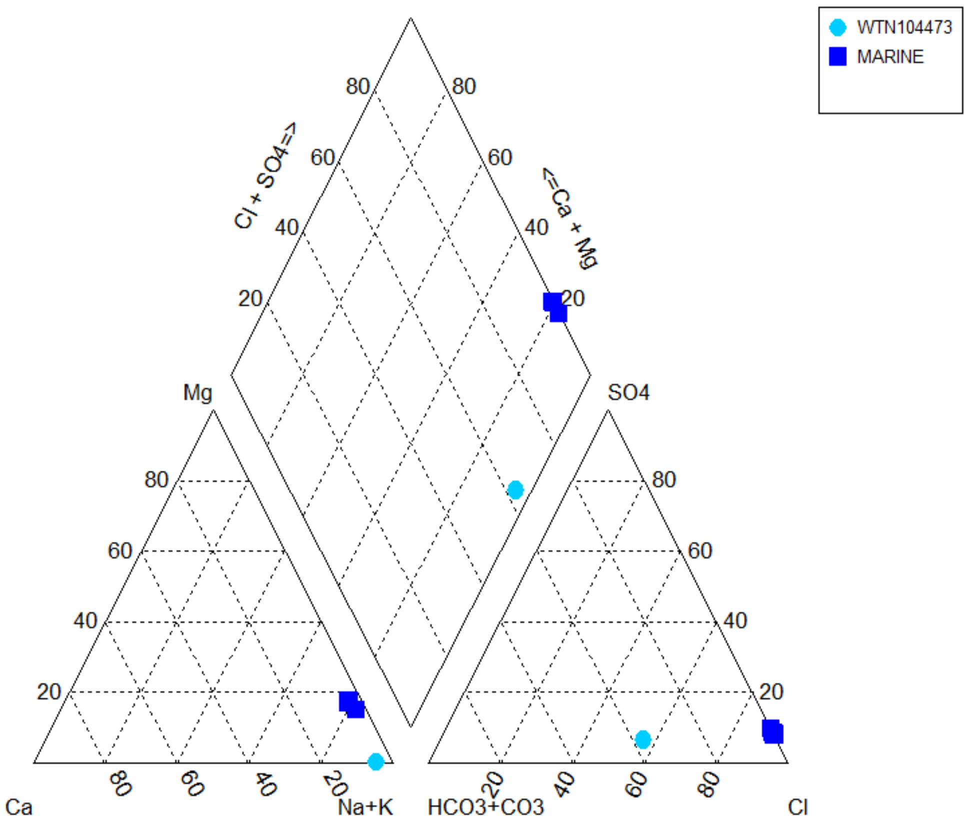


Figure 8: Piper plot showing ion balance in subject well (WTN 104473) compared to sea water

Based on limited available information, groundwater quality from Well 73 is consistent with mature groundwater, that is naturally present at depth within the aquifer in this area. While field parameters (EC) and chloride exceed operational thresholds, it is not believed that operation of the well is causing intrusion, as defined in the WSA. However careful management of water demand, utilizing best practices including deploying the well pump at a shallower depth, regulating maximum discharge rates during pumping, metering usage, utilizing water conservation strategies, developing alternate water supplies and utilizing storage, and sampling of groundwater quality bi-annually (wet and dry season) during the first years of operation to observe if and how groundwater quality changes over time, are recommended to ensure protection of fresh groundwater resources in this area.

Closure and recommendations

Based on a long-term (3.9 day) pumping test completed on Well 73 (WTN 104473) in September 2020, the well was rated to produce 15.8 m^3/d (2.9 USgpm). Based on observations during and following the pumping test, groundwater levels in the well fluctuate in response to adjacent well pumping (e.g. WTN at Gabriola Elementary School), however potential pumping interference from operation of Well 73 is not anticipated to have adverse impacts on adjacent users. Groundwater levels in AQ709 are closely linked to climate conditions and recharge from precipitation, and several provincial monitoring wells in AQ709 have shown long-term declines in annual water elevation or deepening of summer water levels due likely due to influences of climate inputs and groundwater demand. Utilizing one of the unused wells (e.g. Well 72, or former OW194) to measure groundwater levels is recommended to monitor aquifer conditions over time in this area of AQ709.

Due to relatively deep groundwater levels in the subject well, low permeability of the aquifer, and distance from the well, hydraulic connection and adverse impacts of well pumping on surface water licensees and environmental flows in adjacent streams is considered unlikely.

Groundwater quality in the well exceeds operational threshold for chloride, and groundwater quality in the well is consistent with mature groundwater that is naturally present in the aquifer formation at depth. While the water quality in the well freshened from much higher salinity (initial EC >3000 µS/cm) during the pumping test, groundwater sampled from the well had a chloride concentration of 176 mg/L after three days of pumping and is likely to continue to exceed the chloride threshold of 150 mg/L under conditions of normal well operation. Water quality should be monitored during the initial period of well operation, and best practices for prevention of well operation causing intrusion should be implemented, including water conservation, and augmenting water supplies with water from other sources if possible (e.g. rainwater collection).

Respectfully submitted,

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Reviewed technical assessments:

Elanco Enterprises Ltd. December 30, 2019. Re: Assessment of Well Yields on Proposed Housing Development Property, Paisley Place, Gabriola Island, B.C. Prepared for Gabriola Housing Society.

Elanco Enterprises Ltd. August 6, 2020. Re: Concern that Housing Development Well on Paisley Place may have an impact on wells in the vicinity of Lockinvar Lane, Gabriola Island, B.C. Prepared for Gabriola Housing Society.

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Appendix A: Data tables

Table A1: Test well properties

Well	WTN	Description	Distance from pumping well (m)[2,3,4]	Well depth (mbgs)	Static water level (mbgs)[1]	Maximum depth to water during pumping test (mbgs)	Estimated max. drawdown during test (m)	Depth of principal fracture (mbgs)	Available drawdown (m)[5]	Safe available drawdown 30% safety factor (m)	%SAD used during test	Elevation at well head (masl)[2]	Bottom of well (masl)[2]
73	104473	Pumping well	0	62.5	24.60	60.49	35.89	54.9	30.3	21.2	See capacity rating	89.4	26.9
72	104472	Observation well	4	99.1	24.38	46.33	21.95	nr	69.7	48.8	45%	88.5	-10.6
76	104476	Observation well	20	123.4	25.94	30.16	4.22	92.0	66.1	46.2	9%	91.3	-32.1
77	104477	Observation well	40	177.1	27.44	27.47	0.03	nr	nc	nc	nc	91.2	-85.9
OW194	26710	Observation well	230	76.2	21.35	22.02	0.67	nr	49.85	34.9	2%	84	7.8

[1]At start of pumping test September 18, 2019
[2]Reported in Elanco (2019) estimated from well coordinates on Google Earth
[3]Distance between wells estimated from GWELLS coordinates if not reported in Elanco (2019).
[4]OW194 incorrectly located in GWELLS, distance estimated based on approximate well location from Elanco (2019) Fig 3.
[5]Estimated as depth between static water level and principal fracture, or to 5 m above bottom of well, if no fracture reported
nr=not reported

Appendix B – Table B1 Saltwater Intrusion Vulnerability Assessment Criteria

	Criteria associated with increased saltwater intrusion hazard	**Well characteristic**	**Observations**
		WTN 104472	
Assessment criteria			
A. Well construction and siting			
Well depth (mbgs)	Deeper well that is close to drill into fresh-saltwater transition zone, or saline zone	62.5	
Well head elevation (masl)		89.4	
Bottom of well (masl)	Wells drilled below sea level, with static or pumping water level below sea level	26.9	Bottom of hole above sea level
Static water level (lowest reported) (masl)	Static water level at or below sea level	63.0	Static water level above sea level (date)
Elevation of principal fracture (masl)	Elevation of principal fracture at or below sea level	34.5	Principal fracture above sea level
Distance of well from coast (m)	Wells within <1 km from the coast (close proximity to coast)	1050	Approximately 1 km inland
B. Aquifer and physiographic criteria			
Aquifer lithology (subtype)	Properties of aquifer influence potential mechanism of intrusion, e.g. through upconing or inland migration of seawater-freshwater interface during well pumping, or interception of well with and mixing of water from saline fractures	sedimentary bedrock (5a)	Sandstone with shale seams
Hydraulic connection between aquifer and marine coast	Water levels can be tidally influenced, indicating likelihood of hydraulic connection between aquifer and sea		Not indicated (e.g. no tidal signal during pumping test or on long-term hydrograph
Physiographic indicators	Areas of low topographic gradient, peninsulas, small islands have greater intrinsic susceptibility		Located in upland area, in central part of island
Other comments			Area identified as receiving limited recharge (low yielding wells including dry holes, or wells that were hydrofractured to increase yield)

	Criteria associated with increased saltwater intrusion hazard	Well characteristic	Observations
C. Water quality criteria compared to operational threshold [OT]*	**Water quality during well operation in comparison to operational thresholds**		
Chloride (mg/L)[150 mg/L]		176	Exceeds operational threshold
Electrical conductivity (µS/cm) (1000 µS/cm)		906	Field measurements of conductivity ranged from a max. 3058 µS/cm to min. 861 µS/cm during test
Total dissolved solids, TDS (mg/L)(700 mg/L)		534	Below operational threshold
Change in water quality during well operation	Increase in salinity during pumping (correlated to increase in pumping rate, or increased duration of pumping)		Variable. Increased with increased rate of pumping during step test, declined overall during test
Change in water quality long-term	Increase in salinity over long-term		Appears to have freshened during test
Comparison of water quality to marine source (Piper-plot analysis)	Water quality on piper plot in the range of values for marine source, or mix of marine with other (fresh or mature) gw source		Consistent with properties of mature groundwater
Water quality general observations	Comments related to when and how well sampling was completed, other observations		Sample collected after decrease in well pumping rate, after 4000 minutes of pumping
*Water quality from sample collected near end of pumping test on September 21, 2019, values from laboratory results. See also field parameters comparison in section 6.			

References: (Province of B.C., 2017; Klassen & Allen, 2016; Werner, et al., 2013; United States Environmental Protection Agency, 1992).