WATER SCIENCE SERIES

Assessment of Aquifer-Stream Connectivity Related to Groundwater Abstraction in the Lower Fraser Valley

Stream Vulnerability Mapping

Mary Ann Middleton and Diana M. Allen

BRITISH COLUMBIA

No. 2017-04

The **Water Science Series** are scientific technical reports relating to the understanding and management of B.C.'s water resources. The series communicates scientific knowledge gained through water science programs across B.C. government, as well as scientific partners working in collaboration with provincial staff. For additional information visit: http://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-science-data/water-science-series.

ISBN: 978-0-7726-7170-7

Citation:
Middleton, M.A., Allen, D.M. 2017. Assessment of hydraulic connectivity related to groundwater extraction on selected sensitive steams: Stream Vulnerability Mapping. Water Science Series, WSS2017-04. Prov. B.C., Victoria B.C.

Authors' Affiliations:

Mary Ann Middleton
Department of Earth Sciences
Simon Fraser University

Diana M. Allen, P.Geo.
Department of Earth Sciences
Simon Fraser University

Cover Photograph: Photograph of Bertrand Creek in Langley, B.C. by Diana Allen

Acknowledgements

The authors gratefully acknowledge Klaus Rathfelder (ENV) for reviewing this report. This work was supported by the Ministry of Environment & Climate Change Strategy, Groundwater Science Program.

EXECUTIVE SUMMARY

Abstraction of groundwater from a pumping well located beside a stream can result in sourcing of the pumped water directly from the stream and consequent depletion of stream discharge. Sensitive streams, as designated under the Water Sustainability Regulation under the *Water Sustainability Act*, are particularly at risk if hydraulically connected to an aquifer from which groundwater is abstracted.

The purpose of this study was to build an understanding of the interaction between groundwater and sensitive streams for the purpose of identifying streams that are more vulnerable to groundwater abstraction. The project was carried out collaboratively between Simon Fraser University and the Ministry of Forests, Lands, Natural Resource Operations, and Rural Development. It consisted of two parts; first, a targeted Phase 1 field investigation at Steele Park in Langley, B.C. aimed at determining the impacts of pumping on aquifer-stream interactions; and second, a multi-level regional stream vulnerability assessment in the Lower Fraser Valley for determining the vulnerability of other similar types of stream-aquifer systems in order to identify streams that might be similarly impacted by groundwater abstraction. This report documents the results of the multi-level regional stream vulnerability assessment. Hall et al. (2017) report on the Phase 1 field investigation.

A multi-level stream vulnerability assessment was carried out in the Fraser Valley following the methodology described in “Vulnerability Assessment for Groundwater Dependent Streams” by Middleton and Allen (2016). This broad-scale ranking framework was designed to determine stream vulnerability to groundwater abstraction. Level I Assessments (or screening assessments) involve ranking each aquifer (Low, Moderate, or High), based on the productivity and demand classes as defined in Berardinucci and Ronneseth (2002). The rankings are then used to determine the action required as the outcome of the Vulnerability Assessment. The Level I Assessments were completed on an aquifer basis, and the ranking for each aquifer applies to all stream segments that intersect the assessed aquifer.

Level I Vulnerability Assessments were completed for 53 aquifer-steam systems in the Lower Fraser Valley, British Columbia. Of these, 5 are ranked high, 27 moderate, and 21 low for Potential Stream Vulnerability. The 5 ranked high include: 0008 (Vedder River Fan), 0015 (Abbotsford-Sumas), 0027 (Aldergrove), 0035 (Hopington) and 0041 (Brookswood). The recommended action for the high and moderate ranked aquifer-stream systems is to proceed to a Level II Assessment.

A Level II Vulnerability Assessment was completed for seven streams within the Lower Fraser Valley: 1) Fishtrap Creek; 2) Bertrand Creek, 3) Sumas River, 4) West Creek, 5) Salmon River, 6) Serpentine River, and 7) Nicomekl River. Due to the complex nature of the aquifers in some of the watersheds, some of the aquifer-stream systems were evaluated on both the watershed basis, as well as on an aquifer basis, for a total of ten aquifer-stream systems.

Sumas River watershed was rated low vulnerability and no further action is recommended unless there is a significant change in water demand, at which point a Level II re-assessment would be required. Monitoring is recommended to detect changes in the system.

Serpentine River watershed was rated moderate vulnerability and no further action is recommended unless there is a significant change in water demand, at which point a Level II re-assessment would be required.

Eight aquifer-stream systems or watersheds were rated as having high vulnerability:

- Fishtrap Creek watershed
- Bertrand Creek watershed
- West Creek watershed

- Salmon River watershed
- Salmon River – Aquifer 035 system
- Salmon River – Aquifers 027 and 033 system
- Nicomekl River watershed
- Nicomekl River – Aquifer 058 system

The recommended action is to proceed to a Level III Vulnerability Assessment which aims to quantify the impacts to the stream from groundwater-related stressors.

CONTENTS

1. BACKGROUND

Groundwater is vital for sustaining community economic development and social well-being (e.g., industrial use, agricultural use and municipal and rural uses). It is estimated that over one million British Columbians use groundwater for their drinking water supply. In many areas, groundwater is the only feasible source of water.

Groundwater abstraction, however, can have detrimental impacts on streamflow in some aquifer-stream systems. Many streams are in direct hydraulic connection with groundwater and demonstrate a direct correlation between flows and groundwater levels. Often, groundwater provides flow to surface water and surface water recharges the aquifers. However, in most studies of hydrologic systems, each system component (groundwater, surface water) is analyzed and/or modeled individually, treating the other interconnected component as a source or sink. In reality, these components are intricately linked and must be considered simultaneously. Because of the interchange of water between these two components of the hydrologic system, understanding the basic principles of the interaction of groundwater and surface water is needed for effective management of water resources (Winter, 1999). Specifically, knowledge of the hydraulic connectivity between aquifers and streams is essential for the management of both resources.

1.1 Evaluation of Hydraulic Connectivity in B.C.

Evaluation of hydraulic connectivity is required for water licensing decisions under the *Water Sustainability Act* (*WSA*). The *WSA* references hydraulic connection between water in a stream and groundwater in an aquifer in distinct contexts when (British Columbia Government, 2016):

1. considering environmental flow needs (EFNs) in allocating water (section 15 of the *WSA*);
2. considering precedence of rights during times of water scarcity (section 22 of the *WSA*);
3. dealing with foreign matter in a stream or an aquifer (sections 46, 47, 59, and 60 of the *WSA*),
4. considering the operation of a well (section 58 of the *WSA*),
5. determining critical environmental flow thresholds and for issuing fish population protection orders (section 87 and 88 of the *WSA*), and;
6. considering sensitive streams (section 128 of the *WSA*).

As part of the water licensing process, the decision maker must determine whether the aquifer is "reasonably likely" to be hydraulically connected to streams, and if so, whether well pumping will affect streamflow, existing water licences on these streams, and the aquatic habitat (British Columbia Government, 2016). If the test of "reasonably likely" is met for connection to a specific stream(s), the demand from well pumping can then be allocated against the flow in the connected stream to assess the impact of groundwater diversion on EFNs and on holders of water rights on those stream(s), or in taking of action on users during a time of water scarcity (British Columbia Government, 2016).

Sensitive streams are particularly at risk if hydraulically connected to an aquifer from which groundwater is abstracted. A sensitive stream is defined as a stream designated by regulation as a sensitive stream in the *WSA* in order to protect fish populations that are at risk from damage to the stream's aquatic ecosystem. While designated sensitive streams currently fall under the *WSA*, prior to 2016 sensitive streams fell under the *Fish Protection Act*. Fifteen sensitive streams were originally designated under the *Fish Protection Act* (Government of British Columbia, 1997). The *WSA* maintains the sensitive stream designation on all 15 streams. A decision maker may consider an application for an authorization related to a sensitive stream (including a groundwater licence in an aquifer that is hydraulically connected to that stream), but may only grant an authorization if satisfied that any adverse impact is likely to be insignificant.

1.2 Purpose and Objectives of Study

The overall purpose of this study was to build an understanding of the interaction between groundwater and sensitive streams for the purpose of identifying streams that are more vulnerable to groundwater abstraction.

The component of the study documented in this report consisted of a multi-level regional stream vulnerability assessment "Vulnerability Assessment for Groundwater Dependent Streams" following the methodology described in Middleton and Allen (2016). The aim of the assessment was to determine the vulnerability of stream-aquifer systems in the Lower Fraser Valley, in order to identify streams that might be similarly impacted by groundwater abstraction. This report provides guidance of these various approaches for science-based allocation decision-making.

2. LEVEL I ASSESSMENT

The first step of a Vulnerability Assessment for Groundwater Dependent Streams is a Level I Assessment to assess the potential stream vulnerability within the aquifer-stream system based on the hydrologic setting and the level of development of the aquifer in the area of interest (Middleton and Allen, 2016); hydraulic connectivity is not assessed. The main objective of a Level I Assessment is to assess whether the stream is *potentially* connected to the aquifer, and whether the aquifer can produce adequate quantities of water to meet the current demand. The outcome is a ranking of the **Potential Stream Vulnerability** for all stream segments in the aquifer.

Level I Vulnerability Assessments were completed for aquifer-stream systems in the Lower Fraser Valley, British Columbia in the area shown in Figure 1. The area contains fifty-three (53) aquifers (Figure 2). The area is defined to the west by the Serpentine and Nicomekl Rivers, to the east by the municipality of Hope, to the north by the Fraser River, and to the south by the Canada – U.S. border.

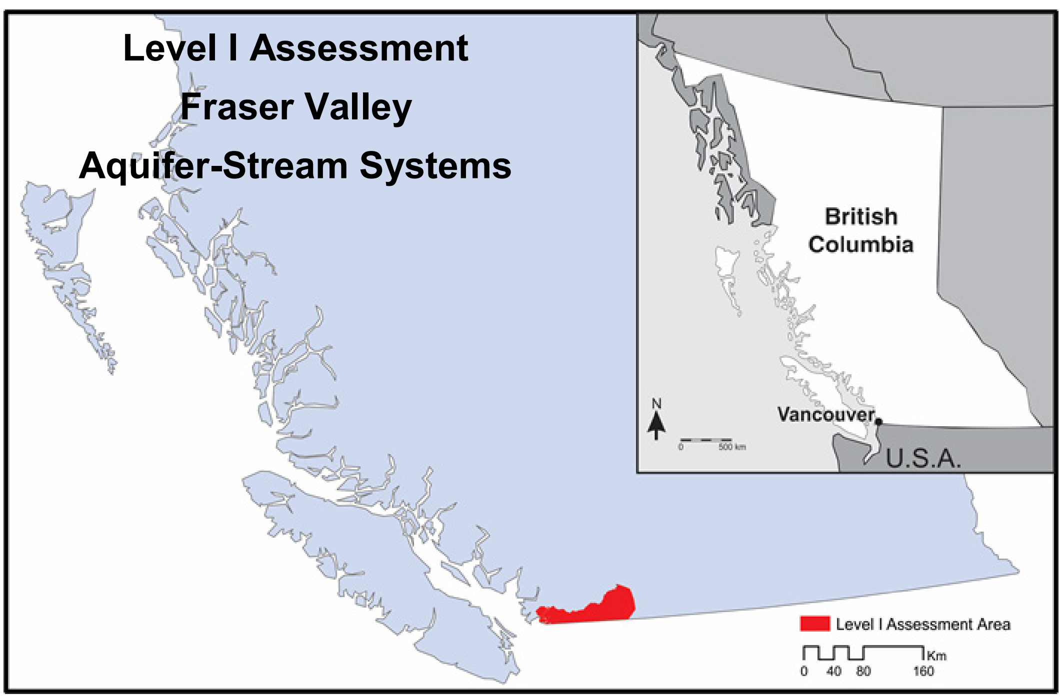

Figure 1: Location of the Level I Assessment Area (red) in the Lower Fraser Valley.

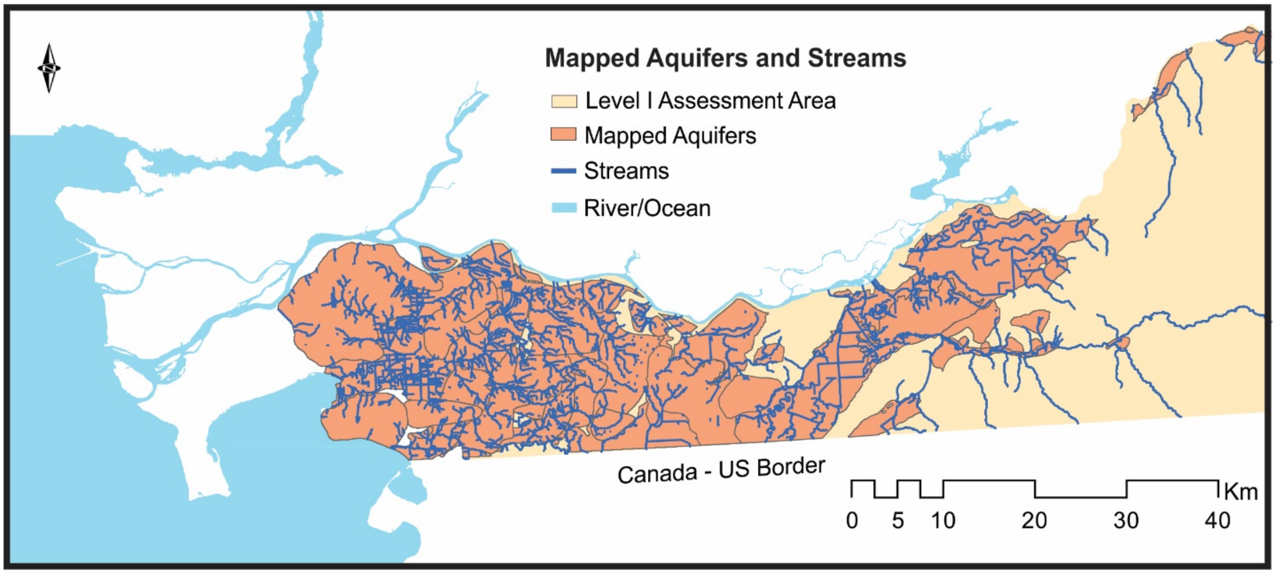

Figure 2: Mapped aquifers (orange polygons) and streams for the assessment area.

2.1 Methodology for Level I Assessment

The Level I Assessments were completed following the methodology described in Vulnerability Assessment for Groundwater Dependent Streams guidance document (Middleton and Allen, 2016).

1. The initial step was to assemble the shapefiles for the aquifers, streams and rivers, and any sensitive streams as originally defined in the *Fish Protection Act* (Bill 25: FPA 1997)[1] in the assessment area. The spatial data were obtained from iMapBC (http://maps.gov.bc.ca/ess/sv/imapbc). The shapefiles were compiled in ArcMap 10.3 (ESRI, 2015).
2. The next step was to rank each aquifer based on its Productivity and Demand classes as defined in Berardinucci and Ronneseth (2002). Level I Matrix Rankings (Low, Moderate, High, along with intermediate rankings), are based on Demand and the inverse of Productivity (Table 1). For example, highly productive aquifers are less likely to be impacted by pumping, and so are ranked as Low. An exception is that aquifers with High demand and High productivity are ranked as Moderate-High rather than Moderate, to put more weight on the demand class.
3. A final ranking was then determined (Low, Moderate, High – no intermediate rankings) based on additional information concerning the aquifer (see additional criteria below).
4. The final rankings are then used to determine the action required as the outcome of the Level I Vulnerability Assessment (Table 2). The Level I Assessments were completed on an aquifer basis, and the ranking for each aquifer applies to all stream segments that intersect the assessed aquifer.

A summary of aquifer properties used for the Level I Assessment rankings is presented in Table A1 in Appendix A. The table shows the Aquifer number, Demand class, Productivity class, Inverse Productivity, the Level I Matrix Ranking (as per Table 1), and the Final Ranking, which takes into consideration other information for the aquifer (Notes in Table A1).

[1] Sensitive streams designations were moved to the Water Sustainability Regulation under the WSA in 2016.

Additional criteria (where available) that were considered for this assessment are listed below, and are summarized in the Notes column in Table A1.

- Aquifer type (as described in Wei et al., 2009), with Type 1a resulting in a lower ranking due to its proximity to a higher order stream or river and so development may have less impact on streamflow. Other aquifer types listed as commonly connected to streams are generally ranked higher;
- Relative position of the aquifer, with confined aquifers having a lower rank and unconfined aquifers having a higher rank;
- Relative proportion of stream segments to aquifer area;
- If the depth to water in the confined aquifer (based on available well records) indicates upward flow (higher head at depth), a lower ranking for that aquifer would be assigned; and
- A higher ranking is assigned to aquifers that have a quantity concern identified in the aquifer inventory.

Table 1: Level I Matrix for Potential Stream Vulnerability (adapted from Middleton and Allen, 2016). Highly productive aquifers are less likely to be impacted by pumping, and so are ranked as Low.

		Productivity[1]		
		Low	**Moderate**	**High**
Demand	**Low**	Moderate	Low -Moderate	Low
	Moderate	Moderate -High	Moderate	Low -Moderate
	High	High	Moderate -High	Moderate -High

[1] The rankings within the matrix reflect the inverse of Productivity.

Table 2: Potential Stream Vulnerability within an aquifer and action required following Level I Assessment (from Middleton and Allen, 2016).

Potential Stream Vulnerability	Description	Action Required
Low	No stream intersects the aquifer in the area of interest. Thus, there is a low potential for connection between the stream and the aquifer. Demand for water is light relative to water availability.	No further action required
Moderate	A stream either passes through the aquifer or borders the aquifer. Thus, there is a moderate potential for connection between the stream and the aquifer, particularly in areas very close to the stream. Demand for water is moderate relative to water availability.	Proceed to Level II Assessment
High	A sensitive stream either passes through the aquifer or borders the aquifer and/or there is a high potential for connection between the stream and the aquifer. Demand for water is high relative to water availability.	Proceed to Level II Assessment

2.2 Results of Level I Assessment

Overall, the outcome of the Level I Assessment for the Lower Fraser Valley aquifers is summarized in Figure 3 and Table A1. The Assessment completed for the 53 aquifers determined that 5 are ranked high, 27 moderate, and 21 low for Potential Stream Vulnerability. As per Table 2, the recommended action for the high and moderate ranked aquifer – stream systems is to proceed to a Level II Assessment.

The presence of a sensitive stream in the aquifer results in an automatic “High” ranking, and supersedes consideration of productivity/demand. If there are no streams, then there is no aquifer-stream system, and thus a low (no) vulnerability is applied in this context.

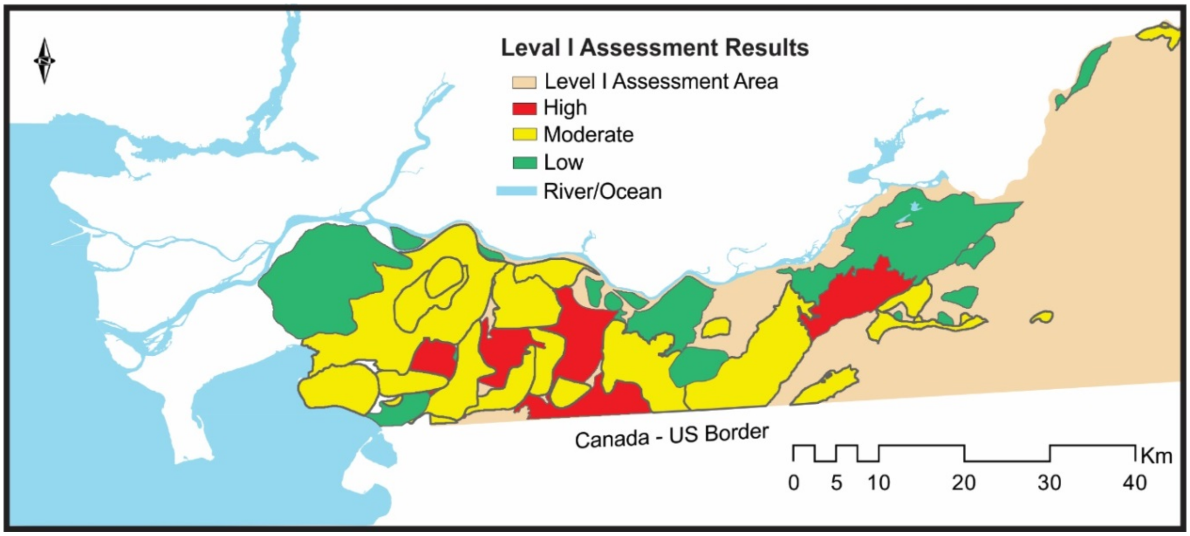

Figure 3: Potential Stream Vulnerability (Level I) ranking results for the mapped aquifers in the Fraser Valley assessment area.

3. LEVEL II ASSESSMENT

For aquifer- stream systems that are identified as having a moderate or high potential vulnerability in a Level I Assessment, a Level II Assessment is carried out (Middleton and Allen, 2016). The outcome of a Level II Assessment is a **Stream Vulnerability** rating, which incorporates the degree of connectivity between the stream and the aquifer and the stressors acting on the system (Figure 4).

The Stream Vulnerability (SV) is the combination of the Stream Susceptibility (SS) and the Hazard (H) described in more detail below.

3.1 Approach for a Level II Assessment

The following summarizes the Level II Assessment approach used in this study. Full details along with a more thorough discussion of limitations can be found in the “Vulnerability Assessment for Groundwater Dependent Streams” guidance document (Middleton and Allen, 2016).

The **Stream Susceptibility** (Equation 1) evaluates the potential for the stream to be influenced by stressors acting on the aquifer system. It represents the natural hydrogeological system, characterized by the aquifer setting, the aquifer properties, the nature of the interconnection between the aquifer system and the stream, and the recharge characteristics:

Stream Susceptibility (SS) = Aquifer Characteristics (A) * Recharge Ratio (QS/QR) (Eq. 1)

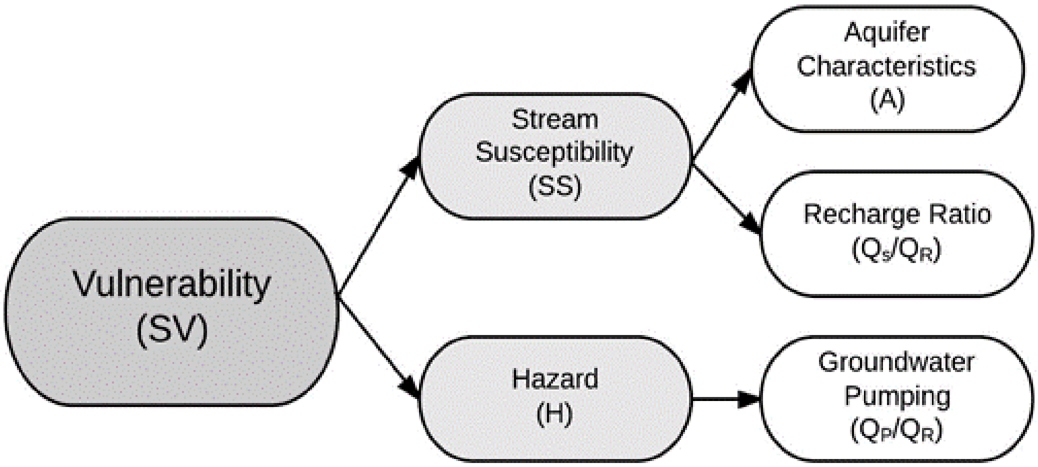

Figure 4: Flow chart outlining the components of stream vulnerability (SV) in the Level II Assessment (Middleton and Allen, 2016).

Table 3 shows the Aquifer Characteristics (A) ratings assigned to each aquifer type according to its likely connection with a stream. A direct hydraulic connection can be disadvantageous to streamflow because pumping could induce infiltration of surface water into the aquifers, and thereby remove water from the stream.

Recharge Ratio (Q_S/Q_R) assesses the reliance of the stream during the summer low flow period on locally-derived aquifer recharge. Annual recharge to the stream (Q_R) is assessed based on the area contributing groundwater discharge to the stream, and is compared to baseflow (Q_S) to estimate the ability of the discharge amount to sustain the streamflow.

A first order approximation of the potential recharge (R) and hence discharge to the stream from the aquifer system (Q_R) is made in a Level II Assessment:

$$R = P - PET = Q_R \qquad \text{(Eq. 2)}$$

Equation 2 assumes the aquifer drains to a stream and that all the recharge to the aquifer discharges to the stream ($R = Q_R$). It assumes no pumping. It assumes that if there is any groundwater inflow from adjacent areas, that this groundwater leaves the aquifer through adjacent areas. It also assumes that there are no gains to the aquifer from the stream.

- Precipitation (P) is obtained from the nearest climate station that is the most representative of the aquifer.
- PET is estimated using a simplified approach that requires the daily solar radiation (SR) and maximum air temperature (Tmax) (Equation 4) (Cohen et al. 2004).

$$-3.26 + 0.201\text{Tmax} + 0.058\ \text{SR} = \text{PET} \qquad \text{(Eq. 3)}$$

where solar radiation (SR) can be calculated for the days of the year using the solar position and radiation calculator (Washington State Department of Ecology, 2014), using longitude/latitude and elevation.

R is calculated daily, because at an annual time scale, PET can exceed P. If precipitation occurred on a particular day, a recharge amount is computed according to Equation 2. If there was no precipitation, then R is assumed to be zero. This approach likely overestimates R, because soil moisture is able to evaporate and plants are able to transpire even on days it does not rain; however, for a Level II Assessment, recharge calculated in this way is a first approximation.

Table 3: Aquifer types and key hydrogeological characteristics (from Wei et al., 2009) with the assigned Aquifer Characteristics (A) ratings assigned through consultation with B.C. Ministry of Environment & Climate Change Strategy. From Middleton and Allen (2016).

Aquifer type	Confined - unconfined	Connection with streams	Rating[1]
1. Aquifers of fluvial or glaciofluvial origin along river valley bottoms	Unconfined		
a. aquifers along low gradient, higher order rivers	Unconfined	Commonly connected but stream size buffers impact	4
b. aquifers along generally higher gradient, moderate order rivers	Unconfined	Commonly connected	10
c. aquifers along lower order streams; limited aquifer thickness and lateral extent	Unconfined	Commonly connected	10
2. Deltaic (sand and gravel) aquifers	Unconfined	Commonly connected	10
3. Alluvial, colluvial (sand and gravel) fan aquifers	Unconfined	Commonly connected near the stream	8
4. Aquifers of glacial or pre-glacial origin	Variable		
a. Outwash and ice-contact sand and gravel aquifers (glacio-fluvial)	Unconfined	Commonly connected near the stream	8
b. Aquifers of glacial or pre-glacial origin	Mostly confined	Possibly connected if unconfined	4
c. Confined aquifers of glacio-marine origin	Confined	Unlikely to be connected	4
5. Sedimentary rock aquifers	Variable		
a. fractured sedimentary rock aquifers	Unconfined near surface	Possibly connected near the stream	3
b. karstic limestone aquifers	Unconfined near surface	Likely connected	5
6. Crystalline rock aquifers	Variable		
a. flat-lying or gently-dipping volcanic flow aquifers	Unconfined near surface	Likely connected	5
b. fractured igneous intrusive, metamorphic, fractured volcanic or metavolcanic aquifers	Unconfined near surface	Possibly connected near the stream	3

[1]The ratings were determined based on expert knowledge of aquifer types in British Columbia. Intermediate rating values could be assigned based on local hydrogeological conditions.

Using values for P (mm/yr) and the calculated values of PET (mm/year) for the aquifer area (m^2), R or Q_R (m^3/year) is estimated. The aquifer area corresponds to the area contributing to streamflow measured at a gauging station (see below). For simplicity, the aquifer area can be considered the same as the watershed or catchment area. This definition assumes that all the recharge within the watershed exits the watershed via the stream. Any deep groundwater flow is neglected.

$\mathbf{Q_R}$ thus represents the volume of groundwater that discharges to the stream on an annual basis as baseflow.

Ideally, the baseflow $\mathbf{Q_S}$ would be calculated from the same period of record as the climate normals. While there are hydrograph separation techniques that can be used to estimate the baseflow, which varies seasonally, the approach used here is to calculate the average summer streamflow, Q_S, (from July to September) over the period of record. In actuality, the summer streamflow will include the baseflow as well as storm runoff from rain events, and so may overestimate summer baseflow. But, countering this is the fact that summer baseflow is less than the average annual baseflow. Therefore, summer streamflow (Q_S) is considered a reasonable approximation to baseflow.

The Recharge ratio **Q_S/Q_R** represents the proportion of the summer streamflow that derives from groundwater recharge. There are three main outcomes for this ratio:

1) If Q_S is equal to Q_R (the ratio is one), the summer streamflow is fully dependent on groundwater recharge, and the stream would be considered sensitive to the amount of recharge in the aquifer;
2) If Q_S is greater than Q_R, then streamflow likely derives from an area remote to the aquifer, such that the streamflow is augmented by upstream contributions and the stream is considered less sensitive;
3) If Q_S is less than Q_R, then what small contributions of recharge to the streamflow there are must be significant, and the stream is considered sensitive.

The rating scheme for Q_S/Q_R is shown in Table 4. The maximum and minimum ratings were determined from the highest and lowest likely recharge ratios expected in British Columbia. The intermediate values were assigned according to order of magnitude changes in the recharge ratio to best capture the observed ranges during testing of the method.

The **Stream Susceptibility (SS)** component of stream vulnerability depends on the recharge ratio and the aquifer characteristics (Table 5).

Table 4: Recharge Ratio (Q_S/Q_R) and the assigned ratings.

Ratio (Q_S/Q_R)	Rating
> 1000	1
> 100	2
> 10	3
1.0 - 9.9	4
0.1 – 0.9	5
0.01 – 0.09	6
0.001 – 0.009	7
0.0001 – 0.0009	8
0.00001 – 0.00009	9
< 0.00001	10

Table 5: Stream Susceptibility (SS), and the assigned ratings.

		Recharge Ratio (Q_S/Q_R)									
		Low (1-3)			Moderate (4-7)				High (8-10)		
Aquifer Characteristics (A)[1]	Low (1-3)	Low	Low	Low	Low	Low	Low	Low	Mod	Mod	Mod
		Low	Low	Low	Low	Low	Mod	Mod	Mod	Mod	Mod
	Moderate (4-7)	Low	Low	Low	Mod	Mod	Mod	Mod	Mod	Mod	Mod
		Low	Low	Mod	Mod	Mod	Mod	Mod	High	High	High
	High (8-10)	Mod	Mod	Mod	Mod	Mod	Mod	High	High	High	High
		Mod	Mod	Mod	Mod	High	High	High	High	High	High

[1]Ranges for Aquifer Characteristics (A) are continuous in this table, but in Table 3 they are not continuous.

The **Hazard (H)** (Figure 4) component of stream vulnerability represents the current stressors to the aquifer, specifically pumping, which may translate into potential changes to the stream. H represents the magnitude and likelihood that the hazards that may change the water quantity in the stream:

$$\text{Hazard (H)} = \text{Groundwater Pumping Magnitude} * \text{Likelihood of Impact} \qquad \text{(Eq. 4)}$$

The **Groundwater Pumping Magnitude** is assessed based on the volumetric pumping rate. The **Likelihood of Impact** is based on the ratio of the pumping volume to the recharge to the stream. The volumetric pumping rate is assessed for either the area of aquifer polygon, or the area of the stream watershed. The annual volume of groundwater pumped (**Q_P**) is then compared to the Recharge to stream (Q_R), as calculated in Equation 2. If Q_P is equal to, or greater than, Q_R, the pumping is very likely impacting the streamflow quantity and represents a hazard. If Q_P is less than the Q_R, pumping may not be impacting the stream; however, the magnitude of the ratio between the two components provides an indication of the condition of the system.

The Hazard rating is derived directly from the Q_P/Q_R ratios. Table 6 shows the Hazard (H) rating for a range of Q_P/Q_R ratios. Intermediate ratings are scaled accordingly.

Table 6: Ratio of volume pumped (Q_P) to the recharge to stream (Q_R) and the assigned ratings.

Ratio (Q_P/Q_R)	H Rating
< 0.19	Low (1)
0.2 – 0.39	Low (2)
0.4 – 0.59	Moderate (4)
0.6 – 0.79	Moderate (6)
0.8 – 0.99	High (8)
> 1	High (10)

The *Stream Vulnerability (SV)* rating can range from low to high, based on the Stream Susceptibility rating and the Hazard rating in Table 5 and Table 6, respectively. Table 7 shows the Stream Vulnerability ratings as a matrix, which captures both components of the assessment. Table 8 describes the whether or not further assessment is required based on the stream vulnerability rating.

Table 7: Stream Vulnerability (SV) Level II Matrix (from Middleton and Allen, 2016).

		Stream Susceptibility		
		Low	Moderate	High
Hazard	Low	Low	Low	Moderate
	Moderate	Low	Moderate	Moderate -High
	High	Moderate	Moderate -High	High

Table 8: Stream Vulnerability (SV) rating and assessment required (from Middleton and Allen, 2016).

Stream Vulnerability Rating	Description	Action Required
Low to Low-Moderate	The stream is currently of low vulnerability.	No further action required unless there is a significant change to the water demand. A Level II Re-Assessment would then be required.
Moderate	The stream is currently of moderate vulnerability.	No further action required unless there are changes to the water demand or the recharge conditions. A Level II Re-Assessment would then be required. Monitoring is recommended to assess potential changes.
Moderate-High to High	The stream is currently of high vulnerability.	Proceed to Level III Assessment

3.2 Fraser Valley Level II Assessment

A Level II Vulnerability Assessment was completed for seven streams within Lower Fraser Valley (Figure 5). The watersheds selected for Level II Assessments (highlighted in blue in Figure 5) are:

1) Fishtrap Creek,
2) Bertrand Creek,
3) Sumas River,
4) West Creek,
5) Salmon River,
6) Serpentine River, and
7) Nicomekl River.

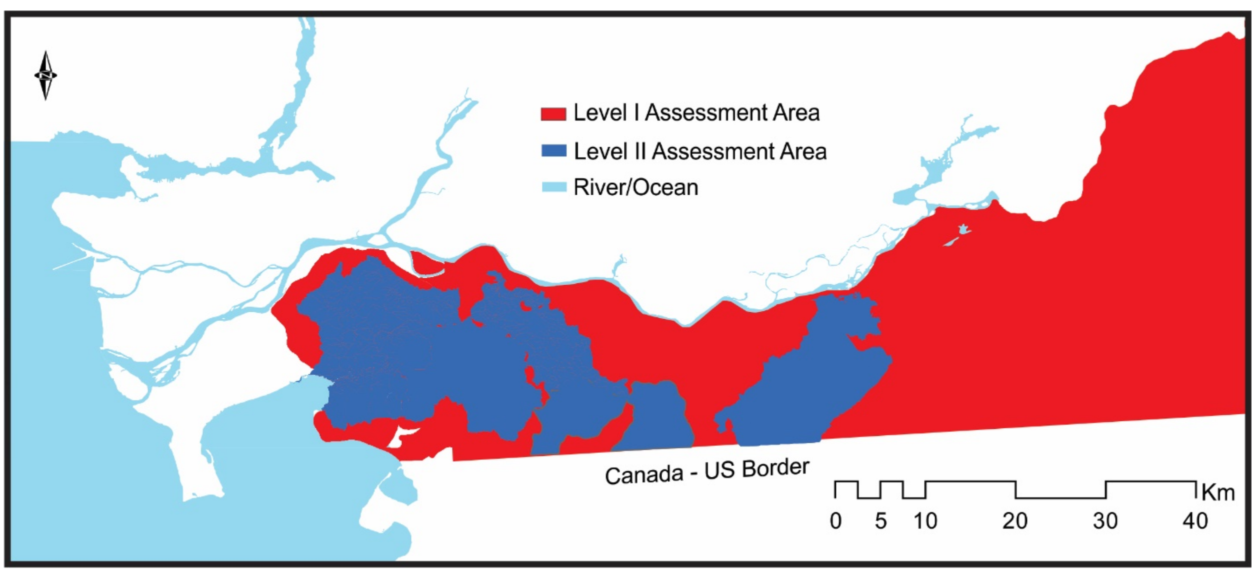

Figure 5: Location of the Level II Assessment Watersheds (blue) within the Level I Assessment Area (red) in the Lower Fraser Valley. The extent of the Level I Assessment polygon shown in Figure 6 is identified by the dotted vertical line.

The Level II Assessment was completed following the methodology described above. Specific details include:

1) The initial step was to assemble the shapefiles for the aquifer-stream systems. Shapefiles assembled included aquifer polygons, sensitive streams, and river segments for each system. The watershed boundaries were defined using a combination of existing watershed polygons, and with the digital elevation model (DEM) using the watershed tool in ArcMap 10.3.
2) The next step was to define the area of interest, which may be defined as the dominant aquifer, or joined polygons for aquifers with similar properties. Some streams may intersect multiple aquifers, or aquifers may be overlain within a watershed. Thus, the area contributing to the aquifer-stream system may be defined by either the watershed or by the aquifer (Middleton and Allen, 2016). The aquifer (or area of interest) and contributing areas for each aquifer-stream system were defined as follows:
    a) For **Fishtrap Creek**, the dominant aquifer (Aquifer 015) was selected as the aquifer of interest, and the contributing area was defined by the watershed boundary.
    b) For **Bertrand Creek**, the dominant aquifer (Aquifer 015) was selected as the aquifer of interest, and the contributing area was defined by the watershed boundary.
    c) For **Sumas River**, the dominant aquifer (Aquifer 021) was combined with another Type 1a aquifer (Aquifer 006) to define the area of interest, and the contributing area was defined by the watershed boundary.
    d) For **West Creek**, the dominant aquifer (Aquifer 032) was selected, and the contributing area was defined by the watershed boundary.
    e) The **Salmon River** has a complex assemblage of aquifers within the watershed area. The Level II Assessment was completed in two stages for this aquifer-stream system based on the rating for the Aquifer type.
        i. One assessment was based on the segment of the Salmon River that intersects the Type 4a aquifer (Aquifer 035), which has a higher rating in the Vulnerability Assessment than the other aquifers. Unconfined aquifers have a greater likelihood of connectivity with the surface water.
        ii. The second stage of the assessment was to combine major aquifers that intercept the watershed based on aquifer type. Type 4c aquifers were combined (Aquifers 032 and 058) and the same was done for Type 4b aquifers (Aquifers 027 and 033). The joined aquifer polygons represent the upper and lower reaches of the watershed and were assessed separately due to the variations in the surficial material and the productivity and demand classifications.
            - For the area of interest defined by the lower reach aquifers (Type 4c, Aquifers 032 and 058), the contributing area was based on the watershed area because that was considered a representative proportion of the aquifer that would have potential hydraulic connectivity with the Salmon River.
            - For the area of interest defined by the upper reach aquifers (Type 4b, Aquifers 027 and 033), the contributing area was based on the aquifer area.
    f) The **Serpentine River** watershed is bisected by two main aquifers (Aquifer 058 and 061), both of which are Type 4 (b and c) - sand and gravel aquifers of glacial or pre-glacial origin and are classified as confined to partially confined. For the purpose of this assessment, the aquifers were grouped together, and the contributing area was defined by the watershed boundary.
    g) The **Nicomekl River** watershed is intersected by a total of ten aquifers, all Type 4 (a, b and c) - sand and gravel aquifers of glacial or pre-glacial origin. The Level II Assessment was

completed in two stages for this aquifer-stream system based on the groupings of aquifers. There are four main aquifers in the Nicomekl watershed (Aquifers 035, 041, 052 and 058).

i. The aquifer that was dominant in the watershed, based on aerial intersection with the river segments is Aquifer 058 a Type 4c confined aquifer and the contributing area for this stage of Assessment was the aquifer area.
ii. The other assessment included the remaining three aquifers (Aquifers 035, 041, and 052) grouped together based on confinement and type and the aquifers were grouped together into a single polygon in ArcMap. These aquifers are partially confined to unconfined. This segment of the watershed includes one tributary to the mainstem Nicomekl, but contains the majority of wells in the watershed.

3) The next step was to assemble shapefiles of all the wells within each area defined in Step 2 and estimate the pumping volume from all wells in each defined region. Pumping volume was estimated using the actual pumping rate (if known) or the estimated yield of the well (when reported in the WELLS database). If no information was available from the WELLS database on estimated well yield, then the well can be assumed to be pumped at the domestic rate of 2,270 L/day, which is defined within the BC Well Protection Toolkit as the estimated water use per household (BC Ministry of Environment, 2004).
4) The cumulative summer baseflow (Q_S) averaged over the period of record was estimated from hydrometric data for available periods of record for each stream for the months of July to September (inclusive).
5) Using the elevation and latitude/longitude from a position approximately at the center of each watershed or aquifer, the solar radiation was calculated for the PET estimation. Using values for P (mm/yr) and the calculated values of PET (mm/year) for the aquifer area (m^2), R or Q_R (m^3/year) was estimated, and it is assumed that all the recharge within the watershed exits the watershed via the stream as baseflow.
6) The Stream Susceptibility (SS) was calculated from the Recharge Ratio Rating (Q_S/Q_R), the Hazard Rating (H) was derived from the ratio of the pumping to the recharge (Q_P/Q_R), and the final Stream Vulnerability was calculated from the Stream Vulnerability (SV) matrix (Table 7). The recommendation of further assessment (Table 8) is based on the outcome of the Stream Vulnerability rating.

3.3 Results of Level II Assessment

As noted above, due to the complex nature of the aquifers in some of the watersheds, some of the aquifer-stream systems were evaluated on both the watershed basis, as well as on an aquifer basis, for a total of ten aquifer-stream systems. All the aquifer-stream systems are in diffuse recharge-driven rainfall dominated hydroclimatic regimes, and have low topographic relief. The results are summarized in Figure 6 and Table B1 in Appendix B. Section 3.4 provides a discussion and the recommended actions based on these results.

3.3.1 Salmon River

The potential Stream Vulnerability for the Salmon River aquifer-stream system was completed for the watershed area, and then separately for Aquifer 035, and also for Aquifers 027-033 as described in methods.

The Salmon River watershed was evaluated by combining Aquifers 032 and 058, which have the largest aerial extent across the watershed. Both aquifers are confined sand and gravel aquifers, with moderate productivity and demand. The Stream Vulnerability for this aquifer-stream system is High (Figure 7).

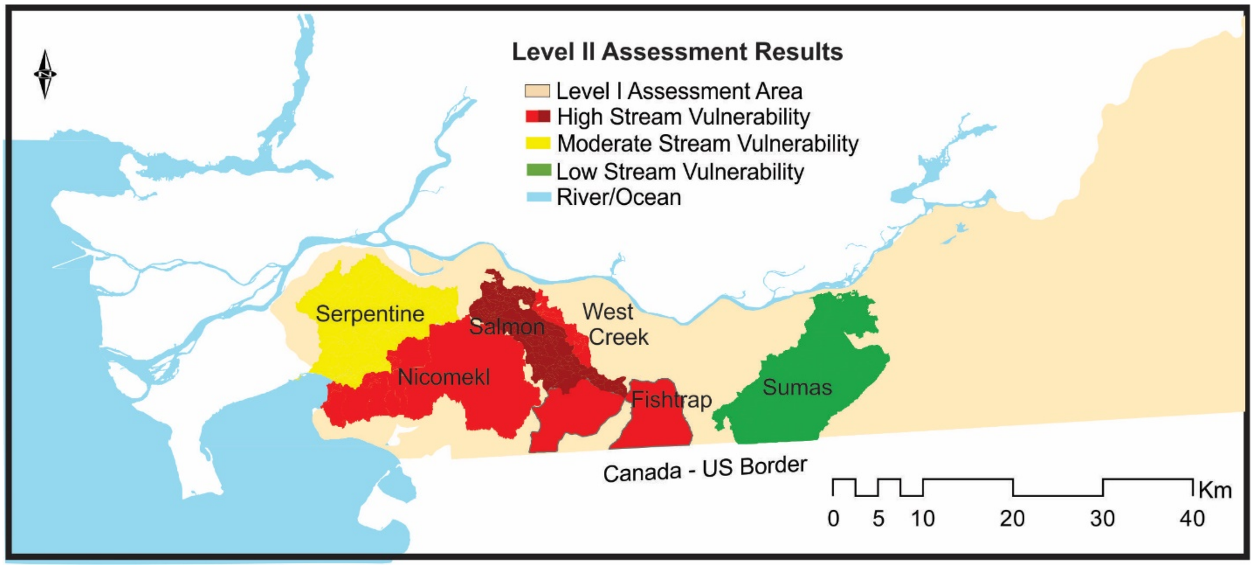

Figure 6: The Level II Assessment Stream Vulnerability ratings for seven aquifer-stream systems in the Lower Fraser Valley, BC. Note that the Salmon River Watershed is shown in a darker red so as to distinguish it from the adjacent watershed

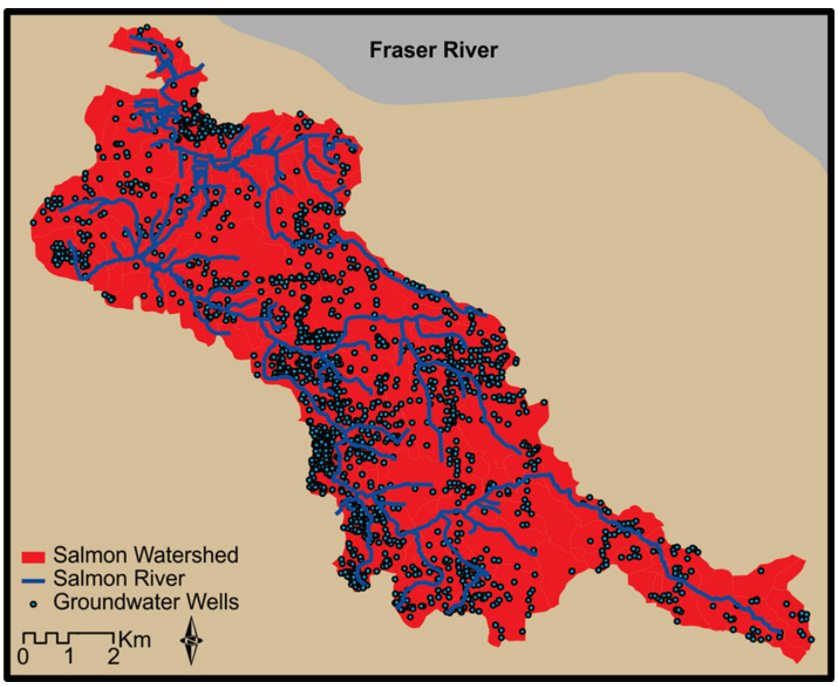

Figure 7: The Level II Assessment Stream Vulnerability ratings for the Salmon River watershed, using aquifer data from Aquifers 032 and 058. The Stream Vulnerability is High for the Salmon River overall.

Aquifer 035 is the partially confined (largely unconfined) sand and gravel Hopington aquifer, with high productivity and demand. The rating for this aquifer-stream system is High (Figure 8).

Aquifers 027 and 033 were combined for the Level II Assessment because of their similar characteristics; they are partially confined to confined aquifers with moderate to high productivity and demand. There were more than 1,900 wells identified in the area of interest defined by these two aquifers. The Stream Vulnerability for this aquifer-stream system is High (Figure 9).

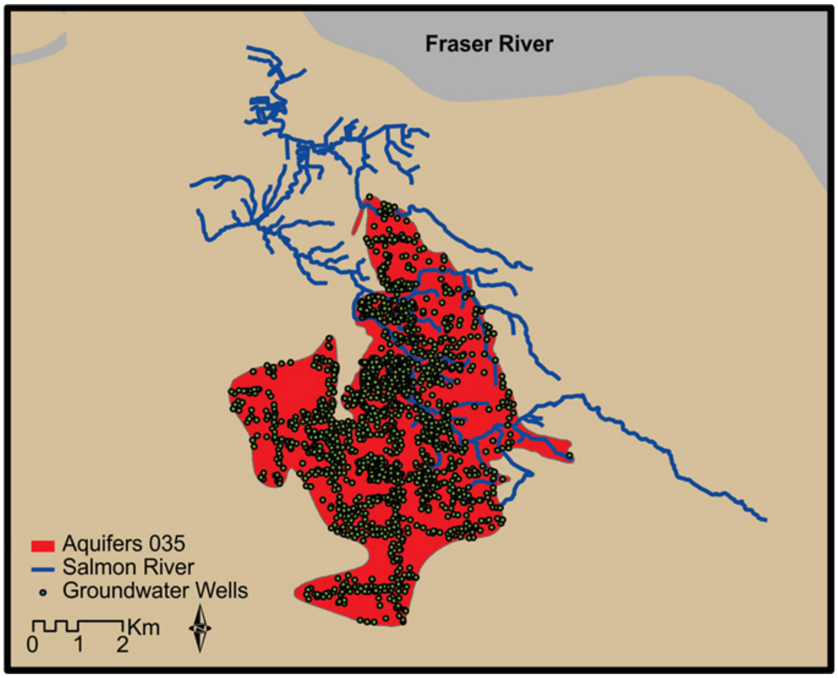

Figure 8: The Level II Assessment Stream Vulnerability rating for the aquifer-stream system of the Salmon River and Aquifer 035. The Stream Vulnerability rating is High.

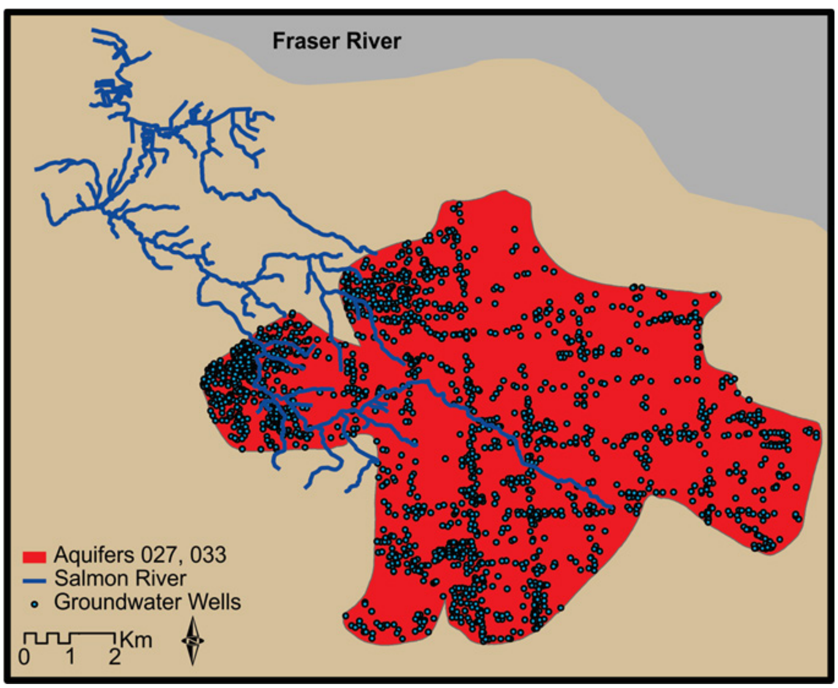

Figure 9: The Level II Assessment Stream Vulnerability rating for the aquifer-stream system of the Salmon River and Aquifers 027 and 033. The Stream Vulnerability rating is High.

The results for the Salmon River aquifer-stream system suggest that the Salmon River and its tributaries are highly vulnerable to groundwater abstraction. For the aquifer-based assessments, the vulnerability rating is for the portion of stream that intersects the specific aquifer only, but for the watershed based assessment, the vulnerability is for the entire watershed, including the portions of aquifer(s) intersected by the watershed boundaries. Due to the complexity of this aquifer-stream system, a more comprehensive evaluation of the watershed and the adjoining aquifers is warranted.

3.3.2 Fishtrap Creek

This is one of two streams evaluated that drain the Abbotsford aquifer in the Lower Fraser Valley. The aquifer is unconfined and comprised of sands and gravels. The aquifer has high productivity and high demand. The potential Stream Vulnerability rating for this watershed is High (Figure 10).

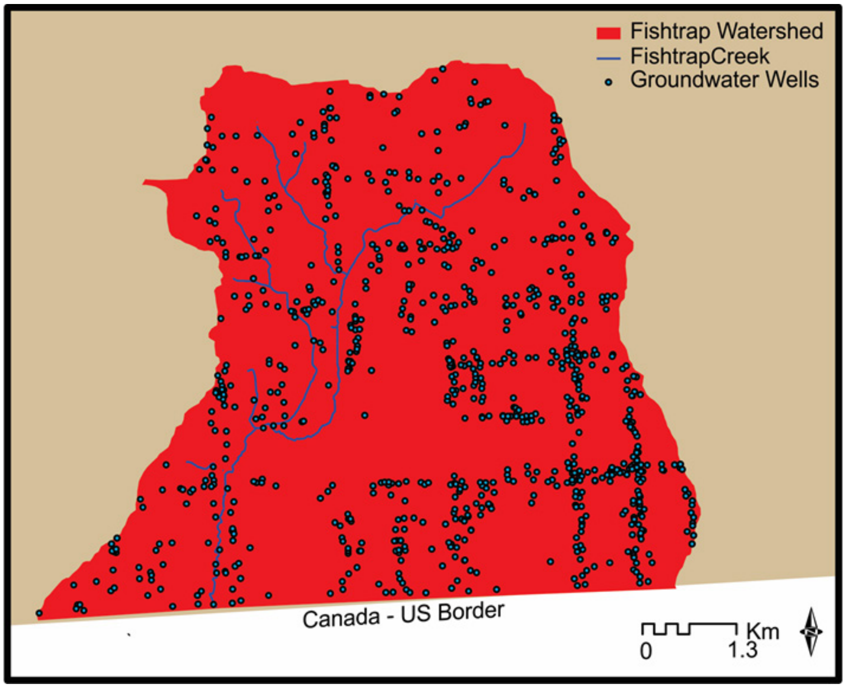

Figure 10: The Level II Assessment Stream Vulnerability rating for the Fishtrap Creek watershed. The Stream Vulnerability is High.

3.3.3 Bertrand Creek

This is the second of two streams evaluated that drain the Abbotsford aquifer in the Lower Fraser Valley. The aquifer is unconfined and comprised of sands and gravels. The aquifer has high productivity and high demand. The potential Stream Vulnerability rating for this watershed is High (Figure 11).

3.3.4 Sumas River

The Sumas River is in the east-central portion of the Lower Fraser Valley. The aquifers in the watershed are along the Fraser River, and the dominant aquifer is a partially confined sand and gravel aquifer, with moderate productivity and low demand. The potential Stream Vulnerability rating for this watershed is Low (Figure 12).

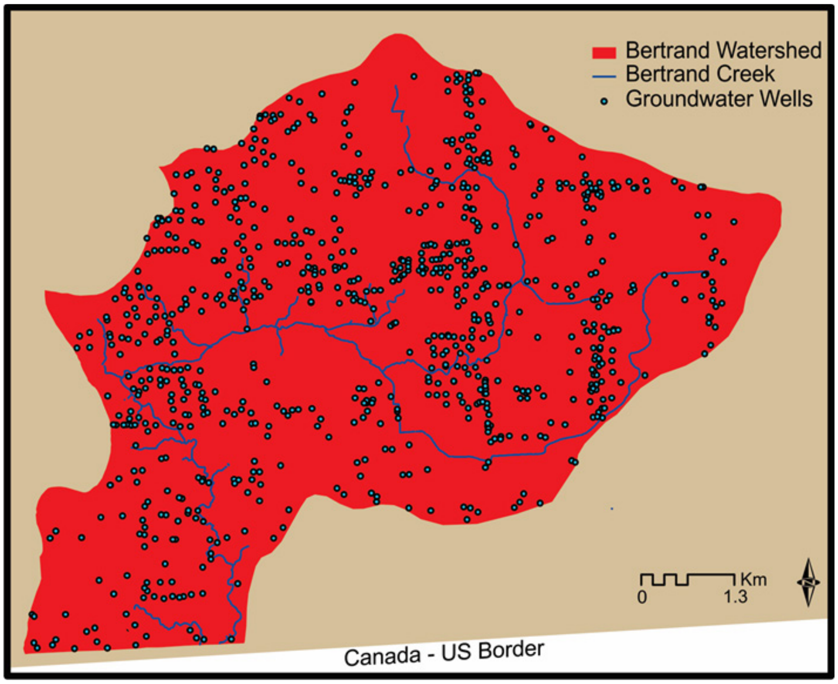

Figure 11: The Level II Assessment Stream Vulnerability ratings for the Bertrand Creek watershed. The Stream Vulnerability is High.

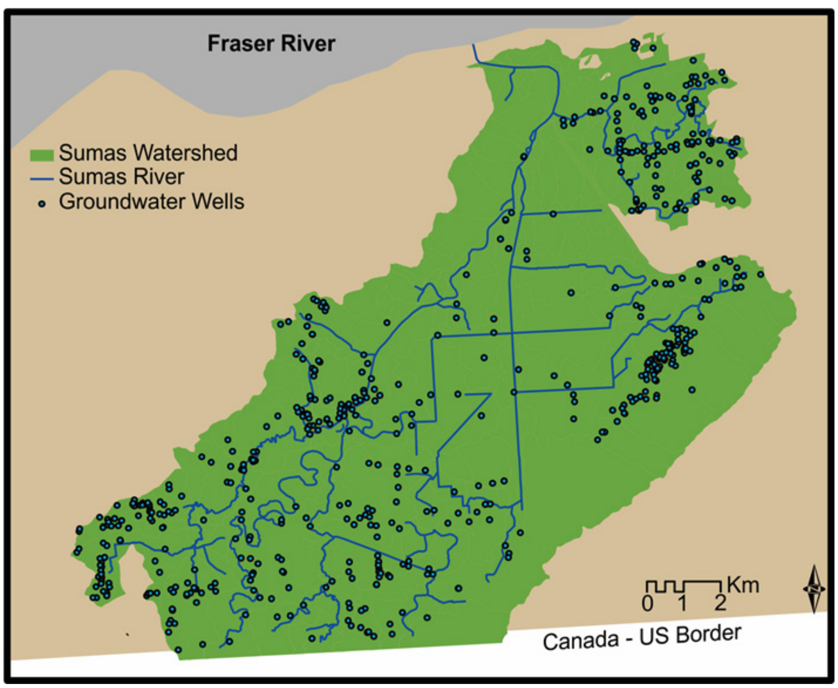

Figure 12: The Level II Assessment Stream Vulnerability rating for the Sumas River watershed. The Stream Vulnerability is Low.

3.3.5 West Creek

West Creek is a small watershed relative to the other watersheds in this Level II Assessment. The dominant aquifer is a confined sand and gravel aquifer, with moderate productivity and demand. The potential Stream Vulnerability rating for this aquifer-stream system is High (Figure 13).

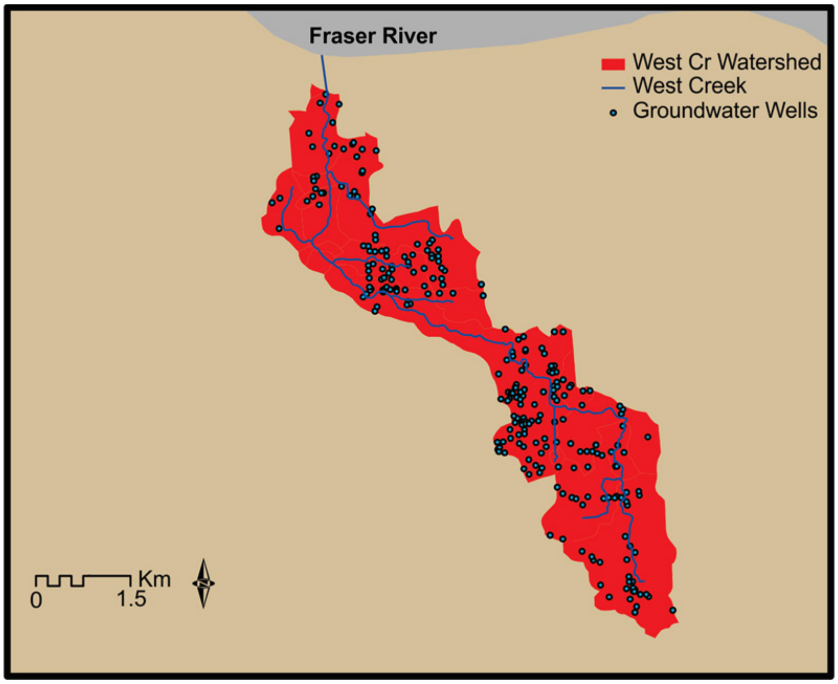

Figure 13: The Level II Assessment Stream Vulnerability rating for the West Creek watershed. The Stream Vulnerability is High.

3.3.6 Serpentine River

The dominant aquifers in this aquifer-stream system (Aquifers 058 and 061) are partially confined to confined sand and gravel aquifers with moderate to high productivity and low to moderate demand. Stream discharge data for the Serpentine River were limited to data from 1960 to 1966, and land use and drainage in the watershed is now significantly different in present conditions (City of Surrey, pers. comm.). However, a sensitivity analysis on the recharge ratio rating showed that stream discharge variations within two orders of magnitude did not impact the outcome of the final stream vulnerability, and therefore this window of stream discharge data are considered appropriate for this level of screening. The potential Stream Vulnerability rating for this watershed is Moderate (Figure 14).

3.3.7 Nicomekl River

The potential Stream Vulnerability for the Nicomekl River aquifer-stream system was completed for the watershed area, and then separately for Aquifer 058. The Nicomekl River watershed was evaluated by combining Aquifers 035, 041, and 052 based on similar aquifer characteristics and also those aquifers having the largest aerial extent across the watershed. The combined aquifers in this Assessment are partially or semi-confined to unconfined sand and gravel aquifers with moderate to high productivity and moderate to high demand. There are a total of more than 3,000 wells reported in this watershed and this watershed has the highest pumping ratio of the aquifer-stream systems in this Vulnerability Assessment. The Stream Vulnerability for this watershed is High (Figure 15). Aquifer 058 is the confined sand and gravel Nicomekl-Serpentine Aquifer, with moderate productivity and demand. However, there are more than 2,200 wells reported in this aquifer so the hazard rating was high, leading to an overall High rating for this aquifer-stream system despite the semi-confined nature of the aquifer (Figure 16).

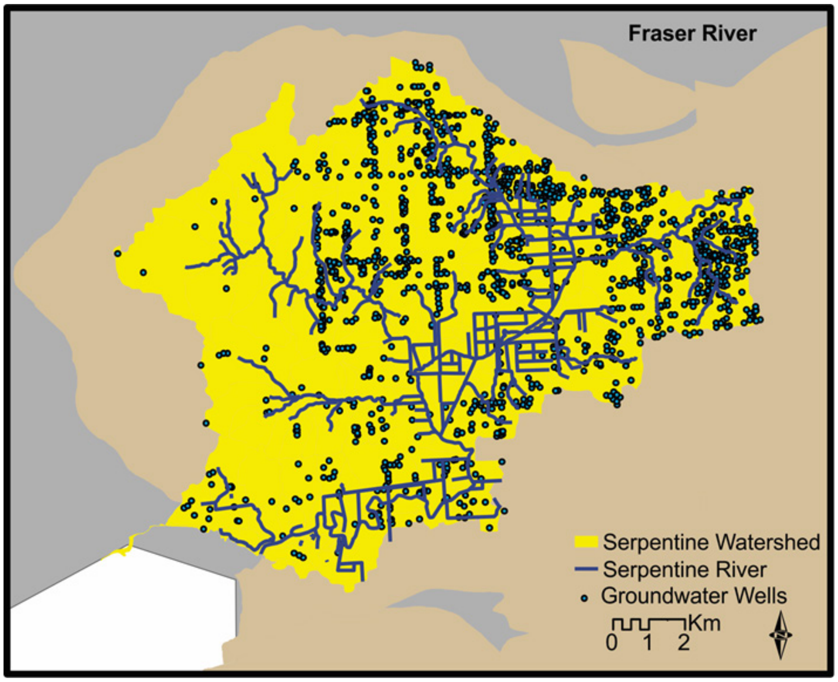

Figure 14: The Level II Assessment Stream Vulnerability rating for the Serpentine River watershed. The Vulnerability rating is Moderate.

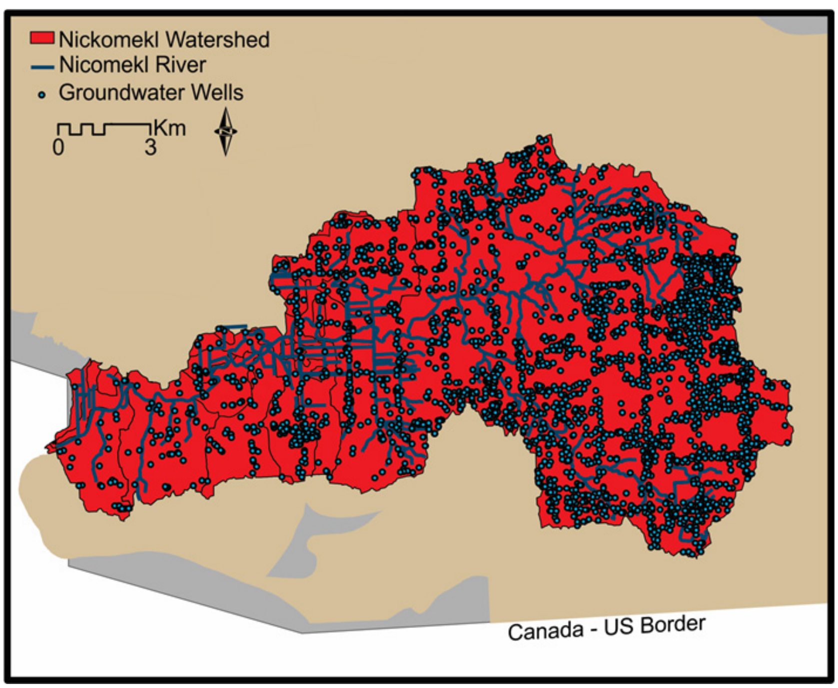

Figure 15: The Level II Assessment Stream Vulnerability rating for the Nicomekl River watershed. The Vulnerability rating is High.

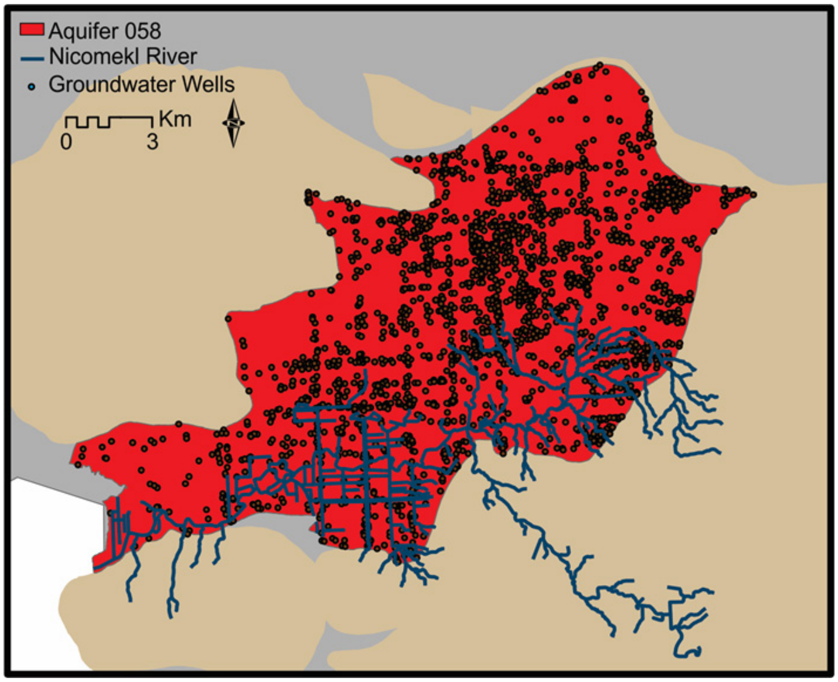

Figure 16: The Level II Assessment Stream Vulnerability rating for the aquifer-stream system of the Nicomekl River and Aquifer 058 system. The Vulnerability rating is High.

3.4 Discussion and Recommended Actions

Of the ten aquifer-stream systems evaluated:

One watershed was rated low vulnerability and no further action is recommended unless there is a significant change in water demand, at which point a Level II re-assessment would be required.

- Sumas River watershed

One watershed was rated moderate vulnerability and no further action is recommended unless there is a significant change in water demand or recharge conditions, triggered for example by land use change or climate change, at which point a Level II re-assessment would be required. Additional monitoring should be carried out to evaluate changes in the system.

- Serpentine River watershed

Eight aquifer-stream systems or watersheds were rated high vulnerability, and the recommended action is to proceed to a Level III Vulnerability Assessment, which aims to quantify the impacts to the stream from groundwater-related stressors.

- Fishtrap Creek watershed
- Bertrand Creek watershed
- West Creek watershed
- **Salmon River watershed**
- **Salmon River – Aquifer 035 system**
- **Salmon River – Aquifers 027 and 033 system**
- Nicomekl River watershed
- Nicomekl River – Aquifer 058 system

The Level II Assessment, as presented here, is intended to identify systems that may require further investigation, whether monitoring or a more detailed or quantitative evaluation. A Level III Assessment does not need to include a numerical model; it could be as simple as refining the results and considering the spatial distribution of data, such as well locations relative to the stream.

In moving to a Level III, the results can be prioritized by considering the individual ratings in Table B1 in Appendix B. For example, Aquifer 35 has high stream susceptibility (SS) rating because of its Aquifer Characteristics. But it also has a large area, so wells that are located further from the stream may have a lesser impact on the stream. In contrast, Aquifer 27/33 has a high Q_P/Q_R which incorporates pumping rates and aquifer area, suggesting wells may be clustered closer to the stream, resulting in a greater vulnerability. A GIS mapping tool could be used to plot pumping rates and distance to streams, or a similar metric could be used as a first-pass to prioritize areas. The Level III Assessment is intended to address the management questions/risk factors specific to the system. A Level III Assessment should be used to set priorities.

4. CONCLUSIONS AND RECOMMENDATIONS

Field experiments clearly show effects of pumping on stream depletion (e.g., Hall et al., 2017) and point to the need to consider surface water impacts during groundwater allocation. However, direct measurements of hydraulic connectivity between an aquifer and a stream are not always feasible, particularly at a regional or even provincial scale. The approach presented in this report offers a practical protocol for assessing stream vulnerability. The approach is based on "Vulnerability Assessment for Groundwater Dependent Streams" by Middleton and Allen (2016). It is a multi-level ranking framework designed to determine stream vulnerability to groundwater abstraction. The approach is demonstrated for the Lower Fraser Valley on the south side of the Fraser River.

The Level I Vulnerability Assessments completed for 53 aquifer-steam systems in the Lower Fraser Valley indicate that 5 are ranked high, 27 moderate, and 21 low for Potential Stream Vulnerability. The five aquifer-steam systems ranked high include: 0008 (Vedder River Fan), 0015 (Abbotsford-Sumas), 0027 (Aldergrove), 0035 (Hopington) and 0041 (Brookswood). The recommended action for the high and moderate ranked aquifer-stream systems is to proceed to a Level II Assessment.

The Level II Vulnerability Assessments indicate the Sumas River watershed currently has a low level of vulnerability to groundwater development, and the Serpentine River watershed has a moderate level of vulnerability to groundwater development. No further action is recommended these watersheds unless there is a significant change in groundwater demand, at which point a Level II re-assessment would be prudent.

Eight aquifer-stream systems or watersheds were rated high vulnerability, including: Fishtrap Creek watershed; Bertrand Creek watershed; West Creek watershed; Salmon River watershed; Salmon River – Aquifer 035, 027 and 033; Nicomekl River watershed and Aquifer 058. The recommended action is to proceed to a Level III Vulnerability Assessment to quantify the impacts to the stream from groundwater-related stressors. Level III Assessments could include, for example, construction of a numerical groundwater flow model to evaluate the cumulative effects of pumping on streamflow.

Level III Vulnerability Assessments should be undertaken for Fishtrap Creek watershed; Bertrand Creek watershed; West Creek watershed; Salmon River watershed; Salmon River – Aquifer 035, 027 and 033; Nicomekl River watershed and Nicomekl River - Aquifer 058. Depending on the management question of interest, a Level III Assessment could include enhanced monitoring, a detailed field investigation, use of analytical models to evaluate stream connectivity or the construction of a numerical groundwater flow model to evaluate the cumulative effects of pumping on streamflow.

REFERENCES

Berardinucci, J., and Ronneseth, K. 2002. Guide to Using the BC Aquifer Classification Maps for the Protection and Management of Groundwater. Victoria: British Columbia Ministry of Water, Land and Air Protection.

British Columbia Government. 1997. *Fish Protection Act*. Retrieved from: http://www.env.gov.bc.ca/habitat/fish_protection_act/act/documents/act-theact.html

British Columbia Government. 2016. *Water Sustainability Act*. Sensitive Streams. Retrieved from: http://www2.gov.bc.ca/gov/content/environment/air-land-water/water/water-licensing-rights/sensitive-streams

Cohen, S., Neilson, D. and Welbourn, R. (eds.). 2004. Expanding the Dialogue on Climate Change & Water Management in the Okanagan Basin, British Columbia. Final report, January 1, 2002 to June 30, 2004. Ottawa, ON: Climate Change Action Fund, Natural Resources Canada.

ESRI. 2015. ArcMap 10.3.

Hall, G. Allen, D.M., Tolera, H., Simpson, M., Jackson, B., Middleton, M.A., Lepitre, M. 2017. Assessment of hydraulic connectivity related to groundwater extraction on selected sensitive steams: Phase 1 Field Investigation. Water Science Series, WSS2017-02. Prov. B.C., Victoria B.C.

Hantush, S. 1965. Wells near streams with semipervious beds. Journal of Geophysical Research, 70(12): 2829-2838.

Middleton, M.A., and Allen, D.M. 2016. Vulnerability Assessment for Groundwater Dependent Streams. Final report submitted by Simon Fraser University to BC Ministry of Environment, December 2014.

Washington State Department of Ecology. 2014. Solrad. v. 1.2: A solar position and radiation calculator for Microsoft Excel/VBA. State of Washington, 2014 [cited 04/15 2014]. Available from http://www.ecy.wa.gov/programs/eap/models.html (accessed 2014/04/15).

Wei, M., Allen, D.M. Kohut, A., Grasby, S. Ronneseth, K., and Turner, B. 2009. Understanding the types of aquifers in the Canadian Cordillera hydrogeologic region to better manage and protect groundwater. Streamline Water Management Bulletin 13(1): 10-8.

Winter, T. 1999. Relation of streams, lakes, and wetlands to groundwater flow systems. Hydrogeology Journal 7:28–45.

APPENDIX A: SUMMARY OF THE LEVEL I STREAM VULNERABILITY ASSESSMENT

Table A1: Summary of the aquifer properties and final rank for the Level I Stream Vulnerability Assessment for 53 aquifers in the Lower Fraser Valley.

AQUIFER NUMBER	DEMAND	PRODUCTIVITY	INVERSE PRODUCTIVITY	LEVEL I MATRIX RANKING	FINAL RANK	Notes
0001	Moderate	High	Low	**Low -Moderate**	**Moderate**	
0003	Low	Moderate	Moderate	**Low -Moderate**	**Low**	Type 1a, Close to Fraser River - likely to buffer demand
0006 (Chilliwack-Rosedale)	Low	High	Low	**Low**	**Low**	
0008 (Vedder River Fan)	High	High	Low	**Moderate -High**	**High**	Type 3, commonly connected, groundwater multiple use, max yield 3,000 gpm, shallow aquifer
0009	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	
0010	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	
0015 (Abbotsford-Sumas)	High	High	Low	**Moderate -High**	**High**	Type 4a, commonly connected, shallow aquifer, multiple use, max yield 2000 gpm, uppermost aquifer
0016	Low	Moderate	Moderate	**Low -Moderate**	**Low**	Type 4a, commonly connected, demand low, small area intersected by stream, max yield 30 gpm
0020 (Columbia Valley)	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	

AQUIFER NUMBER	DEMAND	PRODUCTIVITY	INVERSE PRODUCTIVITY	LEVEL I MATRIX RANKING	FINAL RANK	Notes
0021 (Sumas Prairie)	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	
0022	Low	Moderate	Moderate	**Low -Moderate**	**Low**	Type 1a buffers impact, multiple use, max yield 500 gpm, shallow, demand low
0023	Low	Moderate	Moderate	**Low -Moderate**	**Low**	Type 4a, drinking water use, no major stream segment, moderate depth, max yield 50 gpm
0024	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	
0027 (Aldergrove)	High	High	Low	**Moderate -High**	**High**	**Sensitive stream** in the aquifer - stream system
0028	High	Moderate	Moderate	**Moderate -High**	**Moderate**	Type 4b, confined, drinking water use
0029	Low	Moderate	Moderate	**Low -Moderate**	**Low**	Type 4b, confined, wells deep, multiple use, max 100 gpm
0030	Low	Moderate	Moderate	**Low -Moderate**	**Low**	Type 4b, confined, demand low, drinking water use, deep, max 7 gpm
0031	Low	Moderate	Moderate	**Low -Moderate**	**Low**	Type 4c, confined, deep wells, multiple use, max 180 gpm, close to Fraser River, demand low
0032	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	

AQUIFER NUMBER	DEMAND	PRODUCTIVITY	INVERSE PRODUCTIVITY	LEVEL I MATRIX RANKING	FINAL RANK	Notes
0033	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	
0034	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	
0035 (Hopington)	High	High	Low	**Moderate -High**	**High**	Type 4a commonly connected, partially confined, multiple use, quantity concern regional, max 350
0036	Moderate	High	Low	**Low -Moderate**	**Moderate**	Type 1a, moderate demand, drinking water use, moderately deep aquifer, max 30 gpm, lots streams/area
0037	High	Moderate	Moderate	**Moderate -High**	**Moderate**	Type 4a, close to Fraser River, few stream segs, drinking water use, max 300 gpm
0040	Low	Moderate	Moderate	**Low -Moderate**	**Low**	Type 1a, island, drinking water, shallow, max 11 gpm, very few wells
0041 (Brookswood)	High	Moderate	Moderate	**Moderate -High**	**High**	Type 4a, demand high, multiple use, 438 wells, shallow, max 325 gpm
0047	Moderate	High	Low	**Low -Moderate**	**Moderate**	Type 4a, partially confined, drinking water, max 600 gpm, moderate demand
0050	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	
0051	Low	Moderate	Moderate	**Low -Moderate**	**Low**	Type 4c, confined, multiple use, low demand, deep wells

AQUIFER NUMBER	DEMAND	PRODUCTIVITY	INVERSE PRODUCTIVITY	LEVEL I MATRIX RANKING	FINAL RANK	Notes
0052	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	
0053	Low	Moderate	Moderate	**Low -Moderate**	**Low**	Type 4c, confined, low demand, multiple uses, max 500 gpm, deep wells, shallow water table
0054	Moderate	Low	High	**Moderate -High**	**Moderate**	Type 4b, confined, multiple uses, max 40 max gpm
0055	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	
0056	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	
0057	Moderate	High	Low	**Low -Moderate**	**Moderate**	Type 4b, unconfined, multiple uses, till, max 500 gpm, deep water table
0058 (Nicomekl-Serpentine)	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	
0059	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	
0060	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	
0061	Low	High	Low	**Low**	**Low**	

AQUIFER NUMBER	DEMAND	PRODUCTIVITY	INVERSE PRODUCTIVITY	LEVEL I MATRIX RANKING	FINAL RANK	Notes
0072	Low	High	Low	Low	Low	
073	Low	Moderate	Moderate	Low -Moderate	Low	Type 1a, island, no wells
0890	Low	Low	High	Moderate	Moderate	
0891	Low	Moderate	Moderate	Low -Moderate	Low	Type 5a, drinking water use, demand low
0892	Low	Moderate	Moderate	Low -Moderate	Low	Type 4b, confined, drinking water use, demand low, max 270 gpm
0893	Moderate	Moderate	Moderate	Moderate	Moderate	
0894	Low	Moderate	Moderate	Low -Moderate	Low	Type 4b, confined, drinking water use, demand low, max 50 gpm
0895	Moderate	Moderate	Moderate	Moderate	Moderate	
0899	Low	Moderate	Moderate	Low -Moderate	Low	Type 5a, partially confined, multiple uses, isolated quantity concerns, deep, max 200 gpm
0969	Low	Moderate	Moderate	Low -Moderate	Low	Type 5a, drinking water, few stream segments, demand low

AQUIFER NUMBER	DEMAND	PRODUCTIVITY	INVERSE PRODUCTIVITY	LEVEL I MATRIX RANKING	FINAL RANK	Notes
0987	Moderate	Low	High	**Moderate -High**	**Moderate**	Type 6a, mod demand, drinking water use, isolated quantity concerns
1005	Moderate	Moderate	Moderate	**Moderate**	**Moderate**	Upper aquifer, sand/gravel, demand moderate, small area
1007	Low	High	Low	**Low**	**Low**	Sand/gravel, stream segment only adjacent, demand low.
1009	Low	Low	High	**Moderate**	**Moderate**	Igneous bedrock, demand low, steam segment intersects small relative area. Lower aquifer.

APPENDIX B: SUMMARY OF THE LEVEL II STREAM VULNERABILITY ASSESSMENT

Table B1: Level II Assessment results for seven aquifer-stream systems in the Lower Fraser Valley, BC following the method in Middleton and Allen (2016). The outcome of the Level II Assessment is a Stream Vulnerability (SV) rating for each aquifer-stream system.

	Fishtrap Creek	Bertrand Creek	Sumas River	West Creek	Salmon River			Serpentine River	Nicomekl River	
	Watershed	**Watershed**	**Watershed**	**Watershed**	**Aquifer 035**	**Aquifer 27/33**	**Watershed**	**Watershed**	**Aquifer 058**	**Watershed**
Aquifer #	015	015	006-021	32	035	027-033	032-058	058-061	058	035, 041, 052
Type	4a	4a	1a	4c	4a	4b	4c	4b/4c	4c	4a/4b
Aquifer Characteristics Rating (A)	**8**	**8**	**4**	**4**	**8**	**4**	**4**	**4**	**4**	**8**
Precipitation (mm/yr)[a]	1515.5	1515.5	1731.4	1274.4	1274.4	1274.4	1274.4	1260.8	1259.9	1259.9
PET (mm/yr)[b]	470.1	470.1	427.8	412.1	412.1	412.1	412.1	368.9	470	470
Recharge (mm/yr)[c]	1397.1	1397.1	1662.8	1098.6	1098.6	1098.6	1098.6	1135	1099.4	1099.4
Area of watershed/aquifer (m^2)	3.70E+07	5.10E+07	1.71E+08	1.49E+07	5.06E+07	3.47E+07	8.05E+07	1.47E+08	1.94E+08	2.19E+07
Q_R (m^3/yr)	5.17E+07	7.13E+07	2.84E+08	1.64E+07	5.56E+07	3.81E+07	8.85E+07	1.67E+08	2.13E+08	2.41E+07
Q_S (m^3/yr)[d]	2.07E+06	6.95E+05	8.33E+06	1.11E+06	2.18E+06	2.18E+06	2.18E+06	5.91E+05	3.08E+06	3.08E+06
Q_s/Q_R	0.040	0.010	0.029	0.068	0.039	0.057	0.025	0.004	0.014	0.128
Recharge Ratio Rating (Q_S/Q_R)	**6**	**5**	**6**	**6**	**6**	**6**	**6**	**7**	**6**	**5**
Stream Susceptibility (SS)	**48**	**40**	**24**	**24**	**48**	**24**	**24**	**28**	**24**	**40**
Q_P	2.37E+08	1.22E+08	7.61E+07	2.41E+07	7.36E+07	2.51E+08	1.99E+08	1.31E+08	2.41E+08	2.94E+08
n	856	828	577	257	740	1913	1581	1407	2213	3018
Q_P/Q_R	4.58	1.71	0.27	1.47	1.32	6.58	2.25	0.78	1.13	12.20
Hazard Rating (H)	**8**	**8**	**2**	**8**	**8**	**10**	**8**	**6**	**8**	**10**
Stream Vulnerability (SV)	**High**	**High**	**Low**	**High**	**High**	**High**	**High**	**Moderate**	**High**	**High**

[a] The climate data were for the period spanning 1990-2012 based on availability;
[b] Estimated using the method from Middleton and Allen (2016);
[c] Recharge calculated only for days when precipitation occurred;
[d] Stream discharge data were for the summer periods (July – Sept.) spanning 1980 to 2012 based on availability. Serpentine River the only available stream discharge data were from 1960-1966