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Determining the Likelihood of Hydraulic Connection

Guidance for Determining the Effect of Diversion of Groundwater on Specific Streams

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Photograph of a well adjacent to Haslam Creek, Vancouver Island, BC, by Graeme Henderson.

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EXECUTIVE SUMMARY

The likelihood of hydraulic connection between groundwater in an aquifer and water in a stream is an essential consideration in the allocation and use of water under the *Water Sustainability Act*. Likelihood of hydraulic connection allows demand from well pumping to be accounted for in relation to specific streams to inform the supply-demand analysis of those streams. This document provides simple technical guidance for decision makers, water allocation staff, and professional hydrogeologists in determining the likelihood of hydraulic connection and assigning demand from well pumping to specific streams. This guidance is developed from general principles of surface water-groundwater interaction and generally limited available data in BC. In applying the approaches presented in this document, it may be prudent to seek the direction of a hydrogeologist with local knowledge, especially if the hydrogeology is complex or not well understood. It would also be prudent for the decision maker to maintain flexibility in the authorization of groundwater use to allow for improved understanding of hydraulic connection over time as new information comes to light or improved methods are developed in the future.

CONTENTS

1. BACKGROUND

Historically, the allocation of water diverted from streams in BC did not consider the effects of well pumping from hydraulically connected aquifers because there was no requirement to authorize groundwater diversion and use. Under the *Water Sustainability Act* (*WSA*), the diversion and use of groundwater for non-domestic purposes require an authorization (i.e., a licence or a use approval (use not exceeding 24 months)).

Experience in BC shows that groundwater, especially where it occurs in unconfined sand and gravel aquifers near rivers, creeks, lakes, ponds, wetlands and springs, often exists in hydraulic connection with water in streams[1]. Recognizing this connection is important in water allocation because groundwater diversion from a connected aquifer can increase the water demand on a stream and deplete streamflow. Stream depletion, in turn, reduces the supply of streamflow for future allocation and, if significant enough, can compromise the protection of environmental flow needs (EFNs) and impact the rights of existing stream users. Depletion of streamflow from well pumping occurs by two main processes: 1) interception of groundwater flow that would have originally discharged to the stream and; 2) inducing infiltration of water from the stream into the aquifer (see Figure 1).

1.1 Hydraulic connection and water allocation and use

The *WSA* references hydraulic connection between water in a stream and groundwater in an aquifer in distinct contexts when:

1. considering environmental flow needs 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, or in the operation of a well (sections 46, 47, 59, and 60 of the *WSA*), and;
4. identifying hydraulically connected aquifers in the designation of a sensitive stream (section 128 of the *WSA*).

As part of the allocation process, the decision maker will need to determine whether the aquifer is reasonably likely to be hydraulic connected to streams, and if so, whether well pumping will affect streamflow, stream water users and the aquatic habitat. If the test of “reasonably likely” is met for connection to a specific stream(s), the demand from well pumping can then be accounted for in relation to the connected stream(s) to assess the impact of groundwater diversion on EFNs and on holders of rights on those stream(s), or in taking of action on users during a time of water scarcity (context 2).

1.2 Scope and Purpose of Document

This document provides technical guidance to decision makers, water allocation staff, and professional hydrogeologists on simple approaches to determining the likelihood of hydraulic connection between groundwater in an aquifer and water in a stream(s) and determining the impact from the well pumping on specific streams. This document does not address impacts of well pumping on groundwater

[1] In the *WSA*, the term “stream” is defined broadly to include, for example, a lake, pond, river, creek, spring, water in a ravine or gulch, wetland, glacier. The use of the word “stream” in this document reflects this broad definition of “stream” in the *WSA*.

availability in the aquifer (that should be addressed through the development and use of aquifer water budgets or more detailed quantitative analyses).

The approaches presented here tend to identify situations where hydraulic connection is most likely. There will be situations where the hydraulic connection is uncertain and does not meet the test of "reasonably likely" because of lack of adequate understanding (e.g., hydrogeology is complex or there is very little information). The policy document, Considering Hydraulic Connection in Allocation Decisions, also provides some general guidance on options a decision maker can take as next steps to address this uncertainty.

This document does not address connectivity in relation to foreign matter in a stream or aquifer; that involves different technical considerations (e.g., need to define contaminant pathways). Nor does the document address the assessment of EFNs; for assessment of EFNs, the reader should refer to the Environmental Flow Needs Policy.

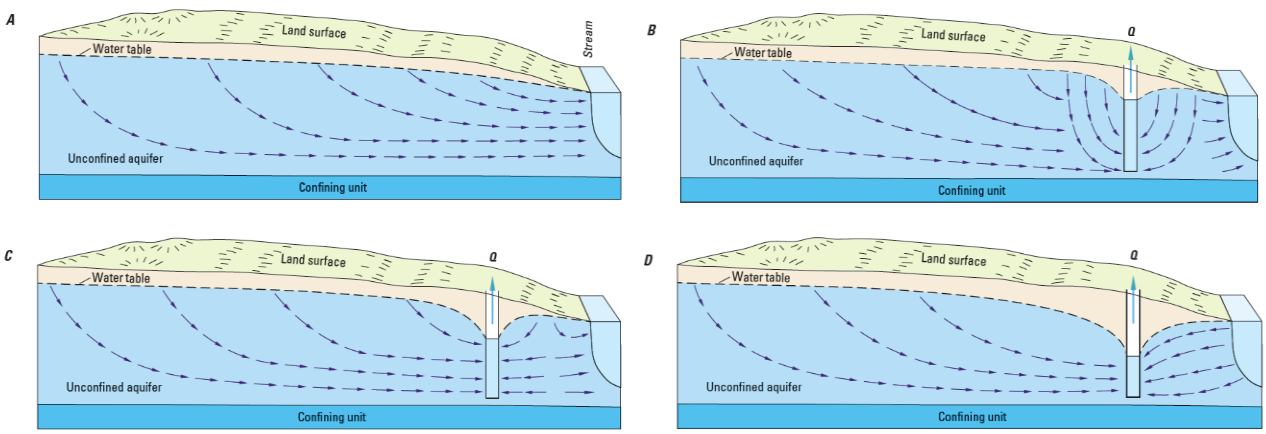


Figure 1 Diagram illustrating the effects over time of well pumping near a hydraulically connected stream (diagram from Barlow and Leake, 2012), from initial non-pumping condition (A), to pumping at early time when much of the groundwater diverted from the well comes from storage in the aquifer (B), to later pumping time when groundwater diverted from the well comes from interception (C) and interception and infiltration of water from the nearby stream (D).

2. ASSESSING LIKELIHOOD OF HYDRAULIC CONNECTION

2.1 Hydraulic connection defined

"*Hydraulic connection*", for the purpose of water allocation and use, means 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. This definition reveals some inherent principles in determining hydraulic connection:

- The person determining likelihood of hydraulic connection is the decision maker;
- "Reasonable likelihood" is the test, a test that should meet a certain level of probability; this level of probability should, in turn, be based on evidence that directly links connection between the pumping well to the stream;

- "Change in the flow of a stream or spring or change in the level of a lake, pond or wetland" reflects the significance of the impact, as well as ability to detect the impact, and;
- "Eventually result" and "a time period" recognizes the often delayed-response of stream depletion (up to years or decades) from well pumping or stream recovery from cessation of pumping, and the relevance of this delayed response in water allocation and taking of action during a temporary period of water scarcity. "Eventually result" also implies considering the cumulative impact of pumping of all wells in the connected aquifer.

In the water allocation process, the information available to assess hydraulic connection is often from the information about the well, a technical assessment submitted by the applicant's professional (if an assessment is required), as well as other information, such as:

- geological mapping covering the area;
- well construction reports of nearby wells;
- available reports on studies and assessments for the aquifer;
- observation well monitoring, as well as
- staff knowledge of the hydrology and hydrogeology of the area, based on experience.

2.2 Assessing likelihood of connection from aquifer type

The most basic, but useful, information for assessing likelihood of hydraulic connection between water in a stream and an aquifer is the aquifer type. Aquifer type is based on geology, a primary factor governing hydraulic connection. For example, groundwater occurring in unconfined sand and gravel deposited along a river (Type 1 aquifer) will likely be in hydraulic connection with the river. For a more detailed explanation of aquifer types, please see Wei et al (2009).

Aquifer type has been determined for all of the classified aquifers in BC; classified aquifers can be viewed via the BC Water Resources Atlas or iMAPBC. Aquifer type can also be interpreted from the location of the well and from the lithologic description in the well construction report (or reports for nearby wells), whether an aquifer has been classified or not. Table 1 lists the types of aquifers and the likelihood of hydraulic connection with a stream for each type. For example, hydraulic connection is likely for a well diverting water from a Type 1 or 2 aquifer and less likely for a Type 4c aquifer.

Figure 2 shows an unconfined fluvial sand and gravel (e.g., Type 1) aquifer in a stream valley bottom and a fractured crystalline bedrock (e.g., Type 6b) aquifer underlying a hillslope with a bedrock spring. The sand and gravel aquifer is likely connected to the stream because of the aquifer type. As such, the pumping demand from both wells 2 and 3 can be assigned to the stream in assessing the supply-demand of that stream.

Figure 2 also shows that groundwater in the fractured bedrock flows towards the stream. However, it is uncertain whether the groundwater in the bedrock discharges to the valley-bottom stream or not. Without further information linking groundwater in the bedrock to the stream, it is unclear as to whether pumping of the bedrock well would deplete the stream. Furthermore, any depletion may also be hard to detect given the likely lower permeability of the bedrock.

With respect to the bedrock spring, however, the pumping drawdown cone for well 1 has a reasonable likelihood of depleting the flow of the spring because of its close proximity (the spring is within the area of drawdown of well 1). Therefore, it is reasonably likely that the bedrock aquifer and the bedrock spring are hydraulically connected.

TABLE 1 Framework for preliminary assessment of likelihood of hydraulic connection of an aquifer to proximal streams.

Aquifer Type	Rationale for Likelihood of Connection	Likelihood of Hydraulic Connection
Types 1a, 1b, 1c - Unconfined fluvial/glaciofluvial sand and gravel aquifers (along large, medium and small streams, respectively). Type 2 - deltaic sand and gravel aquifers. Type 3 - alluvial or colluvial sand and gravel aquifers. Type 4a - unconfined glaciofluvial sand and gravel aquifers.	Unconfined aquifers have a high likelihood to be hydraulically connected to a nearby stream(s) because there is no confining layer present to hydraulically isolate the aquifer from an overlying or bordering stream. The stream(s) that pumping of the well is likely to deplete should be specified so demand can be accounted for (see Section 3 for determining impact to specific streams).	Likely connected to an overlying or bordering stream.
Type 4b or 4c - Confined sand and gravel aquifers.	Aquifers that are separated from an overlying or bordering stream by a confining layer that is continuous are likely not considered hydraulically connected to that overlying or bordering stream. However, many aquifers that have been classified as confined aquifers in BC are variably or partially confined and do exhibit hydraulic connectivity to streams. Evidence that may indicate a confined aquifer is hydraulically connected to a stream include: • Lithological information from nearby wells indicating the lithology, thickness and degree of continuity of the confining layer (i.e., evidence of a semi- confined aquifer or windows in the confining layer) or geological evidence that the stream channel has incised into the aquifer, • Observed reduction in streamflow or water levels linked to pumping from the confined aquifer, • Stabilization of the drawdown during pumping.	Not likely connected or does not currently meet the test of reasonably likely to be connected unless there is evidence directly linking the aquifer to specific streams. Site specific evidence or local knowledge is generally needed before presence of hydraulic connection to specific streams can be confirmed.
Type 5a - Fractured sedimentary bedrock aquifers. Type 6a – Volcanic flow aquifers Type 6b - Crystalline bedrock aquifers.	For main valley bottom areas dominated by unconsolidated aquifers, the transmissivity of underlying or adjacent bedrock aquifers are commonly much smaller than unconsolidated aquifers; therefore the contribution to baseflow is generally smaller. For bedrock regions of higher relief, unstratified fractured crystalline bedrock aquifers (type 6b) can be considered hydraulically connected to headwater or tributary streams within their catchment. Additional evidence from pumping may help confirm connection, such as: • Observed reduction in streamflow linked to pumping from the bedrock aquifer, • Stabilization of the drawdown during pumping.	In general, not likely connected or does not currently meet the test of reasonably likely to be connected unless there is evidence directly linking the aquifer to specific streams. In areas of higher relief likely connected to lower order streams within the same catchment. Site specific evidence or local knowledge is generally needed before presence of hydraulic connection to specific streams can be confirmed.
Type 5b -Karstic limestone aquifers.	Although Karst formations are not well studied in BC, these systems can be highly heterogeneous and unpredictable. They can be hydraulically connected to surface water bodies, and potentially can have large conductivity, which can support base flows.	Likely connected.

Modelling studies by Welch and Allen (2012) and Welch et al (2012) also suggest that in higher relief unstratified fractured bedrock (e.g., type 6b aquifers), groundwater naturally flows to lower order headwater streams and well pumping in these areas would deplete streams via interception. Welch (2016, personal communication) suggests that connection to streams within the same catchment would be likely in these areas. In general, hydraulic connection between a fractured bedrock aquifer and nearby streams may be further evaluated by pumping the bedrock well and observing whether there are any changes to streamflow.

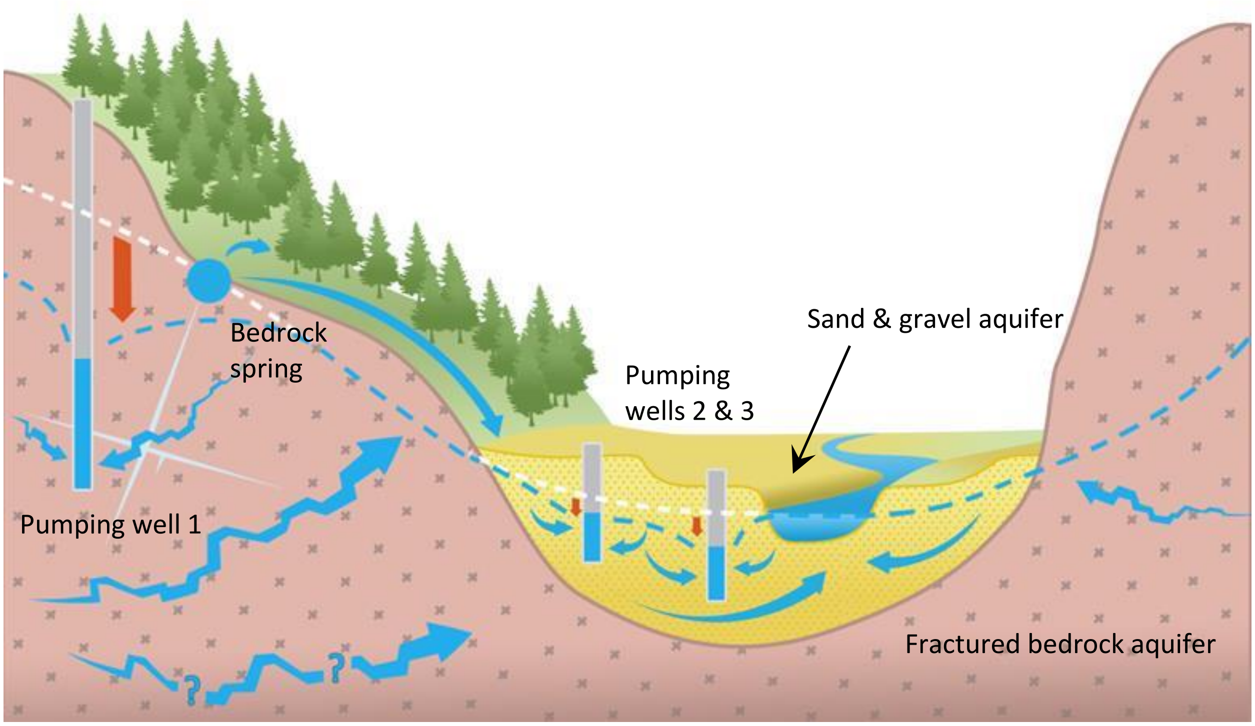
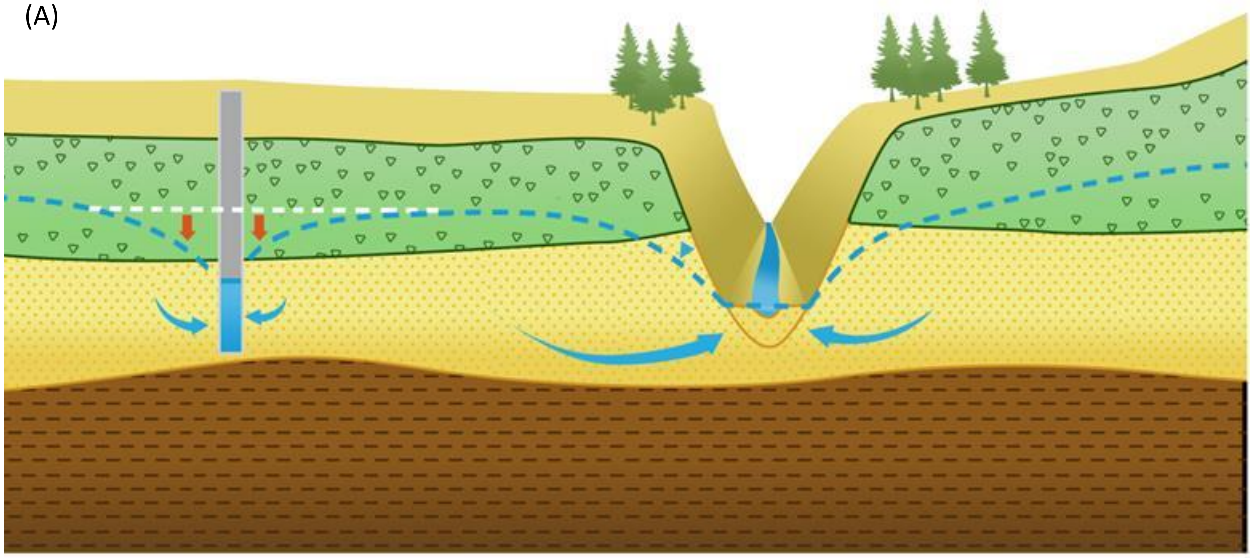


Figure 2 Diagram relating aquifer type and well location to hydraulic connection to nearby streams (valley bottom stream or bedrock spring). Vertical red arrows depict drawdown in the groundwater level as a result of pumping.

While Table 1 is useful for identifying those aquifer types that are most likely to be hydraulically connected to surface water, the corollary that the other aquifer types are not hydraulically connected should be critically viewed. For example, some deeper sand and gravel aquifers along river valley bottoms (e.g., Englishman River near Parksville on the east coast of Vancouver Island or the Salmon River at Westwold near Kamloops) may be confined but a stream may have incised through the confining layer to the aquifer; the confining layer may thin out, allowing groundwater to discharge to a local stream; or the confining layer may be permeable enough to transmit significant quantities of water (Figure 3). In those examples, pumping of wells drilled into the confined aquifer may deplete the stream by intercepting groundwater that may originally have discharged to the stream. Middleton and Allen (2016) also suggest that confined sand and gravel aquifers and bedrock aquifers can contribute significant baseflow to streams, implying existence of hydraulic connection. However, discerning connection to specific streams is a key challenge to determining impact from pumping to a specific stream(s). While aquifer types are useful, it should not override professional judgement. Finally, Table 1 may not be sufficient for licensed springs. Section 4 of this document describes an approach for assessing the likelihood of hydraulic connection between a pumping well and a spring.

(A)



(B)

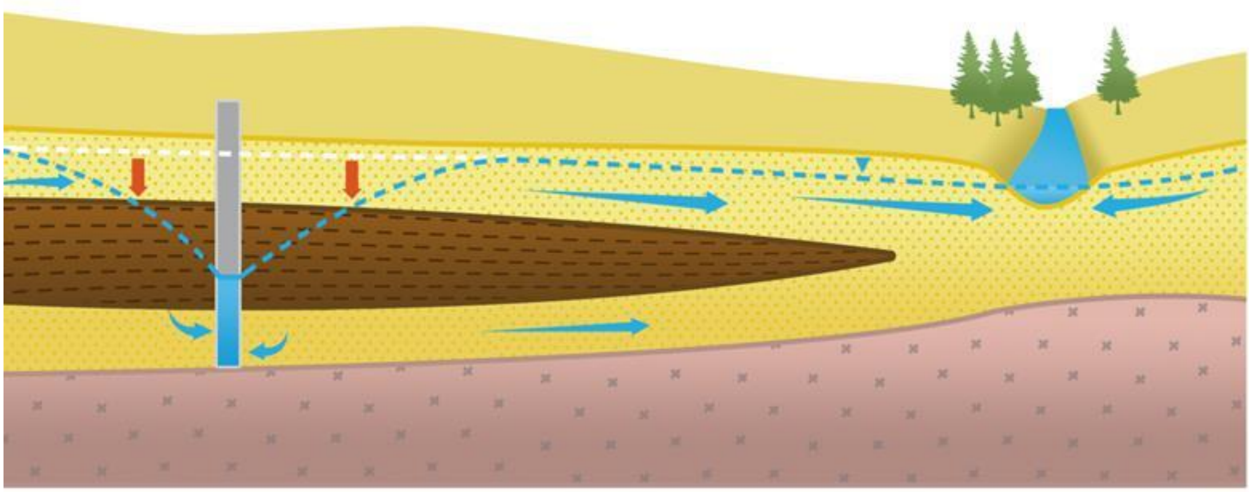


Figure 3 Diagram showing two examples of where a confined aquifer may be hydraulically connected to a nearby stream; (A) a stream has incised through the confining layer (green) and (B) a confining layer (brown) thins out upgradient of the stream.

2.3 Dealing with uncertainty in determining hydraulic connection

In situations where the likelihood of connection is uncertain because of lack of information, the demand from well pumping would not be assigned to a specific stream(s). However, the decision maker has options, please refer to the operational policy: Considering Hydraulic Connection in Allocation Decisions.

Addressing uncertainty is especially important where there are known concerns with streams overlying or bordering the aquifer. The determination of hydraulic connection to streams should also be documented (a sample documentation sheet can be found in Appendix A) so that when hydraulic connection to a stream is reviewed in the future, there will be a record of how the determination was originally arrived at.

Another option for the decision maker and water allocation staff is to identify critical areas where more in-depth technical studies can be conducted to better understand surface water-groundwater interaction and hydraulic connection, including analytical and numerical modelling (see Rathfelder, 2016), risk-based assessments (e.g., Middleton and Allen, 2016), or field measurements. As understanding of the aquifer increases over time, the determination of likelihood of connection can be more likely confirmed.

2.4 Assessing the likelihood of hydraulic connection for existing groundwater users

Many existing groundwater users, particularly smaller users, will not have any information on previous testing or assessments of their pumping well submitted as part of their application for authorization during the *WSA* transition period (as described in S. 55 of the Water Sustainability Regulation). The decision maker determining the likelihood of hydraulic connection would typically base their determination on:

- the aquifer type;
- staff knowledge of the local aquifer, and
- any additional information, such as evidence supplied by other licensees or a previous hydrogeological assessment report done for the well by a groundwater consultant.

2.5 Assessing the likelihood of hydraulic connection for new wells

For an application for new groundwater use, additional site-specific information may be required to inform likelihood of connection to specific streams. This information will be obtained from technical assessments carried out by the applicant's professional in support of the application (see Todd et al, 2016). Information from site-specific testing (e.g., pumping test, water chemistry), monitoring water levels in the aquifer and the stream, or geological analysis (e.g., constructing hydrogeological cross-sections and maps) as a result of a technical assessment will help inform the likelihood of hydraulic connection.

2.6 Example of a well for a subdivision in the West Kootenay

A 34-lot subdivision on the east shore of a large lake in southeastern BC serves as an illustrative example. The subdivision well is 47.5 m deep, drilled into unconsolidated sands and gravels. The well is completed with a 1.2 m, 100-slot screen at a depth of 46.3-47.5 m. The location of the well is shown in Figure 4 and the lithology from the well construction report is presented in Table 3.

The lithology in Table 3 and location of the well within an alluvial fan are evidence that the subdivision well is drilled into the alluvial fan which is an unconfined sand and gravel aquifer (Type 2). This type of aquifer suggests that it is likely in hydraulic connection with the local streams. Several streams border the aquifer: a stream (Wilson Creek), the large lake, as well as unnamed creeks west and east of the subdivision well (Figure 4). A 20-hour pumping test was conducted on the subdivision well. The well was pump tested at a constant rate of 273 m^3/day and experienced 1.01 m of drawdown after 15 minutes before the drawdown stabilized. The stabilization in drawdown during pumping is additional evidence, along with the geology and aquifer type, that there is a hydraulic connection with surface waters. These connections are most likely the stream, the large lake and the two unnamed creeks. The reported static water level of 39.0 m in the well roughly matches the elevation of the large lake and the stream.

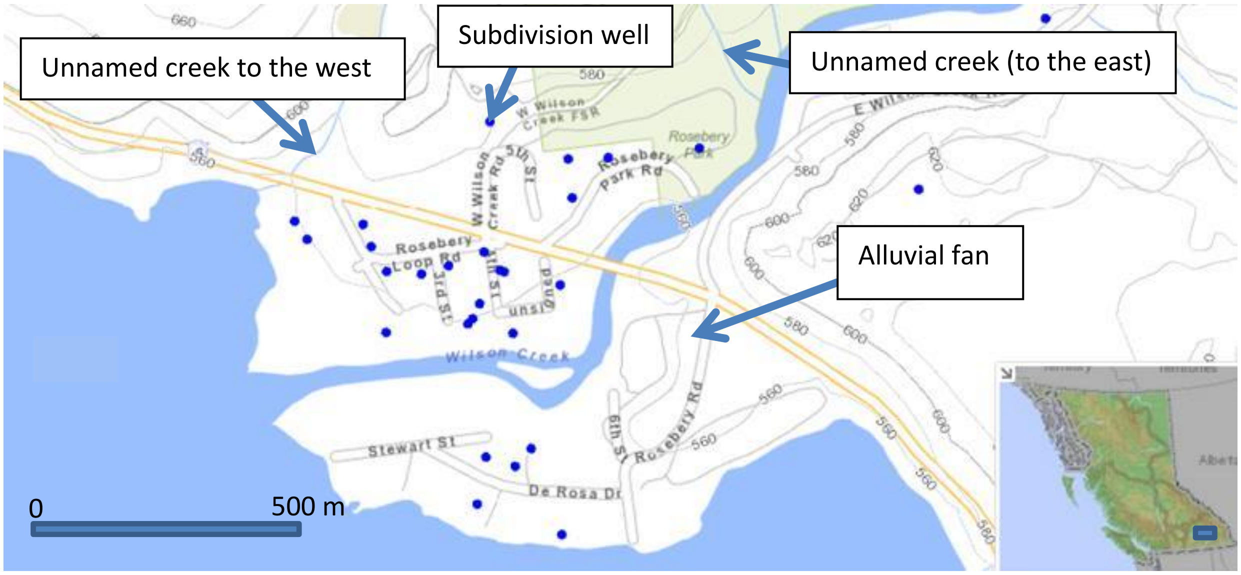


FIGURE 4 Map showing the location of the subdivision well (labelled circled blue dot), neighbouring wells (blue dots), the alluvial fan, as well as nearby streams (from the BC Water Resources Atlas).

TABLE 3 Lithology from drilling of the subdivision well.

From (m)	To (m)	Lithologic Description
0	22.9	Hard brown gravel & boulders
22.9	39.6	Hard brown sand & gravel
39.6	47.5	Hard brown sand & gravel

3. ASSIGNING DEMAND FROM WELL PUMPING TO STREAMS

An important implication of well pumping on a hydraulically connected stream (or streams) is the impact on the stream's supply. Intercepting flow to the stream as a result of well pumping decreases the input of groundwater to the stream. Inducing infiltration of stream water into the aquifer from well pumping increases the component of outflow to groundwater from the stream. Both of these impacts decrease the quantity of water in the stream and need to be accounted for in assessing the availability of water in the stream. This section presents how demand from well pumping can be accounted for in hydraulically connected streams.

3.1 Hydraulic connection to a single stream

If hydraulic connection to a single steam is considered likely, demand from groundwater diversion should be accounted for in the supply-demand analysis of the stream. Depending on the distance the pumping well is from the stream, aquifer hydraulic properties (transmissivity and storativity) and streambed characteristics, this demand may take days to years to fully materialize.

For wells drilled into fractured crystalline bedrock aquifers in high relief regions, ambient groundwater flow can be commonly inferred from topography to identify the stream the pumping well is most likely to deplete (Welch and Allen (2012) and Welch et al (2012)). Figure 5 shows this simple concept (for Well 1). If the pumping well straddles two sub-watersheds (e.g., Well 2 in Figure 5), the approach in section 3.2 can be used to assign a portion of the demand of pumping of well 2 to each stream. An important assumption here is that water is not a limiting factor in the streams (e.g., depletion does not dry up the streams). This assumption may not always be valid in these headwater streams. Where water may be limiting, another option is to assign the demand from pumping to the next higher order stream in the same stream network (because there is not enough water available in the lower order stream).

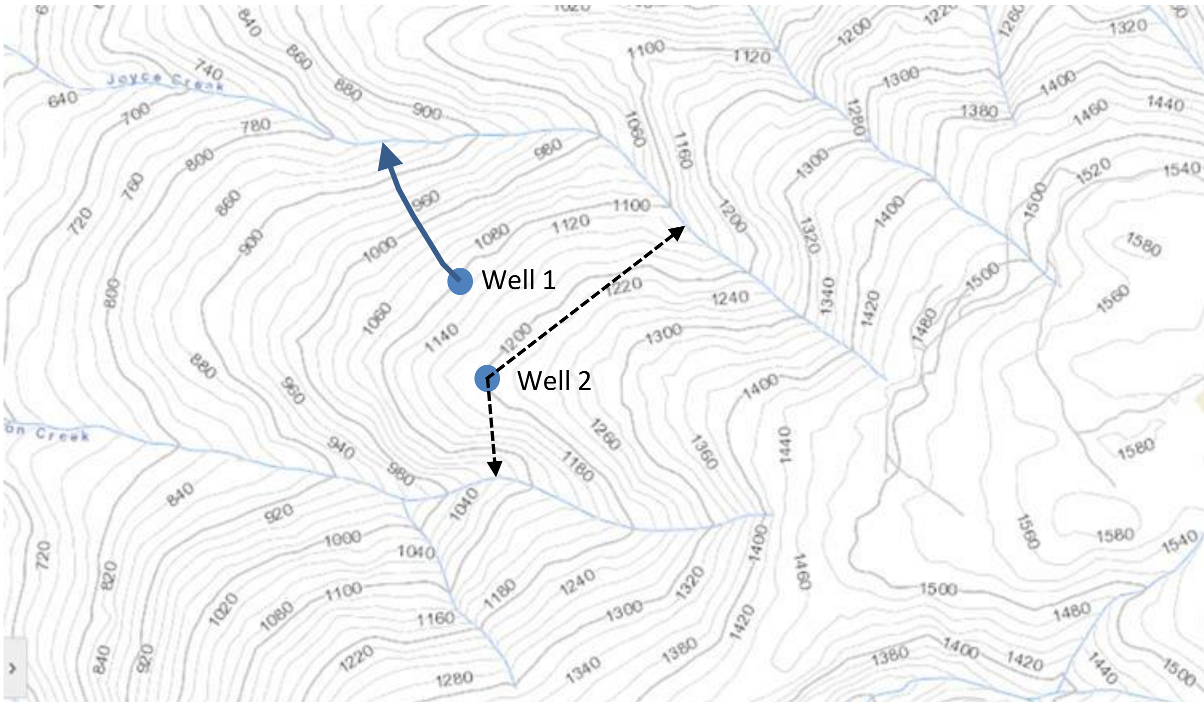


Figure 5 High relief region underlain by unstratified crystalline fractured bedrock. Demand from well 1 (blue dot) is assigned to the creek to the north. Demand from pumping well 2 (blue dot) is split between the creek to the north and the creek to the south.

3.2 Assigning demand to specific streams in a stream network (hydraulically connected to more than one stream)

If a well is located close to more than one hydraulically connected stream, pumping can deplete flow in more than one stream. Assigning a portion of the total demand to each stream can be difficult and can have a degree of uncertainty, especially if the geology is complex and given that information about surface water-groundwater interaction in BC is generally limited. As a first approximation, this section presents a simple method of assigning demand to the most likely streams, based solely on the relative distances between the well and the streams (adopted from Reeves et al (2009)). As more data become available over time, more physically based models can be developed that incorporate greater physical complexity of surface water-groundwater interaction.

When pumping of a well occurs within a stream network, the area of drawdown can propagate in all directions potentially causing streamflow depletion in multiple stream segments and neighboring catchments (Barlow and Leake (2012)). Morgan and Jones (1999) in their study in Washington State outlined three general statements on the characteristics of streamflow depletion from pumping in a stream network:

- A well pumping from an unconfined aquifer in contact with streams will tend to capture most of the groundwater discharge from the nearest stream.

- Increasing the distance between the well and any particular stream within a stream network allows the well to capture more discharge from other stream segments, both up-gradient and down-gradient from the pumping well.
- When a semi-confining layer separates the pumped aquifer from the adjacent stream, the effects of pumping are spread over a broader area, resulting in a wider distribution of surface water depletion; increasing the depth of the well and increasing number of confining layers amplifies these effects.

Decision makers and staff should be aware that well pumping can potentially affect flows in stream segments that are a considerable distance upstream or downstream (e.g., kms) from the stream segment(s) in question. Because groundwater withdrawals can impact more than one stream segment at any time, the allocation of groundwater demand within a stream network requires a two-step analysis:

1. Determine if the well is hydraulically connected to one or more streams.

2. Assign a portion of the total demand from well pumping to each stream segment or other surface water body that underlies or borders the aquifer, using process outlined below.

To assign demand from well pumping among adjacent stream segments, an inverse distance calculation can be used, as a first approximation. Analysis conducted by Reeves et al (2009) in Michigan State found the inverse distance method to be simple, straightforward, and effective when compared to alternative modelling approaches.

The inverse distance method is expressed by the formula:

$$f_i = \frac{\frac{1}{d_i^m}}{\sum_{j=1,n} \frac{1}{d_i^m}}$$

where,

f_i	Is the fraction of the total pumping demand added to stream segment i.
d_i	Is the distance from the pumping well to the closest point of stream segment i.
n	Is the number of stream segments hydraulically connected to the pumping well.
m	Is a weighting factor, usually set to 1 (linear) or 2 (squared). A larger weighting factor results in a greater contribution from the nearest stream segment. A weighting factor of 2 is recommended for general applications.

This method assumes that water in any of the streams is not limiting and the aquifer geology is relatively uniform; this assumption should be accepted with caution especially for smaller streams where flow may be limiting. Professional judgement based on local conditions may help further inform how a portion of the total demand should be assigned to each stream.

3.2.1 Example 1 – Assigning fractional demand among neighbouring streams

Consider a well located in an unconfined sand and gravel aquifer (Figure 6). The well is located in an area tributary to a higher order river and adjacent to neighboring tributary watersheds. Well pumping results in streamflow depletion from each of the three adjacent stream segments. The percentage demand from pumping on each stream can be estimated by:

$$f_{ms} = \frac{\frac{1}{d_{ms}^m}}{\frac{1}{d_{ms}^m} + \frac{1}{d_1^m} + \frac{1}{d_2^m}}; \qquad f_1 = \frac{\frac{1}{d_1^m}}{\frac{1}{d_{ms}^m} + \frac{1}{d_1^m} + \frac{1}{d_2^m}}; \qquad f_2 = \frac{\frac{1}{d_2^m}}{\frac{1}{d_{ms}^m} + \frac{1}{d_1^m} + \frac{1}{d_2^m}}$$

If the distances in this example are: the distance to mainstem, d_{ms}= 300 m; distance to tributary 1, d_1=200 m; and distance to tributary 2, d_2 = 800 m, and a weighting factor of m=2 is used, then the percentage demand from pumping assigned to the three streams is:

Main stem: $$f_{ms} = \frac{\frac{1}{300^2}}{\frac{1}{300^2} + \frac{1}{200^2} + \frac{1}{800^2}} = 29.5\%$$

Tributary 1: $$f_1 = \frac{\frac{1}{200^2}}{\frac{1}{300^2} + \frac{1}{200^2} + \frac{1}{800^2}} = 66.4\%$$

Tributary 2: $$f_2 = \frac{\frac{1}{800^2}}{\frac{1}{300^2} + \frac{1}{200^2} + \frac{1}{800^2}} = 4.1\%$$

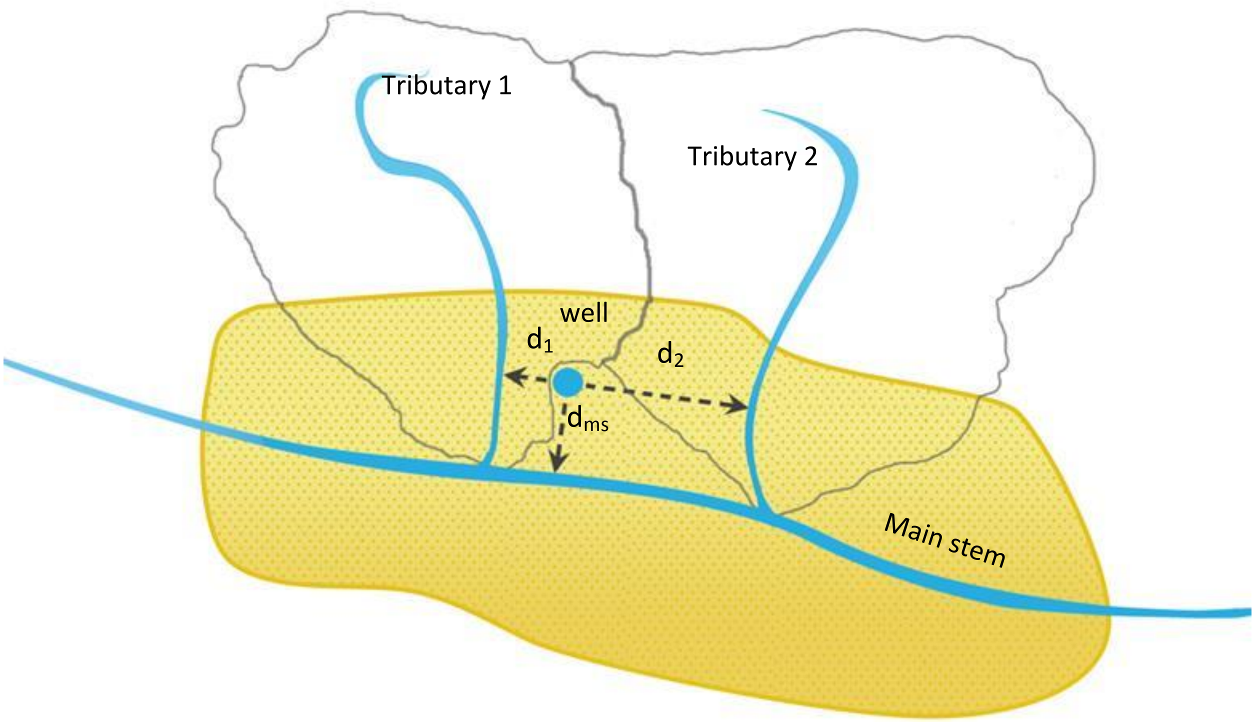


Figure6 Assigning demand among neighbouring streams – example 1.

To focus accounting of demand from pumping on the most likely affected streams, an option may be that the percentage demand for a stream is set to zero when the calculated percentage is less than 10%[2]. The percentage demands are then recalculated for the remaining connected streams. In the example above, the percentage demand from pumping on tributary 2 is considered minor, and the demand would be recalculated considering only the main stem and tributary 1:

$$\text{main stem:} \quad f_{ms} = \frac{\frac{1}{300^2}}{\frac{1}{300^2} + \frac{1}{200^2}} = 30.8\%$$

$$\text{tributary 1:} \quad f_1 = \frac{\frac{1}{200^2}}{\frac{1}{300^2} + \frac{1}{200^2}} = 69.2\%$$

$$\text{tributary 2:} \quad f_2 = 0$$

If the well is intended to pump 20,000 m^3/yr (~ 54.8 m^3/day), then the annual fractional demand from pumping would be assigned to the three streams as follows:

$$\text{main stem} = \left(20{,}000\frac{\text{m}^3}{\text{yr}}\right) \times 0.308 = 6{,}160\frac{\text{m}^3}{\text{yr}}$$

$$\text{tributary 1} = \left(20{,}000\frac{\text{m}^3}{\text{yr}}\right) \times 0.692 = 13{,}840\frac{\text{m}^3}{\text{yr}}$$

$$\text{tributary 2} = 0\frac{\text{m}^3}{\text{yr}}$$

Not assigning a fractional demand to a stream if the percentage demand is <10% may not be appropriate in all cases, especially if water in the stream is limited. Professional judgement should be exercised and the method of calculating fractional demand should be documented.

3.2.2 Example 2 – Assigning demand among neighbouring streams.

At some locations, stream networks can be highly irregular, with numerous tributaries resulting in more ambiguity about which stream segment to assign depletion from well pumping. In many instances it is not possible to extend a line from the pumping well directly to a stream without crossing other streams (Figure 7).

[2] Splitting demand only to streams where the percentage demand is ≥10% was suggested by allocation staff to focus on the most likely affected streams.

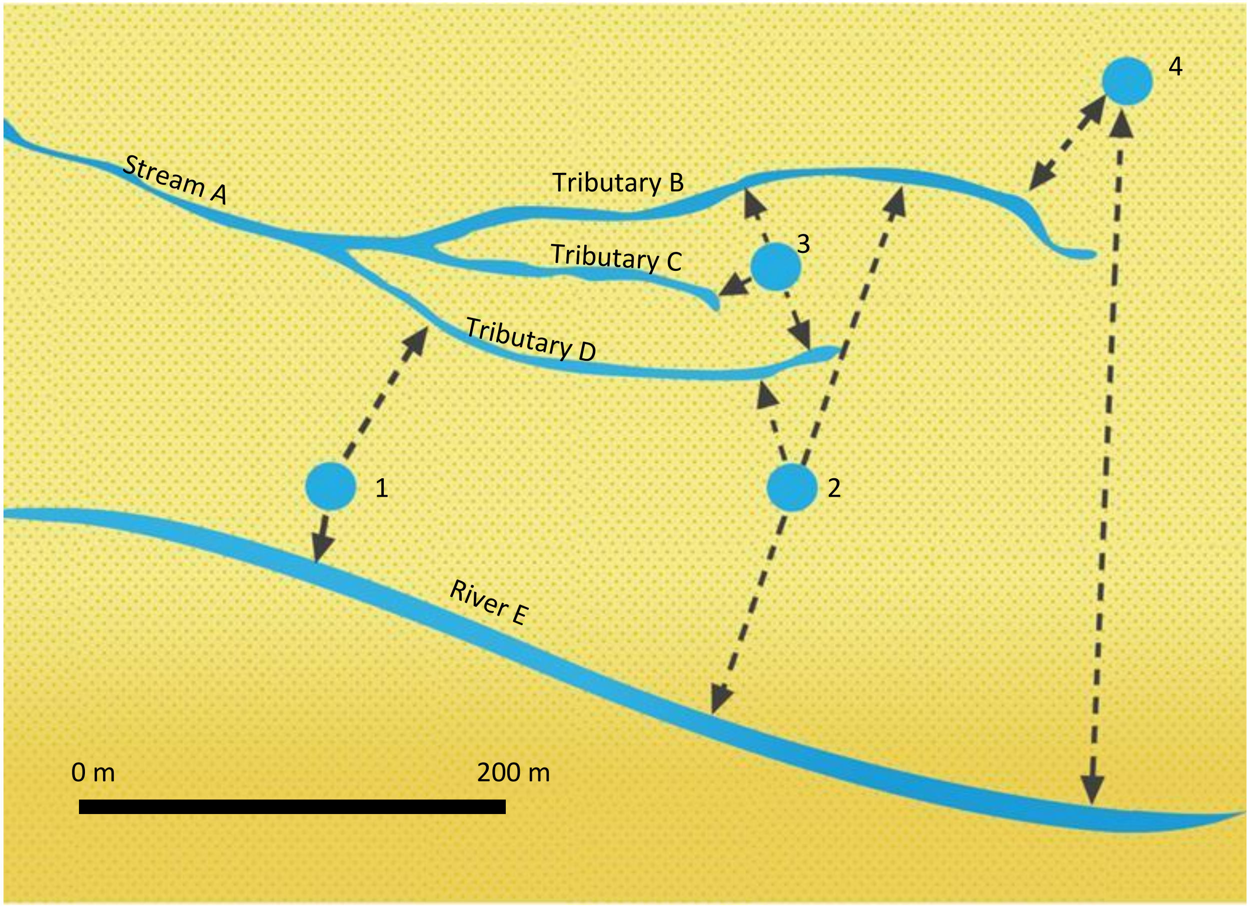


Figure 7 Assigning demand among neighbouring streams - example 2.

Figure 7 depicts a river (E), and a stream (A) with three tributaries (B, C, D). Underlying the entire area is a shallow, sand and gravel aquifer and the flow of groundwater in the aquifer is connected to the stream by the fact that there is no confining geological layer and the elevation of the stream and the water table are similar. There are also four wells (represented by the blue circles) drilled into the underlying aquifer at various locations relative to the stream network.

The following guidance can be used:

- Determine the distance from the well to a stream; select the shortest distance(as shown);
- Do not assign demand to streams where a line can not be drawn from the well directly to those streams, unless evidence exists to the contrary;
- Use a weighting factor of 2 (as recommended for general applications in Section 3.2);
- In applying the method, if the percentage demand to a stream is <10%, that particular stream is ignored and the percentage demand is recalculated for the remaining streams that have percentage demand amounts of ≥10%. Exceptions to this rule of thumb include where water in a stream is limiting and the <10% recalculation rule should not be invoked.

For well 1, depletion is anticipated for river E and tributary D (direct lines can be drawn to those streams). Due to well 1's location, depletion of tributaries B and C do not apply (e.g., direct lines cannot be drawn without crossing a stream). For well 2, depletion is expected for tributaries B and D, and river E (note the line from well 2 to tributary B is not the shortest line, but a direct line is possible). For well 3, depletion is expected for tributaries B, C, and D. Finally, for well 4, depletion is expected for tributary B and river E. By nature of the well locations, no depletion is directly assigned to stream A but depletion to stream A is felt from depletions from the tributaries (Table 4).

TABLE 4 First iteration of calculating percentage demand from the various pumping wells (1, 2, 3, and 4) to neighbouring streams – example 2.

	Stream A		Tributary B		Tributary C		Tributary D		River E	
	Distance	%	Distance	%	Distance	%	Distance	%	Distance	%
Well 1	-		-		-		95 m	18	45 m	82
Well 2	-		170 m	8	-		55 m	76	120 m	16
Well 3	-		40 m	32	35 m	42	45 m	26	-	
Well 4	-		80 m	95	-		-		355 m	5

TABLE 5 Second iteration of calculation – example 2.

	Stream A		Tributary B		Tributary C		Tributary D		River E	
	Distance	%	Distance	%	Distance	%	Distance	%	Distance	%
Well 1	-		-		-		95 m	18	45 m	82
Well 2	-		170 m	0	-		55 m	83	120 m	17
Well 3	-		40 m	32	35 m	42	45 m	26	-	
Well 4	-		80 m	100	-		-		355 m	0

Tables 4 and 5 above show the results of applying the method to the above scenarios and the 4 wells. For example, for well 1, approximately 82% of the groundwater demand is assigned to River E and 18% to tributary D. The proposed approach limits the number of streams to those streams closest in proximity (e.g., a handful or less) where the greatest depletion is expected.

3.3 Example of assigning demand to nearby streams from pumping a subdivision well

Referring back to the example in section 2.6, if the subdivision well is likely hydraulically connected to the stream, the large lake and the two unnamed creeks, demand from pumping on these neighbouring streams can be estimated, based on the methods previously presented. The estimated demand is expected to be greatest on the unnamed creek to the west (46% or 125 m^3/day) and least on large lake (12% or 33 m^3/day – Table 6). Given that the unnamed creeks are near the border of the aquifer, it would be prudent to conduct a site visit to verify local geology at the stream to confirm that the aquifer underlies the unnamed creeks and assess whether streamflow in the unnamed creeks may be a limiting factor (compare the calculated demand with the observed streamflow).

TABLE 6. Percentage and fractional demand on neighbouring streams from pumping a subdivision well.

	Distance	Apportion	Demand
Stream	315 m	28%	76 m^3/day
Lake	475 m	12%	33 m^3/day
Unnamed Creek East	440 m	14%	39 m^3/day
Unnamed Creek West	245 m	46%	125 m^3/day

4. ASSESSING THE LIKELIHOOD OF HYDRAULIC CONNECTION TO LICENSED SPRINGS

A pumping well located near a spring can potentially intercept and deplete groundwater flow to the spring. However, the procedure used to determine the likelihood of hydraulic connection to streams in Section 2 and reliance on Table 1 may not be sufficient for springs because in addition to geology, the magnitude of pumping and location of the well relative to the spring's source area are important factors in how well pumping affects flow to a point discharge, like a spring (see Figure 8). A spring source area is defined as the land area under which groundwater flows contribute to the spring. The spring source area is analogous to a contributing watershed area upstream of an intake in a stream or the capture zone area for a pumping well. Unfortunately, the sources (geology) of licensed springs and the source areas are not readily available (historically not part of past licensing practices to assess the source and source area of springs) so they have to be determined as part of the process in determining likelihood of hydraulic connection.

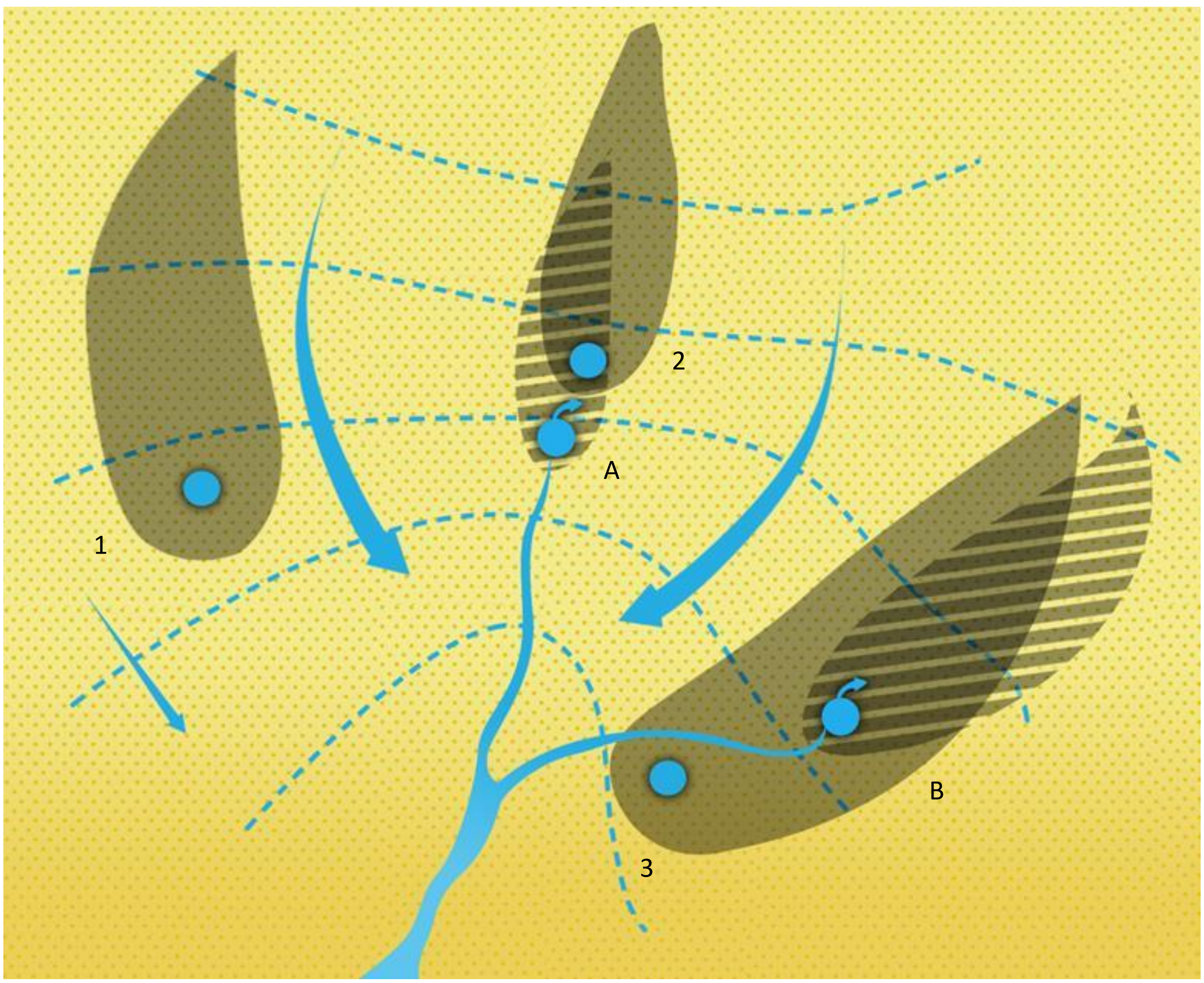


Figure 8 Diagram showing three pumping wells (blue dots - 1, 2, and 3) near two springs (A and B). The wells and springs are sourced from the same aquifer. Well 1 is too far away from the springs for pumping of the well to affect them. Well 2 is directly upgradient of spring A and is in the spring source area. Well 3 is directly downgradient of spring B and Well 3's capture zone and the spring source area intercept. Pumping of Wells 2 and 3 will likely impact springs A and B, respectively.

Spring source areas can be local or regional in extent (Figure 9); the extent of the source aquifer of the spring can provide a clue as to whether a spring is a discharge of a local or regional groundwater flow system. Local springs are characterized by shallow groundwater flow systems that can overlie broader regional groundwater flow systems. Local springs are also typically associated with shallow aquifers of local extent. The source area of local springs will generally follow the local topography. The defined source area of local springs is thus smaller and localized in comparison to the source area of regional springs, and therefore will tend to have smaller and more seasonally variable flows. Regional springs, in contrast, are defined by aquifers and flow systems of regional extent. The source area of regional springs is generally larger and extends beyond the local topographic conditions. It may not be possible to determine the source area of regional springs from local surface features alone. Because of their greater source area, regional springs may have larger and more perennial flows in comparison to local springs. Kreye et al (1996) discusses springs in BC and their source areas in more depth.

Pumping from the well can cause a reduction in spring flow if the well is:

- pumping from the same hydrogeological formation (aquifer) that is contributing to the flow in the spring, and;
- located close enough and along the direction of ambient flow to intercept the groundwater flowing to the spring.

As a preliminary approach, the capture zone of the pumping well and the spring source area may be useful to infer the potential for depletion of a spring from a nearby pumping well (Figure 8).

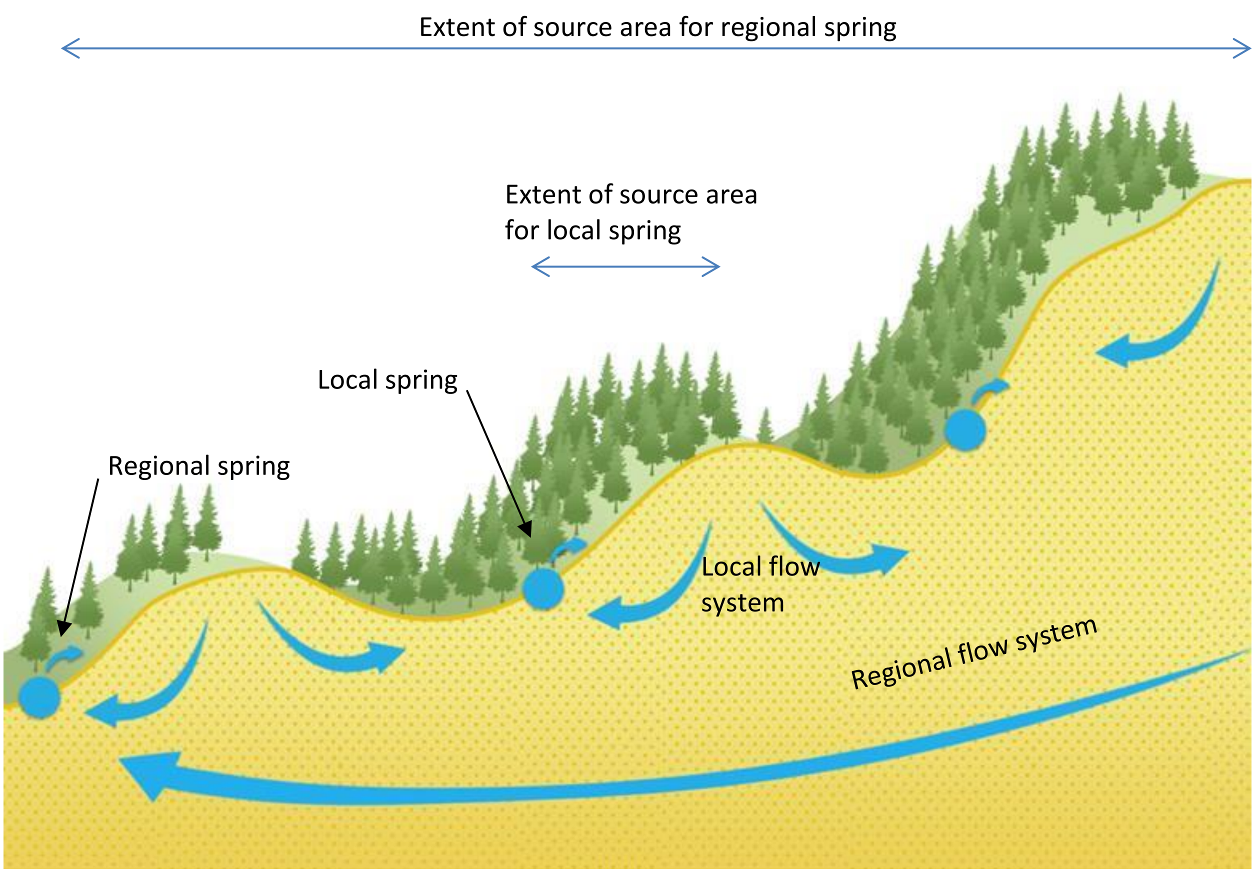


Figure 9 Local and regional groundwater flow systems and extent of local and regional spring source areas (adapted from Kreye et al, 1996).

4.1 Assessing the likelihood of hydraulic connection between existing groundwater users and licensed springs

4.1.1 Local spring systems

Many licensed springs in BC are local springs. Therefore, the procedure for determining the likelihood of connection between existing wells and licensed springs relies on a simplified approach based on the assumption that the spring source area is localized and can be mapped from local topography.

An approach for determining the likelihood of connection between an existing pumping well and a nearby spring is shown in Figure 10 and includes the following steps.

1. ***Determine if the well is diverting from the same aquifer that contributes to the spring.*** Using well construction reports, surficial and bedrock geology maps and even site checking of local geology to determine if the well is diverting groundwater from the same aquifer that contributes to spring flow.
    - If the pumping well is diverting from an aquifer that is different and reasonably isolated (by low permeability aquitards) from the geological formation that contributes to the spring flow, hydraulic connection to the spring is much less likely.
    - If the pumping well is diverting from the same or adjacent water bearing formations that are contributing to flow in the spring, there is a potential that hydraulic connection to the spring exists.
2. ***Map the spring source area.*** Map the spring source area using the local topography and watershed features. For example, use a topographic map to determine the upslope watershed area of the spring. This watershed area is assumed to be the spring source area.
3. ***Determine the likelihood of hydraulic connection to the spring.*** The well may be considered likely connected to the spring if the well:
    - derives water from the same geological deposit (same source) as the spring;
    - is located within the spring source area, or;
    - is outside of the spring source area but is close to the spring such that the well capture zone intercepts the spring or spring source area.

    A well is assumed to be much less likely to impact the spring if it is located outside of the spring source area and the capture zone.

The Well Protection Toolkit (2004) presents several methods of delineating a well capture zone. Use of fixed radius capture zones are not recommended where there is an appreciable ambient flow gradient (or topographic slope). Accurate capture zone delineation is often challenged by lack of data on aquifer transmissivity, ambient hydraulic gradient and aquifer heterogeneity. Professional judgement should be used in delineating well capture zones.

In areas of intensive well pumping, it is recognized that the above approach should be used with caution. Unlike surface water catchments, the shape of spring source areas and capture zones can change as a result of well pumping nearby. There will also be cases where the aquifer sourcing a licensed spring can not be determined with any degree of certainty. In these cases where geological connection is uncertain or the hydrogeology is complex, empirical information linking pumping of the well to reduction of spring flow may be the most reliable evidence to infer likelihood of hydraulic connection. Another approach may be numerical modelling but this requires much information and time and effort to develop. When faced with this uncertainty the decision maker has options, as discussed earlier in Section 2.3.

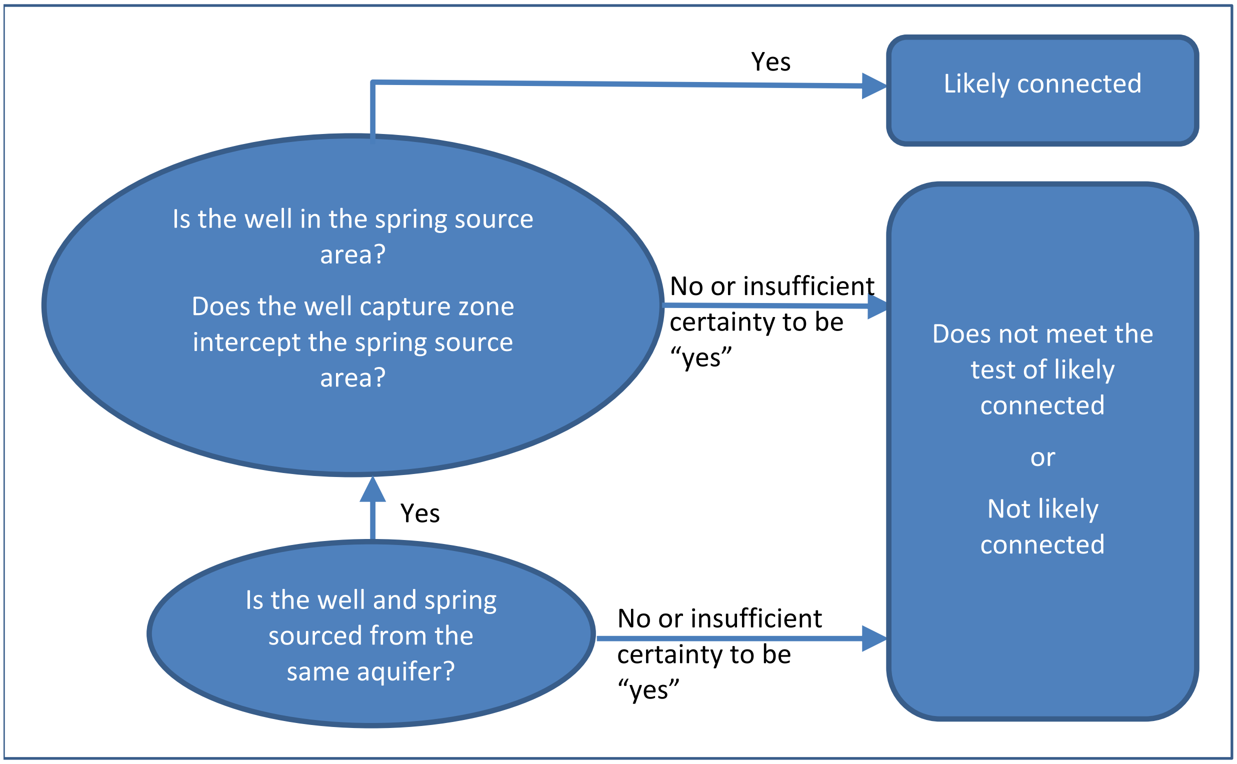


Figure 10 An approach for assessing the likelihood of hydraulic connection of existing wells to springs.

4.1.2 Regional spring systems

The process in Figure 10 may not be sufficient for regional spring systems because the spring source may not be delineated based on local topography. Regional spring systems are more likely to exhibit perennial flows and are associated with aquifers of regional extent. Because of the uncertainty in understanding the source area, monitoring of springflow during a pumping test or even during pumping operation may be the most practical way to assess connection.

4.1.3 Karst springs

Finally, karst springs are a unique case. Karst springs are springs associated with carbonate, gypsum or halite bedrock containing dissolution channels where water flows in underground rivers. The location of these underground channels is generally not well known. The assistance of a professional hydrogeologist to assess the likelihood of connection to existing wells is recommended.

4.2 Assessing the likelihood of connection between new wells and licensed springs

The analysis for new wells follows similar reasoning presented in Section 4.1, but may include site-specific information from drilling and pumping tests, monitoring of flow of nearby licensed springs, and water chemistry data if a technical assessment is conducted.

A pumping test and monitoring the flow in the spring may help verify the likelihood of connection between the well and a licensed spring. A hydraulic connection is inferred when a measured reduction in spring flow correlates after pumping starts and recovery of spring flow after pumping ceases. However, the lack of such responses during a pumping test does not disprove the existence of a hydraulic connection because spring flow depletion effects may occur over a period time much longer than the duration of the pumping test.

4.3 Example of a subdivision well near a licensed spring in Southern Vancouver Island

A 305 mm diameter, 32.3 m deep well that supplies water to a 200-lot subdivision is drilled into an unconfined glaciofluvial sand and gravel aquifer (Type 4a). This is the same sand and gravel aquifer that supplies water to the local community via licensed springs (Figure 11). The well is located up-gradient (south) and 585 m from the licensed springs. The well has an estimated well yield of 327 m^3/day, based on the driller's estimate. The transmissivity of the aquifer, based on pumping tests of nearby wells, ranges between 4 to 122 m^2/day, with a median of 20 m^2/day. The ambient hydraulic gradient is ~0.077, based on hydraulic head contours drawn for the aquifer.

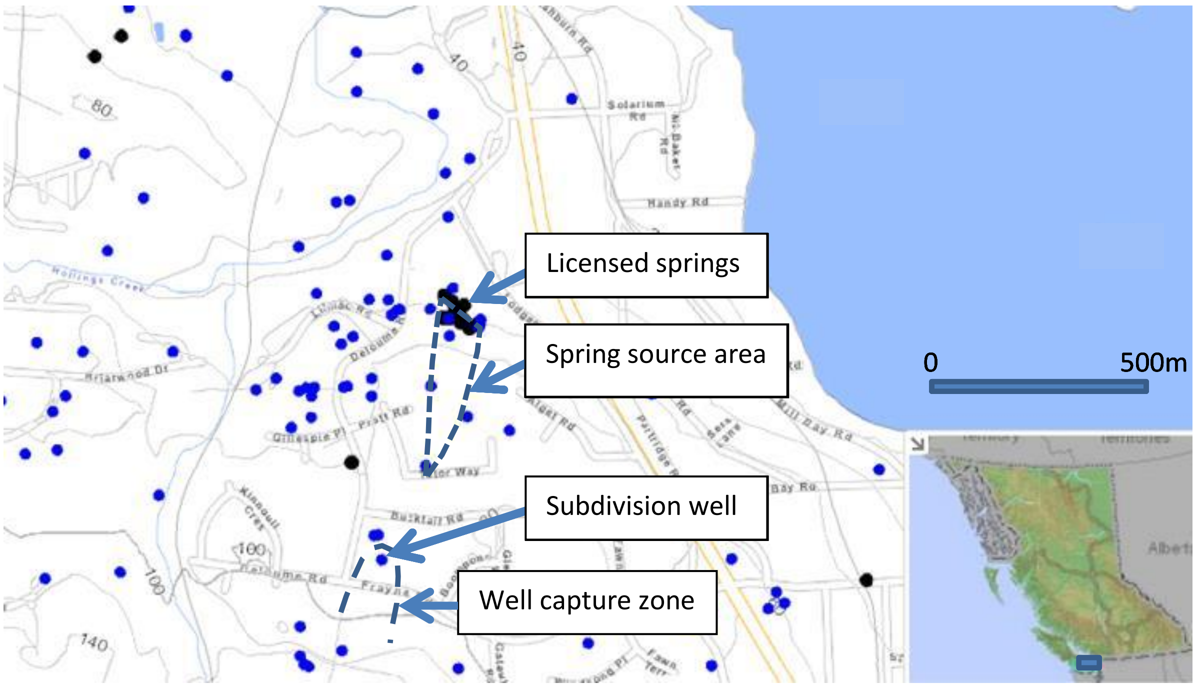


Figure 11 Location of licensed springs, subdivision well (labelled blue dot), and other reported wells (blue dots) in Southern Vancouver Island, along with labelled spring source area and calculated capture zone (blue dashed lines).

The source area for the springs has been mapped based on hydraulic head contours drawn for the aquifer (shown in Figure 11). The subdivision well is located outside of the mapped spring source area and the calculated capture zone for the subdivision well does not intercept the spring or spring source area. Given the distance between the subdivision well and the licensed springs, the depletion of the licensed spring from pumping the well at 327 m^3/day is unlikely even though both are sourcing from the same sand and gravel aquifer.

5. SUMMARY

Allocation of water under the *Water Sustainability Act* recognizes the hydraulic connection between water in a stream and groundwater in an aquifer. The purpose of determining hydraulic connection is to account for the demand from well pumping to specific streams to inform the supply-demand analysis of the streams. Hydraulic connection must meet the test of "reasonably likely". The simple approaches presented here to determine hydraulic connection and assigning demand from well pumping to streams rely on the developing understanding of surface-groundwater interaction and generally limited available data in BC. As more data are collected in the process of managing groundwater use and monitoring the water resource, knowledge and understanding of surface water-groundwater interaction will grow.

The approaches presented here should be used subject to professional judgement. Firstly, there are many cases where the answer of whether there is a likelihood of connection is uncertain because of lack of information. Secondly, the hydrogeology can be so complex that the simple approaches presented here may not be adequate. In these cases, the decision maker can seek the direction of staff with expertise in hydrogeology and local knowledge on how best to determine hydraulic connection and what information is required to do so.

The simple approaches presented in this document should be reviewed once staff has had sufficient opportunity to implement them in practice.

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Appendix A – Documentation for Determining Likelihood of Hydraulic Connection to a Stream(s)

Well Tag Number (WTN) for well: ____

Aquifer source name: ____

Aquifer type (refer to Wei et al, 2009):

- ☐ 1
- ☐ 2
- ☐ 3
- ☐ 4a
- ☐ 4b
- ☐ 4c
- ☐ 5a
- ☐ 5b
- ☐ 6a
- ☐ 6b

How was aquifer type determined:

- ☐ Pre-determined in the WELLS database
- ☐ From the lithology in the well construction report
- ☐ Other (specify):

Hydraulic connection to stream(s):

- ☐ Likely
- ☐ Insufficient information
- ☐ Not likely

Specify stream(s) and calculated % of demand if hydraulic connection is likely:

Stream name	% of pumping demand

Reason for determination: ____

____

____

If likely connected, how was fractional or percentage demand calculated, if well pumping is expected to deplete more than one stream?

- ☐ Numerical model
- ☐ Inverse distance between the well and stream(s)
- ☐ Other (specify): ____

Determined done by: ____________________

Reviewed by: ___________________________

Date (MM-DD-YYYY): ____________________