Modelling Tools for Estimating Effects of Groundwater Pumping on Surface Waters

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Cover Photographs:
Photo by Bilodeau, N. B.C. Ministry of Forest, Lands, and Natural Operations. Visual observation of groundwater flow to the Athabasca River, Jasper National Park.

EXECUTIVE SUMMARY

This report supports implementation of the *Water Sustainability Act* and groundwater licensing by addressing the following objectives:

- Investigating and improving understanding of SW-GW interactions in B.C. and the effects of groundwater withdrawals on surface waters;
- Evaluating modelling approaches for quantifying the effects of groundwater withdrawals on surface waters, particularly analytical models that are simple to implement; and
- Recommending modelling tools for assessing impacts from groundwater withdrawals.

Surface water and groundwater are closely linked in the hydrologic cycle. Groundwater discharges to surface waters, including streams, lakes, springs, and wetlands, often constitute a high fraction of flows and water levels in surface waters. For example, groundwater discharges to streams frequently comprise a high percentage of baseflow, up to 100% of baseflow during seasonal dry periods, and these discharges can be essential for maintaining healthy aquatic habitats, including high value fisheries.

Pumping groundwater from aquifers that discharge to surface waters can reduce flows and water levels of the hydraulically connected surface waters. This can deplete the amount of surface water available for allocation, can affect the existing surface water rights, and can harm aquatic health when flows fall below minimum thresholds for environmental flow needs (EFNs). Increasing the distance between the well and the stream or surface water does not necessarily diminish the effects of surface water depletion, but rather merely delays the impacts over time, sometimes for years. Sustainable allocation of groundwater resources and protection of aquatic habitats requires an understanding of the hydraulic connectivity between water wells and surface water resources. The existing aquifer typing system provides a basis for broadly categorizing SW-GW interaction in province.

Modelling tools provide a means for assessing and evaluating in SW-GW interactions, and can provide estimates of streamflow responses to groundwater pumping. Analytical models use idealized conceptualizations of the natural system to obtain simplified solutions that are generally easy to solve with limited data requirements. They are useful for gaining insights into system behavior and as screening tools for management of groundwater diversion and use. Alternatively, numerical groundwater models attempt to capture hydrogeologic complexities that vary in space and time, providing tools for more comprehensive basin scale management. However, numerical models are time consuming, costly and difficult to construct and calibrate, and are not available to support groundwater allocation throughout the vast majority of the province.

Eight analytical models were tested and evaluated through inter-model comparison with a calibrated numerical model of the Grand Forks aquifer. Each of the analytical models provided conservative estimates of streamflow depletion in the sense they overestimate the rate of streamflow depletion and recovery in comparison to numerical solutions. This report presents guidance for selecting and using analytical models, based in part on these model comparisons.

Recommendations to support allocation staff in groundwater licensing are:

- Promote ongoing awareness and dialogue of SW-GW connectivity and potential impacts.
- Support studies and monitoring activities to improve understanding of SW-GW connectivity in the province.
- Use a conservative approach in high priority, high impact areas.
- Support groundwater modelling training for government staff in order to promote use and appropriate review of groundwater models used in groundwater license applications.

- Use available spreadsheet tools developed by Bruce Hunt for analytical modelling of SW-GW interactions.
- Support development of comprehensive groundwater management models for assessing groundwater allocation and groundwater management strategies in high priority areas of the province.

Contents

1. INTRODUCTION

1.1 Background

B.C. has firmly established surface water regulations, including a long history of licensing diversion and use of water from streams (refer to the definition of "stream" in the *Water Sustainability Act*). The basis for allocation of stream waters has traditionally included the available supply, consideration of existing water rights holders, and potential environmental impacts. Historically, surface water allocations under the *Water Act* have not considered the effects of groundwater diversions on the availability of surface water.

Surface waters and groundwater are closely linked in the hydrologic cycle. In many areas of B.C., groundwater discharges to streams constitute a high percentage of the baseflow, particularly in small streams during critical dry season low flow periods. Groundwater discharges also support and sustain wetlands, lakes, and springs. Pumping groundwater from aquifers that discharge to surface waters can reduce the flows and water levels of the hydraulically connected surface waters. This can deplete the amount of surface water available for allocation, can affect the existing surface water rights, and can harm aquatic health when streamflows fall below minimum thresholds for environmental flow needs (EFNs).

Authorization of use of groundwater in B.C. is comparatively new and evolving. With recent passage of the *Water Sustainability Act* (WSA) the province has moved toward more integrated management of groundwater and surface water resources. Two goals of the WSA are licensing of groundwater and protection of aquatic health. To achieve both goals, regulatory policies must consider the interaction of surface and groundwater systems. In particular, there is a need to understand and quantify the effects of groundwater pumping on surface water depletion, and the associated impacts on surface water rights holders and EFNs.

1.2 Study Objectives and Scope of Work

The study was initiated to investigate and recommend modelling tools for quantifying the effects of groundwater pumping on surface water depletion. Specific study objectives were:

1. Investigate surface water-groundwater (SW-GW) interactions in B.C., particularly in regards to how groundwater withdrawals can affect these interactions.
2. Explore the benefits and limitations of modelling tools for assessing impacts of groundwater withdrawals on EFNs.
3. Recommend modelling tools and guidance on the use of models for assessing impacts from groundwater withdrawals on EFNs.

The project scope was limited to review of available literature information, evaluation of existing studies, and numerical analyses. The scope did not include field studies or data collection. In addition, the scope did not address the effects of pumping on salt-water intrusion in coastal environments. The following are specific tasks addressing each of the project objectives.

1. Improve understanding of SW-GW interactions in B.C.
   - Conduct a literature review and characterize SW-GW interactions for different types of hydrologic systems in B.C.
   - Relate these interactions to B.C. specific hydrogeologic frameworks and characterize how pumping can affect surface water resources in B.C.
   - Identify and discuss B.C. specific investigations on SW-GW interactions.

2. Explore tools for quantifying stream depletion from groundwater withdrawals.
   - Conduct a literature review of modelling approaches and tools. Evaluate benefits and limitations of these approaches.
   - Investigate modelling and assessment approaches used by select jurisdictions.
   - Select potential analytical approaches for further investigation.

3. Recommend modelling tools and provide guidance on the use of these tools.
   - Quantitatively assess the accuracy of analytical tools through comparison with a numerical groundwater model of the Grand Forks Aquifer.
   - Evaluate analytical tools based on ease of use, accuracy and applicability, data requirements and availability, and other qualitative criteria.
   - Recommend analytical tools for use in EFN assessments and management of water rights. Develop guidance for implementing the analytical tools and recommendations for future work and studies.

2. SURFACE WATER-GROUNDWATER INTERACTIONS AND IMPACTS FROM PUMPING

Understanding the general behavior and characteristics of SW-GW interactions supports informed water management decisions. Accordingly, this section presents:

- A general overview SW-GW dynamics and descriptions of SW-GW interactions in different hydrologic settings; and
- A description of how groundwater withdrawals affect surface water bodies.

2.1 Dynamics of Surface Water-Groundwater Interactions

2.1.1 Groundwater Flow Scales
Groundwater moves from areas of recharge to areas of discharge at lakes, rivers, springs, wetlands, and oceans. This movement occurs over a wide range of travel distances and travel times as shown in Figure 1. The distance between recharge and discharge areas may range from a few tens of metres to many kilometres and the corresponding travel times can span from days to millennia. These groundwater flow systems are categorized into local, sub-regional, and regional scales as follows (Winter, et al., 1998; Alley, et al., 1999):

- **Local-scale groundwater flow systems** are the shallowest systems occurring at the water table. Here, recharge to the water table flows to the closest surface water body over a comparatively short time scale (days to years). Local climatic and geomorphic conditions strongly influence local-scale GW-SW interactions.
- **Sub-regional (Intermediate) groundwater flow systems** occur in water table aquifers beneath local-scale flow systems. Groundwater recharge to the water table does not flow to the nearest surface water body, but instead flows to a more distant surface water body. They have intermediate travel times of months to decades. Sub-regional systems may include flows through semi-confined aquifers, where the confining layers are not continuous and/or the confining bed materials are semi-permeable (i.e., an aquitard with permeability that is comparatively lower than the adjacent aquifer, but large enough to transmit water between adjacent geologic units).
- **Regional groundwater flow systems** occur beneath the water table aquifers and may have complicated flow patterns through confined and semi-confined units, and consolidated and unconsolidated units. Regional systems have much longer flow paths and travel times (years to

centuries), but do eventually discharge to surface waters. However, the long travel time and extended contact with geologic materials potentially affect the chemical nature and water quality of groundwater discharges to surface waters.
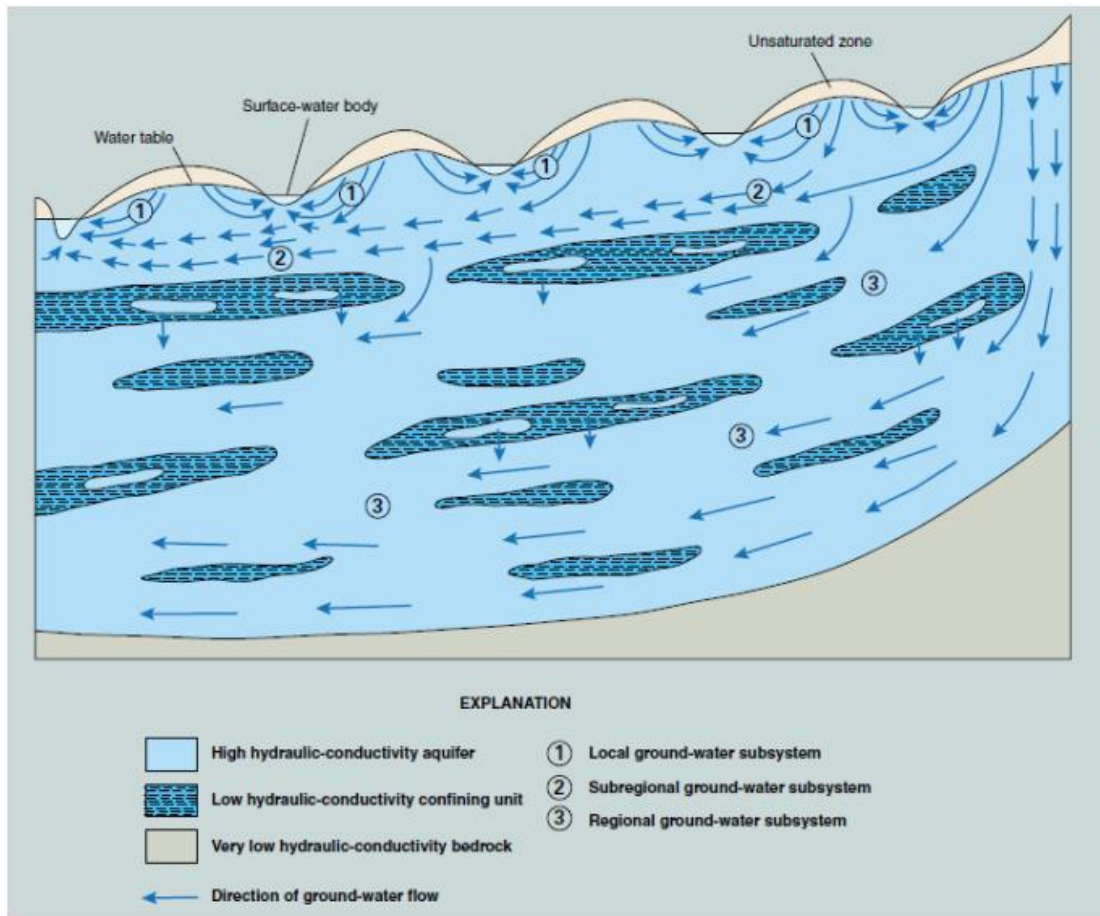
Figure 1 Groundwater flow scales, showing local, subregional, and regional flow systems (Source: Alley et al. 1999).

Consideration of SW-GW interactions is likely to focus on wells in close proximity to surface water bodies. However, water managers should keep in mind that surface waters receive groundwater discharges from local scale, sub-regional, and regional systems, and the connection between recharge and discharge areas is not always evident. Groundwater withdrawals that are not adjacent to the surface water bodies also affect surface waters, but the impacts may take years to become evident (Alley, et al., 1999).

2.1.2   Groundwater Interaction with Streams

Streams either gain water from groundwater discharges or lose water to groundwater by seepage through the streambed. Gaining and losing conditions may occur simultaneously on the same stream, and may vary seasonally or over longer periods due to changes in surface runoff and water table elevations.

Groundwater discharges sustain baseflow in a gaining stream. A stream or stream reach is called a "gaining stream" when groundwater discharges maintain or contribute to a net gain in streamflow.

Gaining stream conditions occur where the elevation of the adjacent water table is higher than the surface water elevation in the stream Figure 2.

Groundwater discharges to gaining streams contribute a high percentage of surface flows and can account for more than half of the annual streamflow (Winter, et al., 1998). The groundwater component increases in the absence of surface runoff from storms or snowmelt. During dry periods, groundwater discharges may account for the vast majority of baseflow in streams, up to 100 percent depending on local conditions. It is during such critical flow periods that sensitive fish populations are most vulnerable to environmental stresses and groundwater discharges may be vital to their survival. For this reason, gaining streams are a primary focus of EFN assessments and regulatory actions.
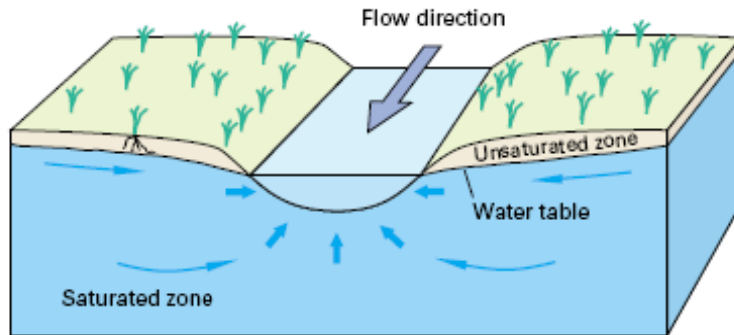
Figure 2   Generalized conceptualization of groundwater discharge to a gaining stream (Source: Alley et al. 1999).

Losing streams supply water to the underlying aquifer. A stream is called a "losing stream" when seepage through the streambed causes a net loss in streamflow. Losing stream conditions occur where the elevation of the adjacent water table is below the water surface elevation.

Losing streams occur in two regimes as shown in Figure 3. A connected losing stream occurs where the stream and aquifer are linked by a saturated zone (Figure 3A). In this situation, a pumping well adjacent to the stream can affect streamflow.
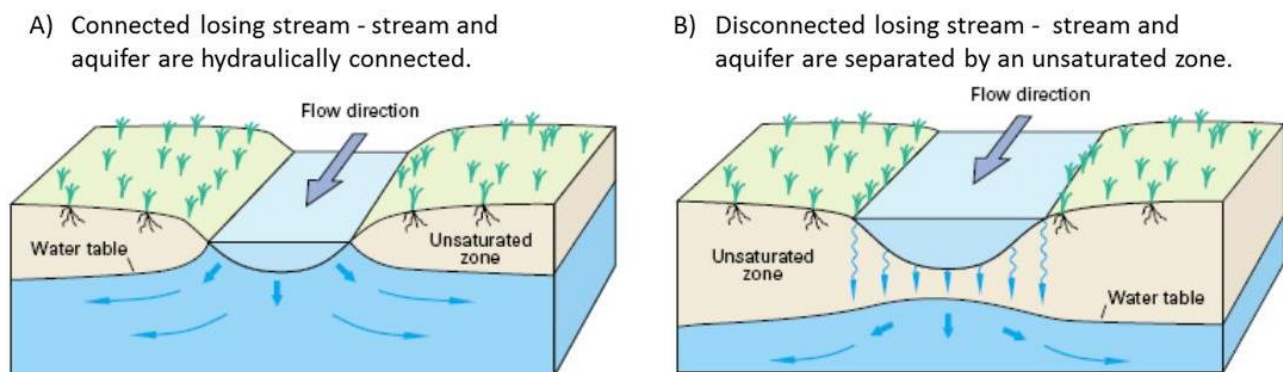
Figure 3   Generalized SW-GW interaction between an unconfined aquifer and a losing stream (Source: Alley, et al. 1999).

A second type of losing stream occurs where an unsaturated zone lies between the stream and aquifer (Figure 3B). Because drainage through the unsaturated zone depends on moisture content, the aquifer may be effectively connected or disconnected to the stream depending on moisture content. The likelihood of a disconnection between a well and the stream increases with increasing thickness of the unsaturated zone (Brunner, et al., 2011). One way to infer this is to compare the water table elevation in a well to the streambed elevation. A large difference in elevations indicates the presence of a thick

unsaturated zone separating the stream and the underlying aquifer. A more definitive way to prove a disconnection is to demonstrate the infiltration flux does not vary with water table depth (Brunner, et al., 2011). This requires concurrent aquifer pumping tests and stream flow measurements, which is not practical on a routine basis.

Bank storage and evapotranspiration affect baseflow.   Many gaining streams in B.C. experience a rapid rise in river stage during spring snowmelt or from runoff from large storms. The rise in river stage may temporally change the direction of the SW-GW gradient from gaining stream to losing stream conditions, causing flow into the aquifer and into the adjacent riverbank and floodplain. Gaining stream conditions are restored after the river recedes, which allows water to gradually drain from bank storage and floodplain storage to the stream. Gradual discharge from bank storage may occur over periods of weeks to months, or even years (Winter, et al., 1998), and can be a significant source of baseflow during the early part of the dry season and in smaller upland ephemeral catchments. Discharge from bank storage can also help to lower stream temperatures and support fisheries habitat during critical low flow periods (Squillace, 1996).

During summer months, evapotranspiration (ET) by riparian vegetation can lower the groundwater elevation similar to the effects from pumping, which can affect stream-aquifer interactions and reduce baseflow. For example, ET is a significant control on baseflow within Bertrand Creek in the Fraser Valley, equaling approximately one-half of the dry season baseflow at the watershed outlet (Starzyk, 2012).

Stream-aquifer interactions are heterogeneous and dynamic. The magnitude and direction of SW-GW interactions can vary greatly in space and time. These variations can be quite heterogeneous, rapid, and transient. High-resolution temperature measurements have shown the distribution of groundwater discharge into streams is often non-uniform and focused at distinct seeps (Schmidt, et al., 2006; Mwakanyamale, et al., 2012). Heterogeneous distributions of streambed and aquifer hydraulic properties largely control the irregular discharge patterns. For example, studies have observed large differences in groundwater flux over distances of a few metres in riverbed sediments where greatest discharge corresponded to breaches in the underlying unit (Hinton, 2014). Streambed heterogeneities also have significant influence on groundwater discharge patterns (Kalbus, et al., 2009). Streambed properties, however, can change over time due to fluvial depositional and erosional processes, edge effects from waves and ice, and biological processes (Rosenberry & LaBaugh, 2008).

2.1.3   Groundwater Interaction with Lakes

Groundwater discharges can be a major source of water to lakes. Assessing the effects of pumping near lakes is relevant to water licensing because: 1) pumping near lakes can potentially withdraw water directly from the lake body, and 2) pumping near lakes may affect the volume of groundwater discharge, the nature of local SW-GW interactions, and potentially near shore habitat.

Lakes have the same types of SW-GW interactions as streams. Lake-aquifer interaction occurs in three general regimes based on the relative location of the water table and the lake surface (Figure 4):

- **Discharge lakes** receive groundwater discharge along the lake perimeter and partially through the lake bottom. Discharge lakes occur where the elevation of the regional water table is above the water surface elevation.
- **Recharge lakes** contribute to groundwater recharge through the entire lake bottom. Recharge lakes occur where the elevation of the regional water table is below the water surface elevation.
- **Flow-through lakes** intercept the regional groundwater flow such that the lake gains water on one side and loses water on the other side. Flow-through lakes occur where the elevation of the regional water table is similar to water surface elevation.

Discharge Lakes

Lake surface

Recharge Lakes

Lake surface

Flow-through Lakes

Lake surface
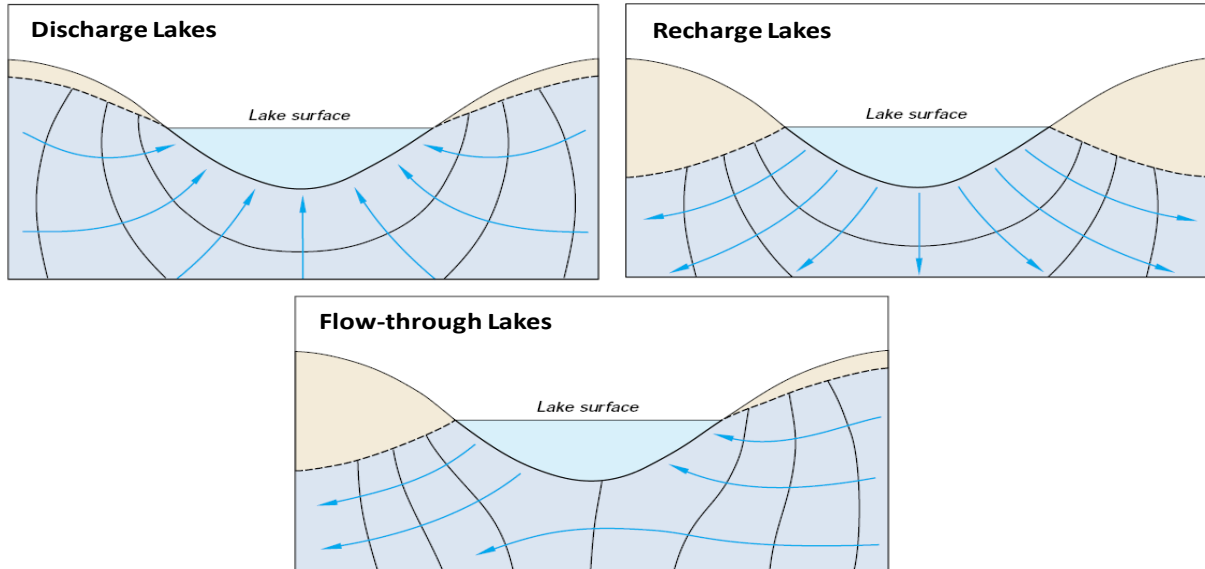
Figure 4   General groundwater interactions with lakes (Source: Winter, et al. 1998).

Seepage into lakes is generally greatest near shorelines. Numerical and field studies show groundwater seepage into lakes, especially large lakes, is greatest near the shoreline and decreases exponentially offshore (Winter, 1983; Cherkauer & Nader, 1989).

Soil heterogeneities influence seepage patterns. Similar to stream-aquifer systems, soil distributions can have a dominant influence on lake-aquifer interactions. High permeability layers or heterogeneities can create preferential flow paths that concentrate seeps in local areas or cause patterns of increasing seepage with distance from the shoreline (Cherkauer & Nader, 1989). Conversely, low permeability layers or organic deposits, aquitards, and anisotropy in the aquifer tend to reduce the groundwater discharge into the lake bottom (Guyonnet, 1991).   Collectively, the distribution of lakebed and aquifer properties together with regional groundwater gradient and groundwater elevations can cause complex seepage patterns, such that different SW-GW interactions may occur within the shallow lake margins and deeper areas in the lake center (Cherkauer & Nader, 1989; Townley & Trefry, 2000).

Lake levels fluctuations affect SW-GW interaction. In lakes that do not fluctuate much, the effects of bank storage on water levels is less important than in rivers. Conversely, due to the comparatively large surface area of lakes, evaporation losses can significantly affect lake levels and SW-GW interactions. Similarly, SW-GW interactions can also be influenced by lake level fluctuations caused by reservoir operations.

2.1.4   Groundwater Interaction with Springs

Springs are areas of focused groundwater discharge at the ground surface. They can range in size from small intermittent seeps that flow only after rainstorms, to large pools that discharge hundreds of cubic metres per day.

Springs are important sources of water supply, and discharges from springs may support or sustain surface water bodies that provide habitat for fisheries or other wildlife.

Springs occur in different hydrogeologic settings. Springs occur where the water table intercepts the ground surface, which can occur in many hydrogeologic settings (Figure 5):

- Hillside springs form where groundwater discharges occur from perched aquifers or where there are breaks in hillside topography.

Depression Springs
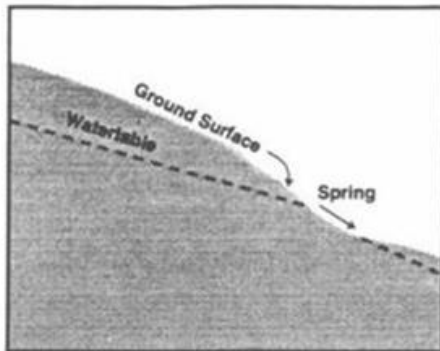
Contact Springs
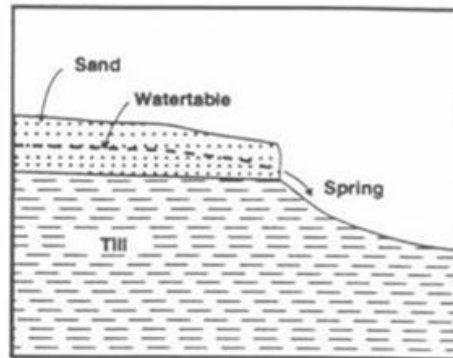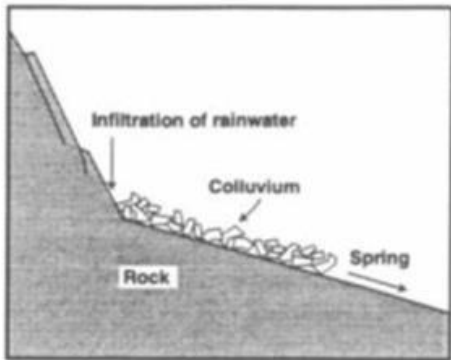
Fault/Fracture/Joint Springs
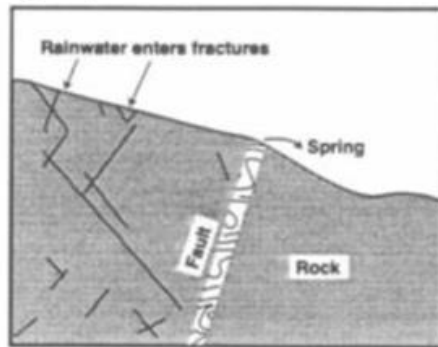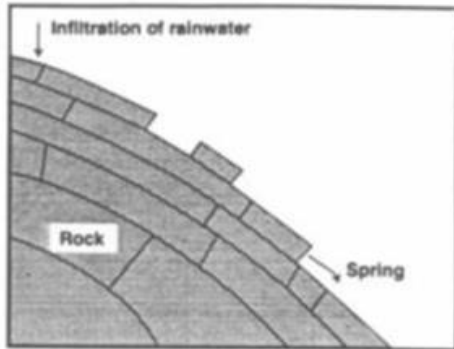
Karst Springs
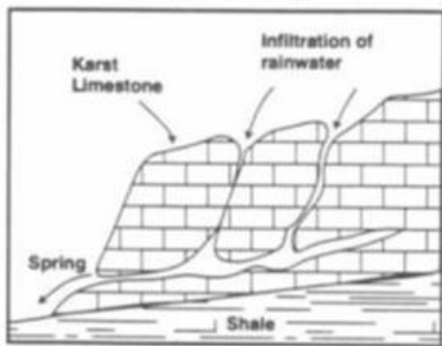
Lava Springs
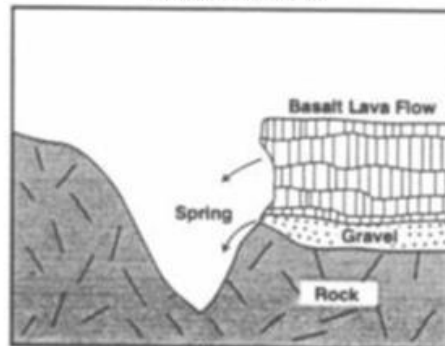
Figure 5   Examples of springs formed in different hydrogeologic settings (Source: Kreye et al. 1996).

- Focused seeps develop where there are sharp contrasts in soil type and permeability creating preferential flow paths to the ground surface.
- Groundwater seeps develop where there are continuous fractures, faults, or conduits in consolidated materials that can convey groundwater to the surface (e.g., from fractured bedrock or from karst formations).

The volume of discharge from springs depends on a number of factors, including:
- The size and volume of the contributing aquifer (i.e., the spring source area or tributary area);
- The hydraulic conductivity of aquifers and groundwater flow paths;
- The pressure or hydraulic head in the spring basin; and
- Antecedent rainfall and groundwater recharge.

Groundwater diversions potentially reduce spring flow and impact dependent EFNs. Assessing the effects of pumping near springs is relevant to water licensing because groundwater diversions potentially affect spring flow and any associated water rights holders of spring flows. Groundwater diversions can also potentially affect aquatic habitats that depend on spring flows. In order to consider these potential impacts in authorization of groundwater use, it is necessary to establish the hydraulic connectivity between groundwater wells and springs and to determine the spring source area. Several provincial reports provide guidance for establishing hydraulic connectivity and spring source areas (Kreye, et al., 1996; Province of British Columbia, 2016a; Province of British Columbia, 2016b).

2.1.5 Groundwater Interaction with Wetlands
Wetlands are areas where the groundwater intersects the ground surface or there is poor drainage of surface water. They can occur in retention areas from land depressions and areas of low relief, in regions of shallow groundwater, along hillside seepage faces, and along the margins of lakes, oceans, and slow moving rivers. Wetlands and associated vegetation can provide significant habitat functions. In addition, wetlands and open waters areas in riparian and floodplains are connected to downstream rivers through physical, chemical, and biological processes, and provide functions that improve downstream water quality (U.S. EPA, 2015).

Groundwater discharges to wetlands can be a major source of water, or may even sustain baseflow to the wetlands. Similar to rivers and lakes, groundwater withdrawals can affect SW-GW interactions near wetlands, potentially affecting habitat quality.

SW-GW interactions in wetlands can be highly complex and dynamic due to shallow groundwater gradients, and the effects of soil heterogeneities and wetland vegetation (Winter, et al., 1998). However, the three general SW-GW flow regimes found in lakes also occur in wetlands; wetlands may behave primarily as groundwater discharge areas, as groundwater recharge areas, or as groundwater flow-through systems (Figure 4). Two main differences between GW-SW interactions in lakes and wetlands are (Winter, et al., 1998):

1. **GW-SW exchange is slower in wetlands.** Fine grained sediments and organic materials found in wetlands tend to impede SW-GW interactions. Wave action along the margins of lakes tends to remove finer grained sediments, promoting more SW-GW exchange.
2. **There is significant pore water exchange in wetlands.** The roots and root zones of wetland vegetation are very conductive, which promotes exchange between surface water and the shallow pore water. This occurs even if GW-SW exchange is impeded by fine-grained sediments.

2.2   Effects of Groundwater Withdrawal

Groundwater withdrawals potentially alter the magnitude and nature of SW-GW interactions, and can negatively affect surface waters through:

- Reduced surface water levels and flows
- Changes in water quality
- Changes in habitat and fisheries

2.2.1   Pumping Impacts on Streamflow

Many streams in B.C. traverse unconfined aquifers (i.e., water table aquifers), where there is strong hydraulic interaction between the stream and the aquifer. Gaining stream systems depicted in Figure 6A occur in water-table aquifers throughout B.C. These aquifers are major sources of the streamflow, especially during periods of critical low flows. However, water table aquifers are also exploited for water supply due to generally shallow water depths, good productivity, and proximity to human development. Understanding the implications of groundwater diversions on streamflow has important implications groundwater allocation and EFN assessments.

A)   No pumping: Groundwater discharges to the gaining stream under natural conditions.
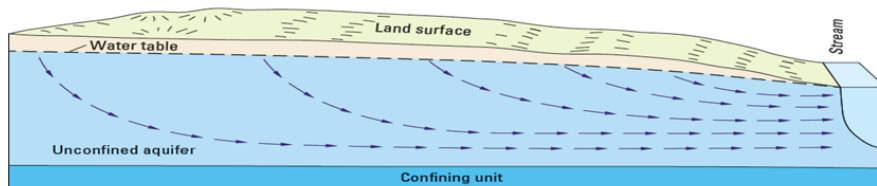
B)   Start of pumping: the well initially draws water from aquifer storage, which does not affect streamflow.
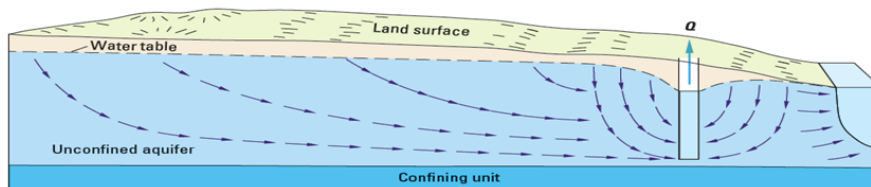
C)   Continuous pumping: Over time, the drawdown cone of depression expands and eventually stabilizes. The well no longer draws water from aquifer storage, rather it draws water that would flow to the stream in the absence of pumping. Pumping reduces streamflow by intercepting groundwater flow to the stream.
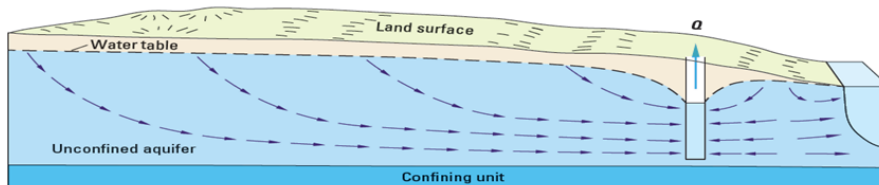
D)   Wells close to a stream can reverse local flow gradients. The well draws water directly from the stream by inducing infiltration through the streambed into the aquifer.
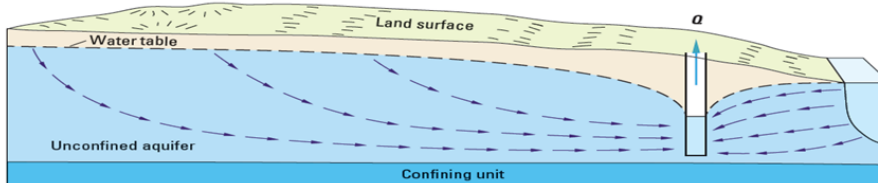
Figure 6   Effects of pumping on SW-GW interaction in a gaining stream system (Source: Barlow and Leake. 2012).

Groundwater diversions reduce streamflow through interception and induced infiltration. When a well diverts groundwater from a gaining stream system, the well initially draws water from aquifer storage (Figure 6B), which does not affect streamflow. However, with continued pumping, the cone of depression expands outward from the well (Figure 6C). Over time, the amount of water removed from storage diminishes as the effects from pumping approach a maximum zone of influence (Figure 7).

Correspondingly, the well increasingly intercepts groundwater that would otherwise flow to the stream in the absence of pumping (Figure 6C). This results in a reduction of streamflow because less water is reaching the stream than would occur in the absence of pumping. Eventually, a new equilibrium is reached in which there is no change in aquifer storage and all groundwater withdrawal is from groundwater interception (i.e., streamflow capture in Figure 7).
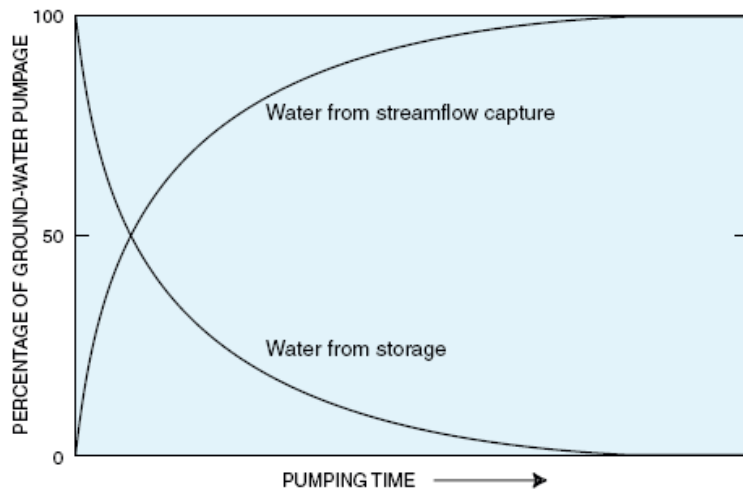
Figure 7   Idealized representation of changes in water sources to a pumping well with time (Source: Alley et al. 1999).

Figure 6C shows groundwater diversion reduces streamflow solely by intercepting groundwater flow to the stream. This process does not depend on the proximity of the well to the stream. Wells located far from streams may cause streamflow depletion through interception.

However, if a well is close to the stream and the pumping rate and duration is sufficiently large, then pumping stresses can reverse the local flow gradient near the stream (Figure 6D). This induces infiltration from the stream, effectively changing the local SW-GW interactions from a gaining stream to losing stream conditions.

Figure 6D shows groundwater pumping reduces streamflow by a combination of two processes: 1) the interception of groundwater flow to the stream and 2) induced infiltration from the stream. These combined effects are termed streamflow depletion.

Groundwater diversions adjacent to losing stream reaches can also cause streamflow depletion. Groundwater diversion from wells in close proximity to a connected losing stream (Figure 3A) can readily cause streamflow depletion through direct capture as described above. This occurs because the aquifer and stream are hydraulically connected by a fully saturated soil system. In fact, groundwater pumping can more easily induce infiltration from the stream because flow gradients are already established in the direction from the stream to the aquifer (Brunner, et al., 2011).

By definition, a disconnected losing stream occurs where groundwater pumping does not influence flows in the adjacent stream reach through direct capture (Figure 3B)). In this case, groundwater

diversions do not affect streamflow in the adjacent stream reach. However, pumping can potentially extend the length of stream reach that is disconnected (Brunner, et al., 2011), or can potentially reduce streamflow to downstream reaches through interception of groundwater flows.

Streamflow depletion may be represented in different ways. There are three common alternatives for quantifying and expressing streamflow depletion:

- **Volumetric streamflow depletion:** The most direct approach is to calculate streamflow depletion as the difference in stream discharge with and without pumping, plotting the differences over time (Figure 8A). This assumes no other factors affect streamflow, or these factors are accounted in the calculations. The volumetric approach is useful when assessing or administering surface water rights.

- **Normalized streamflow depletion:** In this approach, the volumetric streamflow depletion is divided by the pumping rate (constant or average). The normalized streamflow depletion is dimensionless and ranges between 0 (indicating no streamflow depletion) to 1 (indicating 100 percent of the groundwater withdrawal is from streamflow depletion) (Figure 8B). This approach is widely used because it allows for direct comparison of pumping impacts from different pumping scenarios and locations.

- **Cumulative streamflow depletion:** The cumulative approach expresses the total volume of streamflow depletion from pumping over a specified period (Figure 8C). This approach is useful for assessing cumulative effects from pumping throughout an aquifer or management area.
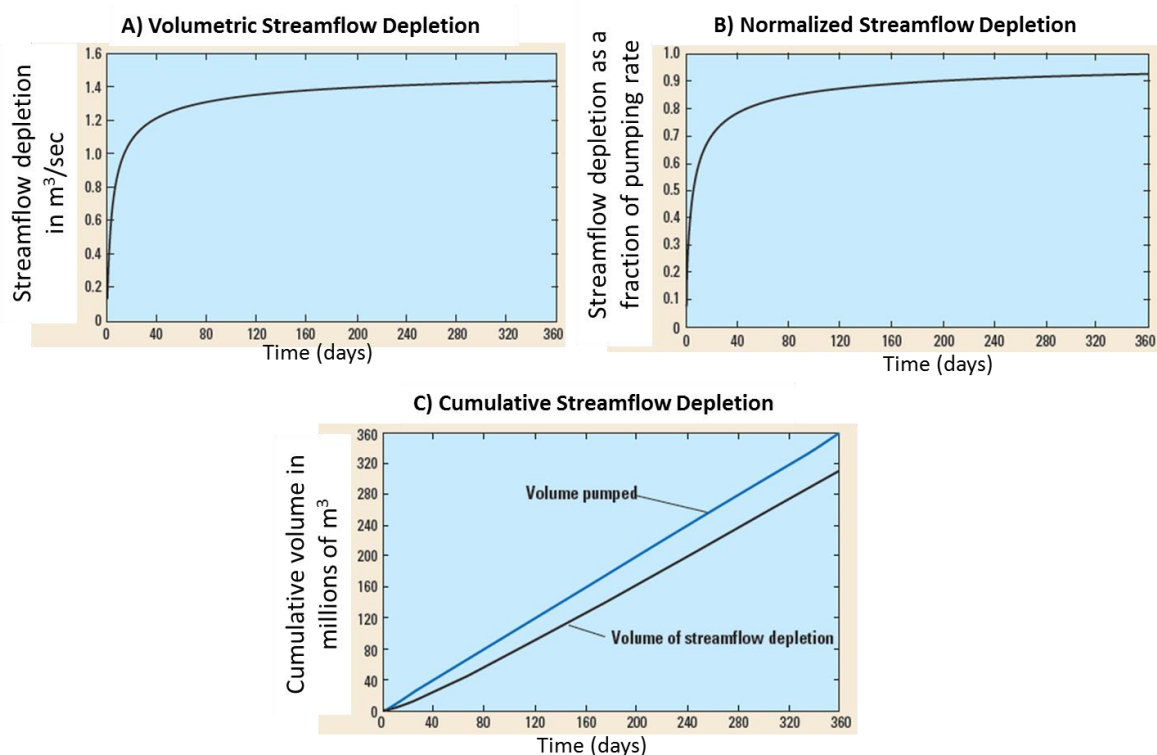
Figure 8   Alternatives for expressing streamflow depletion over time (Source: Barlow and Leake. 2012).

The effect of pumping on streamflow depletion is not immediate but increases over time. Figure 6 and Figure 7 show the effect of groundwater diversion on streamflow occurs progressively over time. This streamflow response period can span a very wide range, from very rapid responses in minutes to delayed responses requiring years or decades. The main factors affecting the rate of streamflow

depletion are the horizontal and vertical distances of the well to the stream, the hydraulic properties of the aquifer (transmissivity and storativity), and the permeability of the streambed sediments (Barlow & Leake, 2012).

The Stream Depletion Factor (SDF) is a measure of how rapidly streamflow depletion occurs in response to new pumping stresses:

$$SDF = \frac{d^2 S}{T} = \frac{d^2}{D}$$

In this equation, d is the distance from the well to the stream and D is the hydraulic diffusivity of the aquifer. Table 1 shows representative values of D and *SDF* for aquifer types in B.C., based on available data.

Table 1 Representative values of hydraulic diffusivity and stream depletion factors in B.C.

Aquifer Type	Transmissivity (m²/d)	Storativity or Specific Yield	Diffusivity (m²/day)	SDF (day) for d= 100 m
1a - Unconfined or partially confined fluvial and glaciofluvial aquifers along high-order rivers	4,500 [1]	0.2 [2]	22,500	0.4
1b - Unconfined or partially confined fluvial and glaciofluvial aquifers along moderate-order rivers	1,800 [3]	0.14 [4]	12,900	0.8
2 - Unconfined deltaic aquifers formed in river deltas	1,000 [5]	0.07 [6]	14,300	0.7
3 - Unconfined alluvial fan aquifers	420 [3]	0.02 [4]	21,000	0.5
4a - Unconfined aquifers of glaciofluvial origin	650 [3]	0.04 [4]	16,300	0.6
4b - Confined aquifers of glaciofluvial origin	340 [3]	0.00044 [4]	775,000	0.1
5a - Fractured sedimentary bedrock aquifers	0.86 [7]	0.0034 [7]	250	40
6b - Granitic, metamorphic, meta-sedimentary, meta-volcanic, and volcanic rock	0.4 [3]	0.0085 [4]	47	850

(1) Geometric mean of compiled values in B.C. (Wei, et al., 2014)
(2) Typical value of specific yield (Freeze & Cherry, 1979)
(3) Geometric mean of pumping test results in the Okanagan Basin (Carmichael, et al., 2009)
(4) Median value of pumping test results in the Okanagan Basin (Carmichael, et al., 2009)
(5) Geometric mean of pumping test results in the Regional District of Nanaimo (Carmichael, 2013)
(6) Median value of pumping test results in the Regional District of Nanaimo (Carmichael, 2013)
(7) Typical value for fractured sandstone on Salt Spring Island (Carmichael, 2013)

Hydraulic diffusivity is the ratio of transmissivity to storativity ($D = T/S$). It is a measure of aquifer sensitivity to hydraulic stress (i.e. pumping). Larger values of hydraulic diffusivity indicate groundwater levels or hydraulic head will change more rapidly in response to pumping or streambed properties. Table 1 shows greatest aquifer diffusivity occurs in confined aquifers due to the small storativity of these systems. Thus, the cone of depression associated with a pumping well will generally be larger and develop faster in a confined aquifer than in an unconfined aquifer.

The SDF is a relative measure used to compare the streamflow depletion response time to different pumping scenarios. Smaller values of SDF indicate a comparatively rapid occurrence of streamflow depletion following the start of pumping. Larger values of SDF indicate a comparatively longer response time. Note, the SDF does not depend on the well's pumping rate. Rather, a relatively rapid response time for streamflow depletion (small SDF) occurs where the distance between the well and stream is short or the hydraulic diffusivity is large. Table 1 shows streamflow depletion responses are comparatively most rapid in unconsolidated aquifers (types 1-4), and comparatively slower in bedrock aquifers.

Low permeability streambed sediments impede the rate of streamflow depletion caused by induced infiltration.   When pumping wells are sufficiently close to streams such that they cause induced infiltration, then another factor affecting the rate of streamflow depletion is the permeability of streambed sediments. In many streams, the streambed has fine-grained sediments and organic materials that have a lower permeability than the adjacent aquifer. These low-permeability sediments impede flow through the streambed, which effectively lengthens the response time of streamflow depletion caused by induced infiltration (Figure 9).
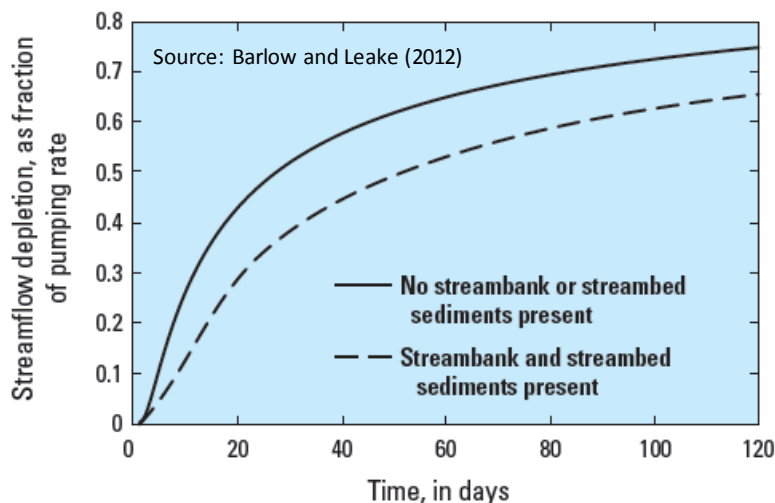
Figure 9   Effect of streambed permeability on streamflow depletion (Source: Barlow and Leake, 2012).

There can be a large time lag between the start of groundwater diversions and the effect on streamflow depletion.   Water managers should be aware that pumping wells located at considerable distances away from streams can also affect streamflows, and there can be significant delay between the start of pumping and observed effects of streamflow depletion. The time delay can range up to years depending on the distance between the well and the stream and the aquifer properties (Barlow & Leake, 2012).

A numerical study of the Eastern Snake River Plain Aquifer in Idaho illustrates the delay of streamflow depletion response (Alley, et al., 1999). This aquifer system is highly conductive and discharges to the Snake River through major springs (e.g., Thousand Springs area). Figure 10 shows the aquifer location and groundwater discharge areas along the Thousand Springs reach of the Snake River.

Using a transient groundwater model, researchers investigated the effects of groundwater pumping at locations in Figure 10 on the response of groundwater discharges. Modelled pumping rates were constant during a 100-year simulation period, except for well location D where pumping stopped after 20 years.

Simulation results are represented in terms of normalized stream depletion responses to pumping (Figure 11). Pumping wells closest to discharge areas show the fastest and greatest effects on streamflow depletion. For example, pumping well B adjacent to both the Snake River and the Thousand Springs causes a rapid and sharp response in streamflow depletion at both locations, with almost 90 percent of groundwater withdrawal from streamflow capture after less than 5 years.   At the other extreme, pumping well D is furthest from the Thousand Springs, resulting is a time lay of 20 years between pumping and depletion responses at the Thousand Springs. Wells at locations A and C are at intermediate distances from discharge areas, and exhibit intermediate responses in time delay and magnitude of streamflow depletion.
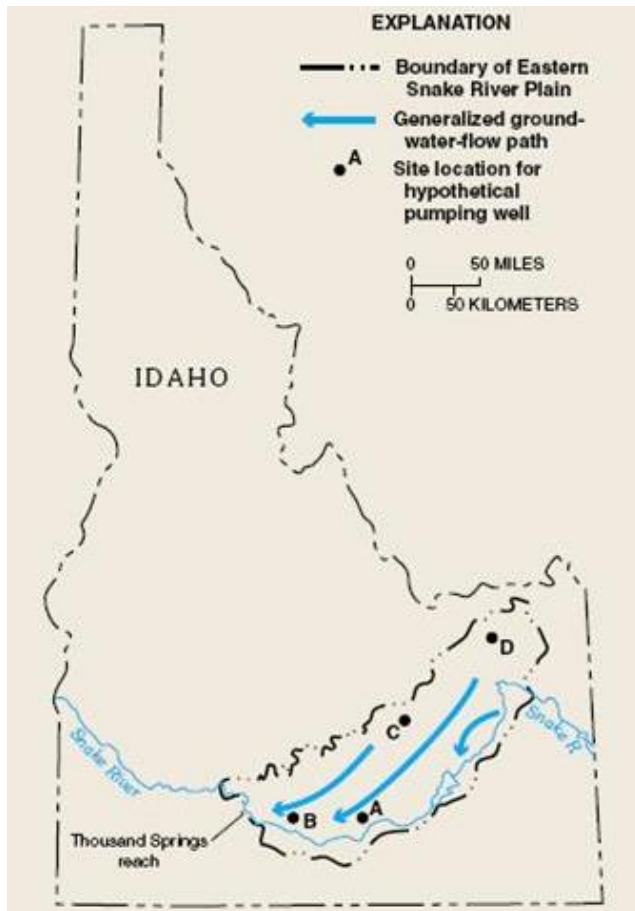
Figure 10   Location of the Eastern Snake River Plain aquifer and modelled pumping wells (Source: Alley et al. 1999).
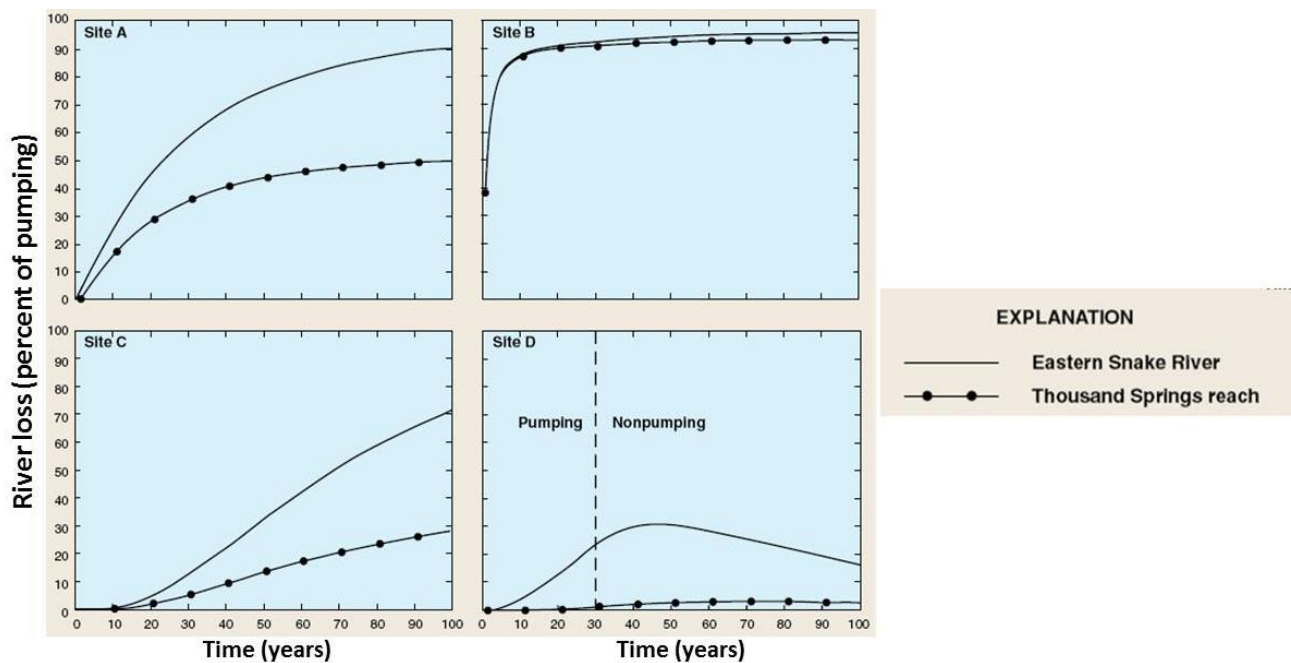
Figure 11   Streamflow depletion responses to pumping in the Eastern Snake River Plain aquifer (Source: Alley et al. 1999).

The effects of streamflow depletion can spread over multiple streams and neighboring watersheds.
Groundwater pumping lowers of the water table (or potentiometric surface) creating a cone of depression around the well or well field that spreads in all directions. When pumping occurs in a stream network, the cone of depression can potentially intercept groundwater flow paths to multiple stream segments and different watersheds, reducing the groundwater discharge in multiple streams.

The effect of groundwater diversion in a stream network has been illustrated in a numerical modelling study of alluvial aquifers of the Puget Sound lowlands (Morgan & Jones, 1999). The groundwater model included a complex sequence of unconfined and confined aquifers that discharge to an upland stream network, foothill springs, and a major river valley (Figure 12).   The researchers investigated three pumping scenarios in the stream network at pumping well locations shown in Figure 13. Table 2 describes the pumping scenarios and the corresponding model predictions for streamflow depletion along various stream segments.
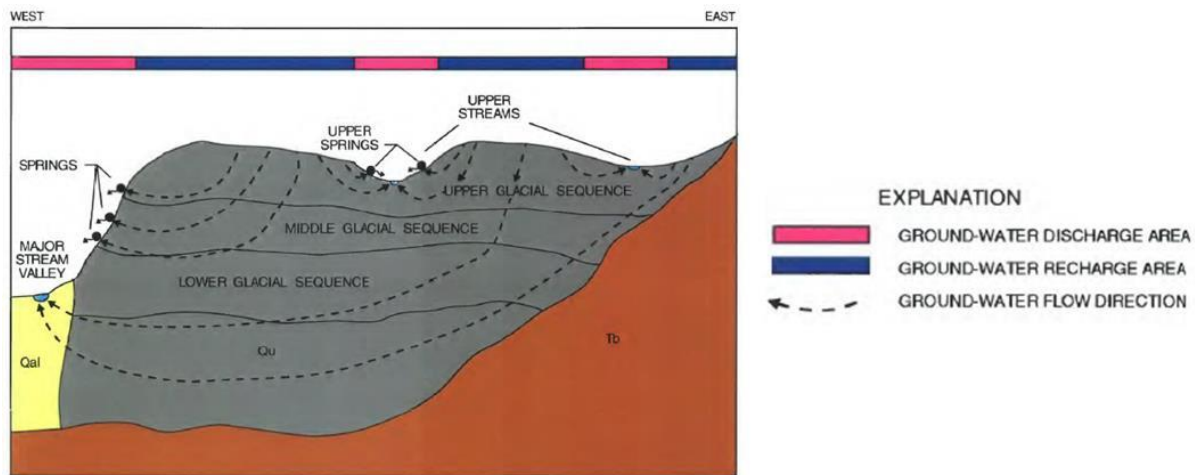
Figure 12   Typical cross-section of modelled sequences and groundwater discharge areas in the Puget Sound lowland modelling study (source: Morgan & Jones, 1999).
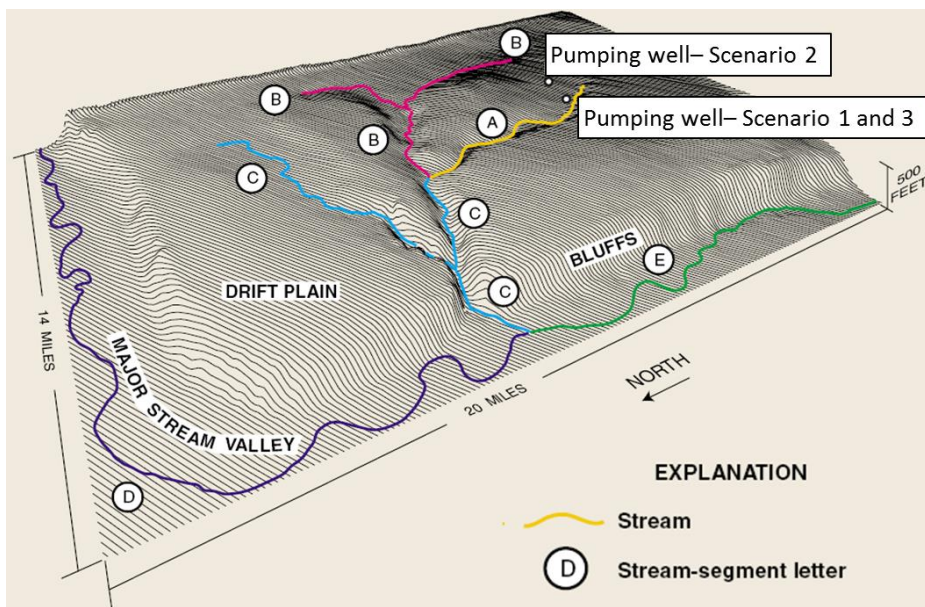
Figure 13   Location of pumping wells and stream segments in the Puget Sound lowland modelling study (Source: Alley at al. 1999).

Results from the steady-state numerical model (Table 2) highlight several characteristics of groundwater diversion effects on the distribution of streamflow depletion in the stream segments:

- A well pumping from an unconfined aquifer in contact with streams will tend to capture most of groundwater discharge from the nearest stream (Scenario 1).
- Increasing the distance between the well pumping from an unconfined aquifer and the stream allows the well to capture some of the discharge from other stream segments (scenario 2). These segments can be both up-gradient and down-gradient from the pumping well as shown in scenario 2. Here, most the water is still captured from the closest stream segment (70% from segment A), but about 10% captured from the up-gradient stream segment B, and about 10% is captured from the down-gradient stream segment E.
- When a semi-confining layer separates the pumped aquifer and the adjacent stream (scenario 3), the cone of depression spreads over a wider area (i.e., a confined aquifer with greater diffusivity). Consequently, there is a greater distribution of surface water depletion, affecting both local and regional systems. Increasing the depth of the well and increasing number of confining layers amplifies these impacts.

Table 2 Simulated pumping scenarios and streamflow depletion results in the Puget Sound lowland modelling study (Source: Morgan and Jones. 1999).

Stream segment	Streamflow depletion expressed as percentage of pumping		
	Scenario 1: Pumping from an unconfined aquifer adjacent to segment A	Scenario 2: Pumping from an unconfined aquifer 1830 m (6000 ft) from segment A	Scenario 3: Pumping from a semi-confined aquifer adjacent to segment A
A	97	70	51
B	<1	12	13
C	<1	<1	5
D	<1	3	5
E	1	12	26

Streamflow depletion continues after pumping stops. When groundwater pumps are shut off, there is a recovery period during which the natural groundwater levels and groundwater flow pattern is re-established. During the recovery period, the cone of depression gradually fills and groundwater levels begin to recover (Figure 14A). Streamflow depletion continues after pumping has stopped because groundwater that would otherwise discharge to the stream is going into aquifer storage. Eventually, groundwater levels and streamflows recover to pre-pumping conditions (Figure 14B). Factors that affect the rate of water table recovery include the distance between the well the stream, the hydrogeologic and hydraulic properties of the aquifer, and the presence of fine-grained streambed sediments.

Barlow and Leake (2012) note the following key points regarding the persistence of streamflow depletion following stoppage of groundwater pumping:

- Maximum streamflow depletion can occur after pumping stops. This is more likely when the distance between the well and stream is large, or the aquifer hydraulic diffusivity is small.
- The duration between the end of pumping and full recovery of the water table can be longer than the duration of pumping because the recovery rate is constrained by diminishing groundwater flow gradients.
- The total volume of streamflow depletion between the start of pumping and full recovery of the water table is equal to the total volume pumped.

- Low-permeability streambed sediments can extend the duration of streamflow depletion after pumping stops.

The rate of streamflow recovery following reductions in pumping is a consideration for managing surface flows during periods of water scarcity or drought. It is important that regulators keep in mind that streamflows recover quickly after pumping shutoff only if the well is close to the stream. In extreme low flow events where regulatory intervention is under consideration, simply requiring a stoppage of pumping will not necessarily guarantee a rapid reduction in streamflow depletion. Rather the rate of recovery will depend on well's distance from the stream, the pumping rate and the hydraulic properties of the aquifer. A screening tool to support water manages with groundwater curtailment planning has been developed by the B.C. Ministry of Environment (Province of British Columbia, 2016b).

A) After pumping stops, groundwater levels gradually recover as aquifer storage increases. Streamflow depletion diminishes but continues after pumping stops.
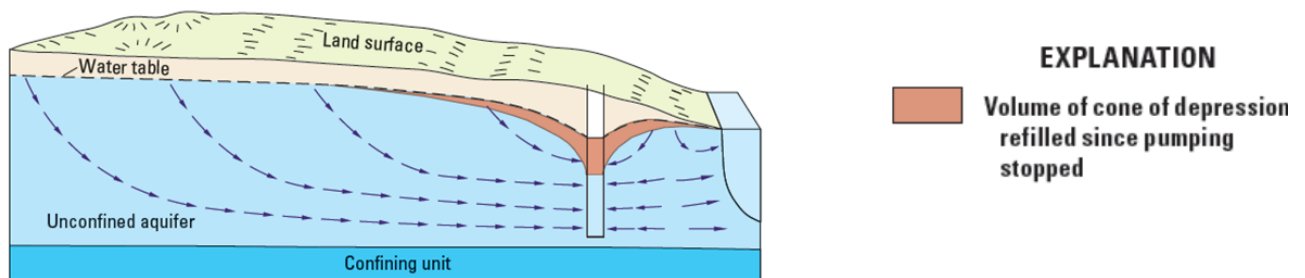
B) Eventually, groundwater levels and streamflows recover to pre-pumping conditions..
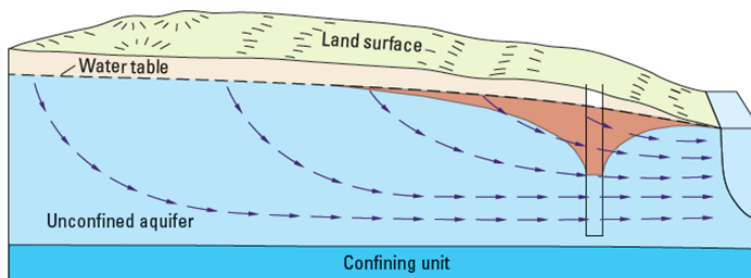
Figure 14   Water table recovery following stoppage of groundwater pumping (Source: Barlow and Leake. 2012).

Time-varying pumping patterns cause time varying responses in streamflow depletion. Critical baseflow periods in many areas of B.C. occur during summer months corresponding to irrigation seasons. Streamflow depletion caused by seasonal pumping patterns will reflect the cyclical patterns of pumping. However, the magnitude of streamflow depletion and the persistence after pumping shutoff both depend on the distance between the well and the stream and the aquifer properties. An understanding of seasonal pumping impacts on streamflow is important for both authorization of groundwater use and assessment pumping impacts on EFNs.

Figure 15 illustrates streamflow depletion responses to seasonal pumping and the influence of the well distance from a stream. Figure 15A shows the seasonal pumping rate (pink line) and the equivalent annual pumping rate (black line). Figure 15B and C show the corresponding streamflow depletion for pumping wells spaced at 91 m (300 feet) and 914 m (3000 feet) from the stream, respectively.
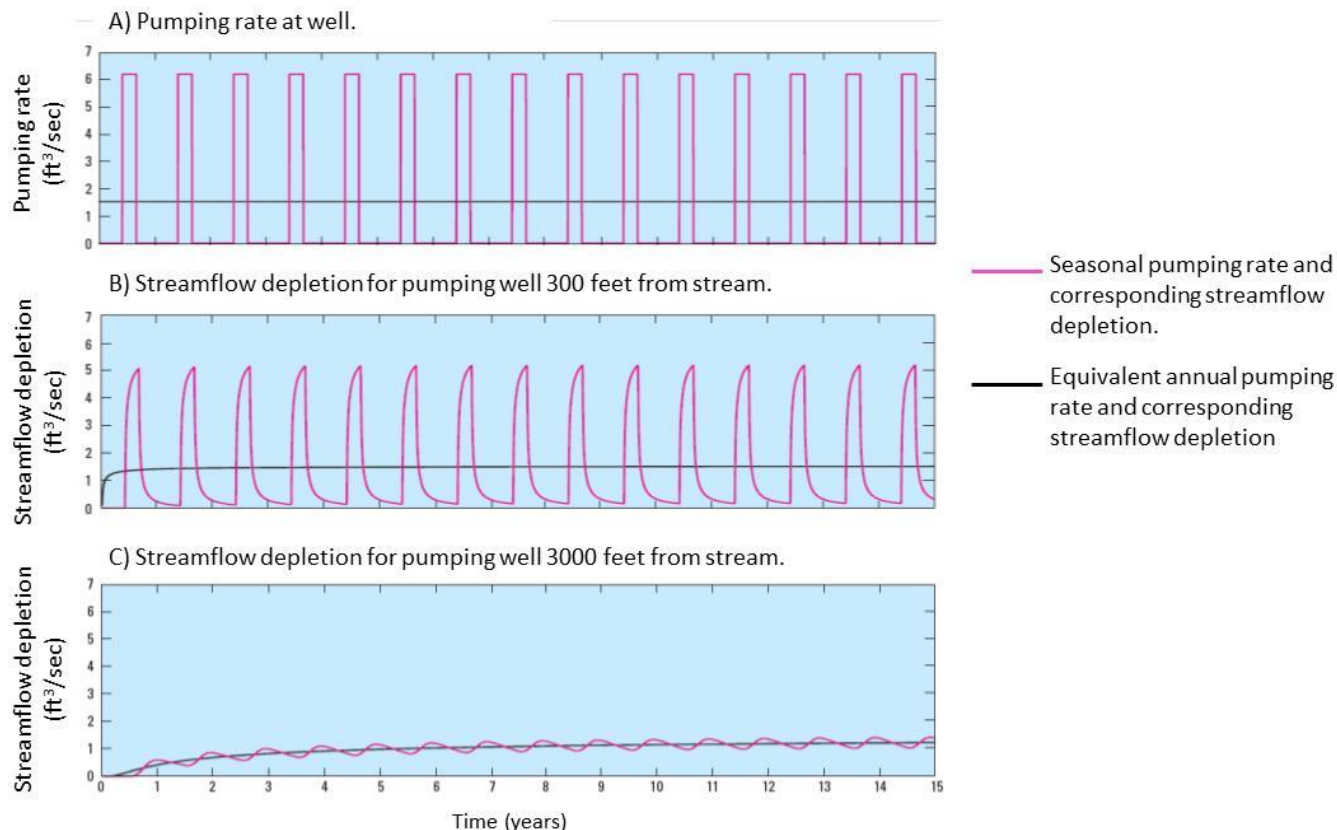
Figure 15   Streamflow depletion responses from by seasonal pumping patterns (Source: Barlow and Leake. 2012).

The pumping well close to the stream produces a quick response in streamflow depletion, with a peak magnitude approaching the pumping rate (Figure 15B). Following pump shutoff there is a rapid falloff in streamflow depletion and minor persistence at low levels.   If the period of seasonal pumping from this well overlaps the critical low flow period in streamflow, then there will be a close correspondence in the seasonal pumping volume and the volume of baseflow reduction. For this scenario, water managers may wish to consider restricting seasonal pumping to non-critical periods. Figure 15B also shows very poor agreement between the cyclical streamflow depletion response (pink line) and the streamflow depletion response estimated with an average annual pumping rate (black line). Consequently, it is not appropriate to use equivalent average pumping rates when wells are relatively close to the stream.

In the case where the pumping well is far from the stream (Figure 15C), seasonal pumping produces a slower response in streamflow depletion, with a maximum streamflow depletion much less than the pumping rate (Figure 15C). However, the effects of stream depletion persist longer after pumping stops. Additionally, the stream response to pumping approaches the response obtained for continuous groundwater withdrawal at an equivalent average annual pumping rate. Thus, cyclical pumping at wells far from streams results in less variable streamflow depletion response, with maximum values slightly above the average pumping rate.

The cumulative streamflow depletion caused by multiple pumping wells is the additive response of individual wells. Many shallow productive aquifers in B.C. have tens or hundreds of pumping wells in close proximity to streams. Although, individual wells may have limited impacts to streamflow, the cumulative impact of a well field can be significant.

Figure 16 illustrates the cumulative streamflow depletion of three pumping wells, each pumping at a rate of 1 Mgal/day but over different timeframes. In this figure, the cumulative pumping is 1 Mgpd for the first 5 years (well A), 2 Mgpd for the second 5-year period (well A & B), and 3 Mgpd for the third 5-year period (wells A, B & C). The total streamflow depletion caused by the three wells is the sum of streamflow depletion caused by each individual well, i.e., streamflow depletion from individual wells is additive. This additive response assumes the saturated thickness of the aquifer does not significantly decrease as a result of pumping drawdown.

	Pumping Conditions		
Well	Distance to stream (ft)	Pumping rate (Mgpd)	Pumping period
A	300	1.0	Year 1 to 15
B	1000	1.0	Year 6 to 15
C	3000	1.0	Year 11 to 15
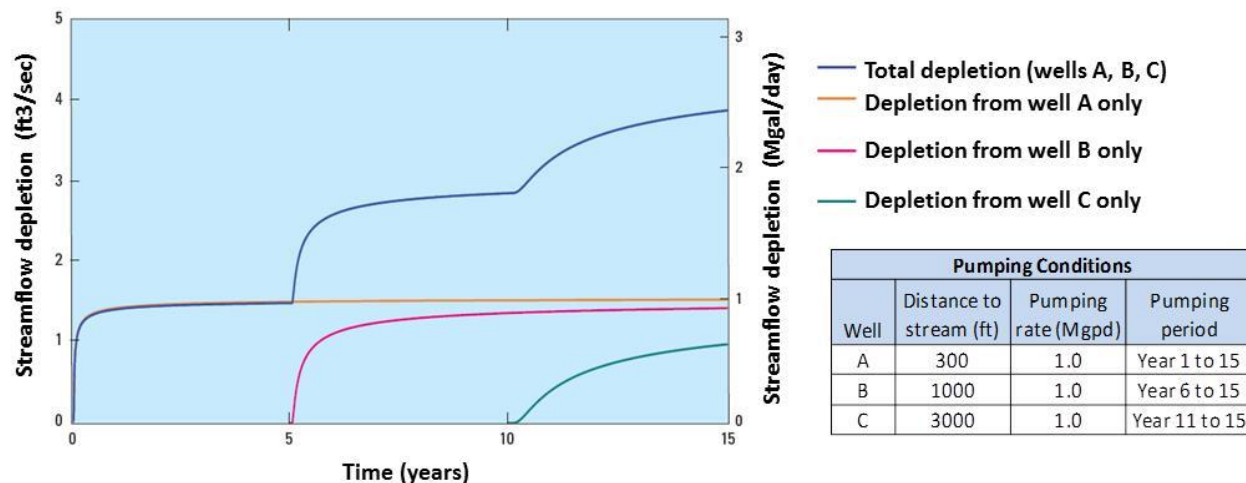
Figure 16   Streamflow depletion caused by multiple wells (Source: Barlow and Leake. 2012).

The additive property of streamflow depletion implies EFN assessment and assessment of impacts on water rights can be conducted independently on a well-by-well basis. In addition, it may be practical to gain estimates and preliminary insights of cumulative streamflow depletion for local well fields. However, more detailed groundwater modelling may be required for a comprehensive assessment of basin wide water resources and pumping impacts.

2.2.2   Pumping from Confined Aquifers
Confined aquifers occur between geologic zones or strata of low permeability such as clay, silt, till, and bedrock. The confining strata or layers, called aquitards, have permeability that is low in comparison to adjacent aquifer materials. Aquitards may be laterally continuous or discontinuous across the confined aquifer. Often, low permeability aquitards are considered to effectively limit flow between adjacent aquifers.   However, Freeze and Cheery (1979) note that while the permeability of an aquitard may not allow completion of a production well, the aquitard can still be permeable enough to transmit water in quantities that are significant in the study of regional groundwater flow.

Pumping from confined aquifers does not eliminate the possibility of streamflow depletion. Hydraulic connections between confined aquifers and surface waters may occur in the following three ways.

1. **Direct connection occurs where confined aquifers outcrop along surface water bodies**: Confined aquifers and aquitards can outcrop at the ground surface and along surface water bodies providing a direct connection between surface water and the aquifer. An example of such outcrops are confined Quadra sand aquifers near Parksville B.C. (GW Solutions, Inc., 2012). These aquifers outcrop along the banks of the Englishman River Channel, providing a significant source of baseflow. Pumping from the confined aquifers likely contributes to streamflow depletion.

2. **Aquitards may have sufficient permeability to allow vertical movement of water between aquifers and surface waters:** Although the permeability of aquitards is small in comparison to the aquifer, leakage or flow through the strata does occur. Freeze and Cheery (1979) note that few formations fit the classical definition of an aquiclude, which is a formation that is incapable of transmitting significant quantities of water under ordinary hydraulic gradients. Moreover, Barlow and Leake (2012) state it is not reasonable to expect that pumping beneath an extensive confining layer will eliminate depletion, as this would imply the aquifer is completely isolated from surface waters.

   Pumping below aquitards will generally impede streamflow depletion but does not necessarily prevent it (semi-confined aquifers). Drawdown from pumping can also propagate through the aquitards into the overlying water aquifers (Sophocleous, et al., 1988). Barlow and Leake (2012) point out that since pumping stresses in confined aquifers propagate faster than in unconfined aquifers, the drawdown from pumping at a particular location can readily spread to distant edges of the aquifer or locations where drawdown can more easily propagate upward. These effects are demonstrated in numerical studies of the Puget Sound lowlands where groundwater withdrawals below a semi-confining aquitard resulted in a wider distribution of surface water depletion, affecting both local and regional systems (Morgan & Jones, 1999).

   Many aquifers classified as confined aquifers potentially have some degree of connectivity to surface waters. Two examples of hydraulic connectivity between confined aquifers and surfaces waters are along the Cowichan River and Mission Creek. Analyses of pumping tests from confined aquifers adjacent to the Cowichan River near Duncan display rapid equilibrium and recovery, indicating strong connectivity to the river (Foweraker, et al., 1976). Confined aquifers in the Bonaparte and Semlin Valleys near Cache Creek, B.C. display connectivity to surface waters as evidenced by water level response to river stage and pumping test analyses (Hy-Geo Consulting, 2015)

3. **Confining aquitards can be discontinuous such that contact windows occur between the underlying confined aquifer and the overlying water table aquifer.** These windows may act as bridges or preferential flow paths between confined aquifers and surface waters (Nielsen & Locke, 2012). Pumping from confined aquifers where confining layers are discontinuous can both decrease and increase the rate of streamflow in comparison to conditions with no confining strata (see Barlow and Leake, 2012). The rate of streamflow depletion depends on the relative location of the discontinuous strata and the pumping wells. Streamflow depletion occurs more slowly when low-permeable strata are under the stream and pumping occurs at depth away from the stream. Conversely, the rate of streamflow depletion increases when the low-permeable strata are located along the margins of the aquifer and pumping wells are located below the strata.

2.2.3   *Pumping from Bedrock Aquifers*
Bedrock aquifers are a main water supply source in many parts of B.C., often for small domestic users. The primary porosity (e.g., pore spaces) of bedrock is typically small and has minor influence on the storage and transport of groundwater. Groundwater flow in bedrock aquifers occurs primarily through fracture zones, contacts, faults, as well as through zones of broken weathered rock. Therefore, groundwater development in sedimentary and crystalline bedrock depends on the degree to which such fracture and fault zones (secondary porosity) are present and the success in locating productive fracture zones. Flow through karst formations can also occur through dissolution channels, but such aquifers are not well studied in the province.

It is difficult to characterize the size and orientation of fracture zones, faults, and weathered zones, as they are often highly heterogeneous, anisotropic, and discontinuous in nature. Consequently, it is challenging to assess well interference effects in bedrock aquifers, and to determine the hydraulic connections between the aquifer and surface waters. As a broad generality, bedrock aquifers are typically deeper, less productive, and have lower yields than unconsolidated aquifers. For these reasons, there is generally a lower level of concern regarding impacts from pumping on streamflows, in comparison to unconsolidated aquifers.

Where fracture and fault zones of bedrock aquifers intercept surface water bodies and springs, there is a potential for groundwater withdrawals to affect surface water flows or levels. Evidence of hydraulic connections between bedrock aquifers and surface water can be circumstantial, based on general geologic descriptions, topographic patterns, and observations of bedrock outcrops at the ground surface. Stronger evidence of connectivity includes the presence of baseflow in bedrock terrains, bedrock springs, and information gained from pumping tests and chemical signatures. For example, analyses of pumping tests in bedrock aquifers of northeast B.C. sometimes display rapid equilibrium and recovery. This suggests the aquifer is hydraulically connected to a transmissive source of water, such as a surface water body or a more conductive adjacent unconsolidated aquifer.

Where there is evidence or suggestions of surface water connections to bedrock aquifers, water managers should consider the potential for streamflow depletion from pumping. For example, the Michigan screening tool includes a statewide aquifer database and maps indicating areas where bedrock aquifers are potentially connected to surface water (Reeves, et al., 2009). The screening model explicitly includes bedrock areas of the state for analysis using default aquifer parameters. In B.C., a main challenge is the ability to identify and characterize areas of the province where bedrock aquifers are connected to surface water bodies.

2.2.4   *Pumping near Low Order and Small Ephemeral Streams*
Low order and small ephemeral headwater streams in semi-arid areas can have dynamic SW-GW interactions (Winter, et al., 1998). They may be dry through much of the year, except during large storms or freshet when there is continuous flow. During these times, they behave as losing streams recharging the aquifer. In response to recharge, a transient rise in the water table causes a reversal in SW-GW interchange from losing conditions to gaining conditions in lower reaches, and the point of reversal gradually moves up the stream reach. After the recharge sources are exhausted, the transient groundwater mounds dissipate and aquifer storage gradually diminishes. The duration and timing of streamflows is variable, from weeks to months, or they may be perennial in lower reaches. Winter et al. (1998) note that SW-GW interactions in low order headwater streams are particularly variable.

Few studies were identified regarding pumping impacts to low order and small ephemeral drainages. The extent that groundwater withdrawals and associated EFN impacts occur in such areas in B.C. is unknown. However, due to the dynamic and variable nature of these systems, any pumping induced changes to groundwater elevations adjacent to low order and ephemeral streams has the potential to affect SW-GW interactions including the magnitude, timing, and duration of surface flows. Studies have noted that intermittent and ephemeral drainages support a diversity of habitat and ecological functions, even in the absence of surface flows (Levick, et al., 2008). Pumping near these drainages can stress or kill riparian vegetation by reducing the frequency of surface flows or by lowering the water table below the root zone. This promotes invasion of non-native and more drought-tolerate species, which in turn affects wildlife habitat.

2.2.5   *Pumping Impacts to Lakes, Springs, and Wetlands*
The discussion above has focused on pumping impacts to streams because streams are the often the primary discharge areas of groundwater, and EFN assessments often focus on fisheries habitat in

streams. The impact of groundwater withdrawals to lakes and springs is similar to that of rivers and streams. Therefore, descriptions of pumping impacts on streams in the foregoing sections also apply to springs and lakes.

Pumping near lakes potentially reduces lake levels by intercepting groundwater discharge and/or by inducing direct recharge from the lake. However, lake levels may also be influenced by other factors such as surface runoff, evapotranspiration rates, aquifer recharge, and natural variability in groundwater levels, and reservoir operation rules. Therefore, key information for assessing pumping impacts on lakes includes: 1) an understanding of the natural water balance of the lake, 2) an understanding of the hydrogeology and aquifer connectivity to the lake, particularly the presence of low-permeable aquitards and lakebed properties, 3) the aquifer properties, and 4) the location and pumping schedule of wells, and reservoir operation rules.

Pumping near springs potentially reduces the flow rate and the timing of flows to springs by intercepting groundwater that would otherwise discharge at the spring. In general, the impacts diminish greatly as the distance between the well and the spring diminishes. However, spring flows are strongly influenced by site-specific hydrogeologic conditions and it may be difficult to infer pumping impacts. Key information for assessing pumping impacts on springs includes: 1) the spring flow rates and patterns in undeveloped conditions, 2) an understanding of the hydrogeology and contributing aquifer area to the spring (spring basin), 3) the aquifer properties of the spring basin, and 4) the relative location and pumping schedule of the well. Kreye et al. (1996) provide a very good overview on the types of springs that occur in B.C., and describe a detailed procedure for defining the source area to springs.

Wetlands form in a variety of topographic and climatic settings and many are supported by groundwater inputs and can have complex hydrogeologic interactions (Winter, et al., 1998). In addition, wetlands ecosystems include plant communities whose root zones can promote shallow SW-GW exchange. Groundwater withdrawals from shallow aquifers can affect both the hydrologic and ecologic characteristics of the wetlands. Similar to lakes and springs, groundwater withdrawals affect wetlands by depleting groundwater discharges and lowering of the water table. Additionally, groundwater withdrawals can change the amplitude and frequency of seasonal groundwater level fluctuations, which can affect the type of vegetation, nutrient cycling, and the type of invertebrates (Alley, et al., 1999).

2.2.6   Importance of Groundwater for Ecological Health and Fisheries Habitat
Groundwater discharges to surface waters are a crucial component of fisheries habitat in many areas of B.C. Groundwater can influence the distribution, reproductive success, behavior, biomass and productivity, and movements of fishes. Because groundwater temperature is approximately equal to the mean annual air temperature, it is generally more stable than surface water temperature. Consequently, groundwater discharges have a moderating influence on surface water temperatures, which can be especially important during winter and summer low flows.

The hyporheic zone encompasses the saturated pore areas below the streambed where there is significant mixing between surface and groundwater (Figure 17). The hyporheic exchange helps to supply and retain nutrients and solutes that are essential to organisms and the ecological health of the stream. When pumping near streams changes the nature of SW-GW interactions, it can also affect the hyporheic exchange and associated habitat functions.

Table 3 lists the roles and functions of groundwater discharges in supporting fisheries habitat. In northern and interior areas of B.C., winter streamflows are minimal due to reduced runoff from freezing conditions. Groundwater discharges substantially or wholly sustain baseflow during winter, and groundwater discharges help to warm stream temperatures, which can delay or eliminate ice formation.

Areas of groundwater discharge provide key fisheries habitat for migration and overwintering throughout northern B.C. (Power, et al., 1999; Hatfield, et al., 2003).
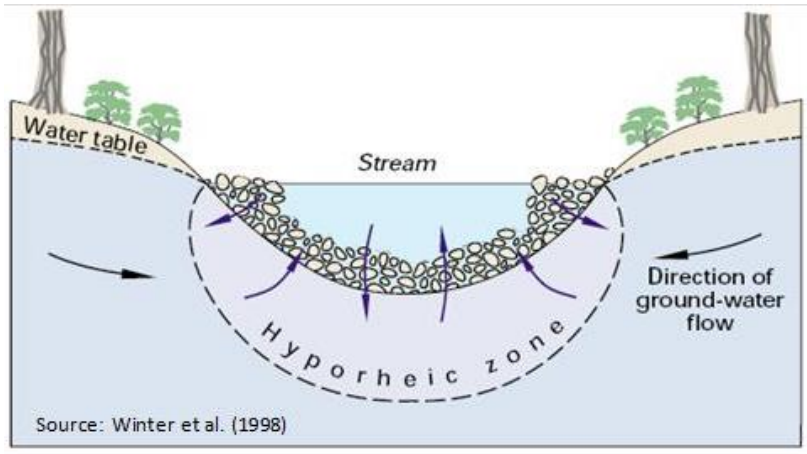
Figure 17   Depiction of the hyporheic zone (Source: Winter et al. 1998).

In summer, groundwater is important for maintaining discharge and moderating stream temperatures. During critically hot weather, groundwater refugia protect species exposed to temperatures approaching their thermal limits (Power, et al., 1999). Studies have noted that cool water areas need to be abundant and available to fish, and that the availability of appropriate holding habitat within mainstem rivers may affect long-term population survival (Douglas, 2006). In some systems, groundwater is the limiting resource during summer months. Consequently, excessive groundwater withdrawal can significantly affect fisheries habitat (Falke, et al., 2011). Figure 18 shows the location of summer and winter low flow sensitivity throughout B.C.

Because of the importance of groundwater discharges for fisheries habitat, Powers et al. (1999) and Douglas (2006) stress the importance of coordinated management of surface and groundwater resources for protection of groundwater-dominated habitats.

Table 3   Roles and functions of groundwater discharges for fisheries (Source: Power et al. 1999).

Groundwater role	Fall/winter season	Summer/autumn season
Provision of baseflow	• Maintain free flowing water, habitat, and migratory channels	• Maintains minimal flows and living space
Modulation of temperature	• Prevents or delays ice formation • Provides areas with temperature above 0 ^{o}C	• Dampens daily temperature fluctuations • Slow and limits seasonal warming • Delays cooling in autumn
Influences water quality	• Supplies dissolved inorganic and organic nutrients and oxygen to stream • Water quality tempered by hyporheic exchange	• Aids stream productivity by steady input of nutrients • Stimulates macrophyte growth • Water quality tempered by hyporheic exchange
Provision of refuge	• Sets size and quality of winter refugia • Influences mortality • May set overwintering carrying capacity	• Provides protection from upper lethal temperatures • May set carrying capacity in hot dry summer weather
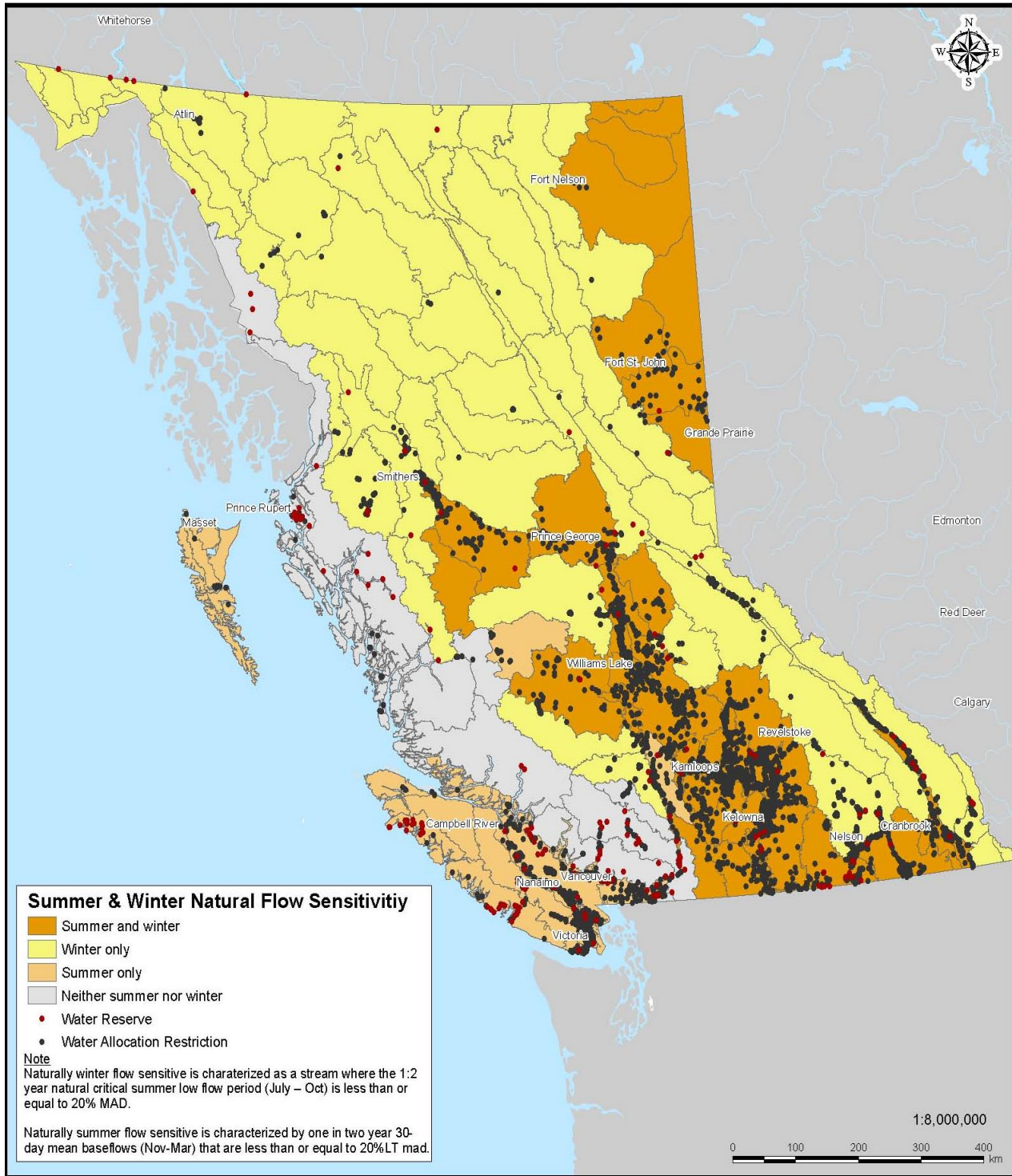
Figure 18   Location of summer and winter flow sensitivity in B.C. (Source: Ron Ptolemy, B.C. Ministry of Environment).

3. SURFACE WATER-GROUNDWATER INTERACTIONS AND IMPACTS FROM PUMPING

For any given location, the nature of SW-GW interactions can be unique and complex due to the influence of local-scale hydrogeologic, climatic, and human factors. Characterizing SW-GW interactions and defining the risks of groundwater withdrawal on surface flows at specific locations is challenging. Nevertheless, understanding the local SW-GW connectivity is a key requirement for properly assessing pumping impacts on EFNs and administrating associated water rights. To support this effort, this section presents broad classifications of SW-GW interaction in B.C., and presents a review of specific SW-GW studies in B.C., which serve to highlight attributes and complexities of SW-GW interactions found in the Province.

3.1 General Characteristics of Surface Water-Groundwater Interactions in B.C.

3.1.1 Physical Setting

The majority of B.C. is within the Canadian Cordilleran Hydrogeological Region (Figure 19). A portion of northeast B.C. falls within the Interior Plains Hydrogeologic Region, on the eastern side of the Rocky Mountains (Sharpe, et al., 2014).

Figure 19   Hydrogeologic regions in B.C. (Source: Wei et al., 2014).

The Cordilleran Hydrogeological Region is physiographically and geologically diverse, comprised of massive mountain ranges, highlands, foothills, plateaus, basins and lowlands. There are three major physiographic areas from west to east (Wei, et al., 2014):

1. Western system of northwesterly-trending coast mountain ranges, coastal lowlands and basins.
2. Interior system comprising of several major and minor mountain ranges, plains, plateaus, and basins.
3. Eastern system of northwesterly-trending Rocky mountain ranges, foothills and the Liard plateau.

Plateaus are most extensive in the north, and larger inter-montane valleys are more prominent in the south.

Characteristics of the Western Plains Hydrogeological Region are low relief topography with flat to gently rolling and hummocky terrain (Sharpe, et al., 2014).

3.1.2   *Climate Regimes and Groundwater Level Responses*
Climatic variations in B.C. affect the amount and form of precipitation, which in turn affects the timing and characteristics of streamflow, groundwater levels, and SW-GW interactions. There are four broad hydroclimatic regimes in B.C. (Table 4).

Table 4   Hydroclimatic Regimes of B.C. (Adapted from Hartfield et al. 2012).

Hydroclimatic Regime	Locations	Characteristics
Rain-dominated	• Coastal lowland areas • Lower elevations of the West side of the Coast mountains • Example: Carnation Creek on West coast of Vancouver Island	• Streamflow follows precipitation patterns • Highest monthly discharge in winter • Lowest monthly discharge in summer • Groundwater levels are highest in winter, early spring (e.g. Nanaimo, Abbotsford in Figure 20) • Groundwater contributes to baseflow in perennial streams • Baseflow duration ~ 100 days
Snow-dominated	• Interior plateau • Mountain regions • Higher-elevations of the Coast mountains • Examples: Fishtrap and Redfish- Interior; Coquihalla, Coast.	• Winter precipitation typically falls as snow and remains 'stored' as snow until the spring melt • Low flows throughout the summer, fall and winter • High flows in spring and early summer • Groundwater levels are highest in late spring, early summer (e.g. Kelowna, Kamloops in Figure 20) • Baseflow duration ~ 200 days
Mixed (hybrid)	• Coastal regions • Near-coastal regions • North-eastern region • Example: Capilano River	• A blend of rain and snowmelt-dominated regime characteristics • The influence of the rain regime decreases inland from the coast, northwards up the coast, and at higher elevations • Rain-dominated high flows from late fall through winter • Snowmelt-dominated high flows in spring • In the Northeast, high flows are typically in early summer
Glacier-dominated	• Occurs in drainage basins with more than 2-5% of the area covered by glaciers • Example: Lillooet River	• Similar to snowmelt dominated, but glacier melt augments summer low flows • Low flows through the winter • High flows from early spring to late summer or early fall • Baseflow duration ~ 150 days

Rainfall dominated climate regimes are generally in lowland coastal regions of B.C. These areas experience wet and dry seasons with highest precipitation during the winter and early spring followed by relatively dry periods during the summer and early fall. Precipitation generally falls as rain, except at higher elevations where it falls as snow in the winter months. Coinciding with these precipitation patterns, groundwater recharge occurs predominately in the winter months when the rate of evaporation and transpiration are at their seasonal lowest. Natural groundwater levels in coastal regions show a seasonal high during winter or early spring, and generally decline from spring to late fall (see Nanaimo and Abbotsford in Figure 20) Streamflow is generally highest following winter storms, when soils are saturated and runoff is highest. Streamflow is typically lowest in the late summer and early fall, when baseflow is largely sustained by groundwater discharge (see Figure 18).
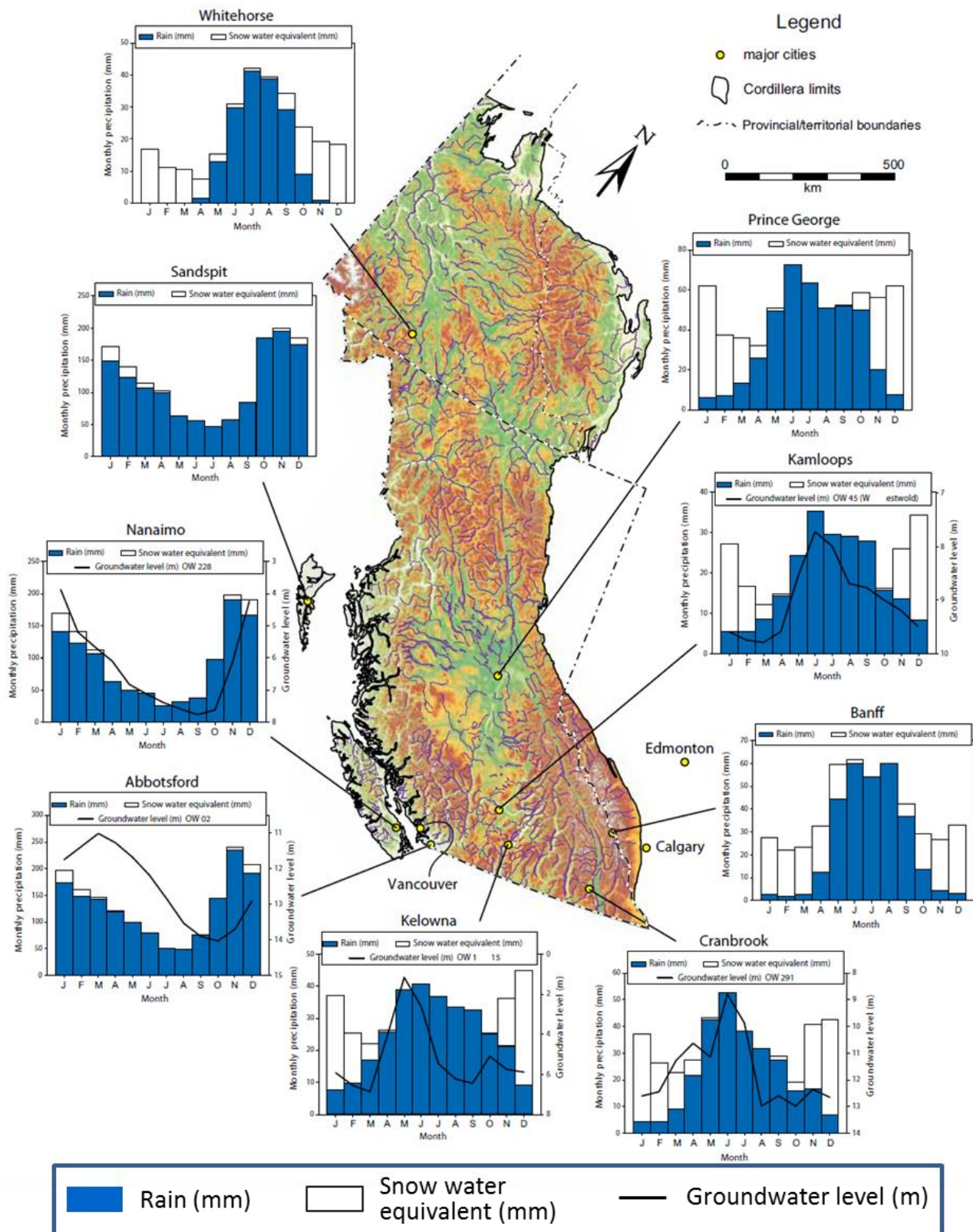
Figure 20   Precipitation and GW level variation at select locations in the Cordilleran Region (Source: Wei et al. 2014).

Snow dominated climate regimes occur in interior regions of B.C. These areas experience year-round precipitation, and highest precipitation may occur during the summer months, mostly as rain. However, much of this precipitation is not available for recharge because evaporation and transpiration are highest during the summer, and there may be little excess water available to infiltrate past the root zone to recharge aquifers. Precipitation in the winter falls mostly as snow, which accumulates at higher elevations and frozen ground conditions restrict direct recharge during winter months. Greatest recharge occurs during and immediately after freshet in the spring and early summer. Thus, highest natural groundwater levels generally occur in late spring or early summer and then decline over the summer and early fall, reaching a seasonal low during the winter months (see Kamloops in Figure 20). Similarly, streamflows are highest during freshet and lowest during winter months and late summer. Groundwater discharges may greatly support winter baseflow and late summer baseflow (Figure 18). In glacial regions, glacial melt may support and contribute to baseflow through the summer.

Climate in the interior plains region of northeast B.C. is semi-arid due to the rain shadow effects of the Rocky Mountains (Sharpe, et al., 2014). Summers are short and warm, and winters are very cold. Recharge to local groundwater systems during freshet is constrained by semi-arid conditions and the presence of low-permeability geologic materials that overlie aquifers. Recharge may also occur in summer due to heavy rains associated with convective storm events, despite high evapotranspiration during the summer (Sharpe, et al., 2014).

Figure 21 shows a framework for classifying stream-aquifer responses in different hydroclimatic regimes (Allen, et al., 2010). For simplicity, the framework includes two types of hydroclimatic regimes and two types of aquifer-stream systems.
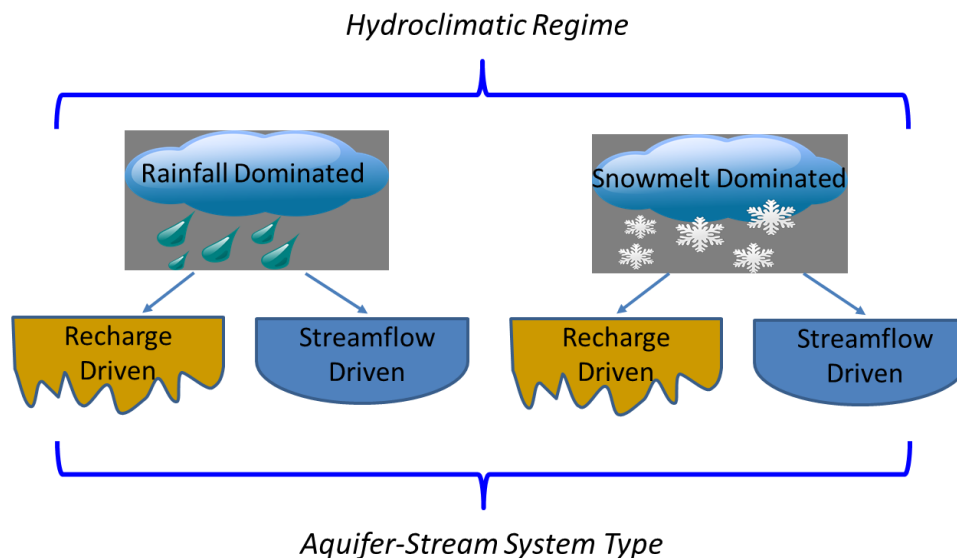
Figure 21   Framework for classifying stream-aquifer systems (after Allen et al. 2010).

Aquifer-stream systems types are:

- **Recharge driven systems** where groundwater recharge occurs mainly from direct recharge of precipitation over the land surface. Groundwater levels are typically above the stream such that gaining stream conditions are generally dominant.
- **Streamflow driven systems** where significant groundwater recharge occurs along the stream course in response to elevated streamflows during freshet. In these systems, the direction of SW-GW interaction may vary seasonally in response to stream stage.

Recharge driven and streamflow driven systems can occur in both hydroclimatic regimes. Also, the distinction between recharge and streamflow driven systems is not always clear and hybrid systems are possible (Allen, et al., 2010).

3.1.3   Surface Water-Groundwater Interactions in Hydrological Landscapes of B.C.

At a broad scale, there are common features of SW-GW interactions among similar geomorphic and hydrologic settings. As a unifying concept, Winter et al. (1998) characterized the general nature of SW-GW interactions in hydrologic landscapes. A hydrologic landscape is defined by the land-surface form, geology, and climate, and provides a conceptual framework for describing SW-GW interactions in actual systems (Winter, 2001). The land-surface forms are distinguished by the width and slope of uplands, lowlands, valley sides, and the topographic relief between these land features. In B.C., there are three dominant types of hydrologic landscapes:

- **Mountainous terrains** consisting of narrow lowlands and uplands separated by high and steep valley sides;
- **Riverine terrains** consisting of broad lowlands (flood plains) with nested terraces separated from regional uplands of various size and slopes; and
- **Plains terrains** consisting of narrow lowlands separated from very broad uplands by valley sides of various slopes and heights.

These hydrologic landscapes occur on different scales. Smaller hydrologic landscapes may be superimposed on larger regional scale landscapes.

SW-GW Interactions in Mountainous Terrains: Mountainous areas have steep slopes with streams that are typically of low to moderate order and confined within steep valleys. Mountainous terrains generally have shallow alluvium directly underlain by bedrock, sedimentary and crystalline rocks, or glacial deposits overlying bedrock. Unconsolidated alluvial aquifers are typically shallow and of limited lateral extent. The alluvial aquifers are usually unconfined or partially confined. Alluvial fans may occur at the edge of the mountain valleys.

Mountainous terrains occur throughout B.C. Examples of groundwater development in mountainous landscapes are the narrow shallow alluvial aquifers adjacent to Lemieux Creek near Little Fork and adjacent to Bonaparte River near Cache Creek.

The general characteristics of SW-GW interaction in mountainous terrains are described by Winter et al. (1998) as illustrated in Figure 22:

- Water moves rapidly both above ground and below ground due to steep slopes, soils with macropores created by plants and animals, and the presence of weathered and fractured bedrock.
- Groundwater discharges from shallow alluvium support much of the valley streamflow between storms and snowmelt (Figure 22A). Deeper groundwater recharge and flow through shallow fractured bedrock also support baseflow in mountain streams (Welch, et al., 2012).
- During large storms or freshet, much of the water travels rapidly as interflow through the shallow unsaturated soils to the stream (Figure 22B).
- Water that infiltrates during large storms or snowmelt recharges the adjacent aquifer, causing a rise in the water table. This groundwater may discharge at the base of steep slopes or near streams (Figure 22C). It may also emerge as perennial springs or wetland areas.
- Because of the steep slopes and coarse soils, there is a strong down-valley gradient of flow with frequent SW-GW interactions occurring through riffle-pool systems. Gaining stream conditions

occur at the downstream end of riffles and upstream end of pools. Losing stream conditions occur at the downstream end of pools

- Losing stream conditions occur where the stream traverses high permeable alluvial fans at the walls of mountain valleys.
- Deeper regional groundwater flow paths through underlying bedrock formations also occur, which can contribute to baseflow in valley bottoms (Welch & Allen, 2012).
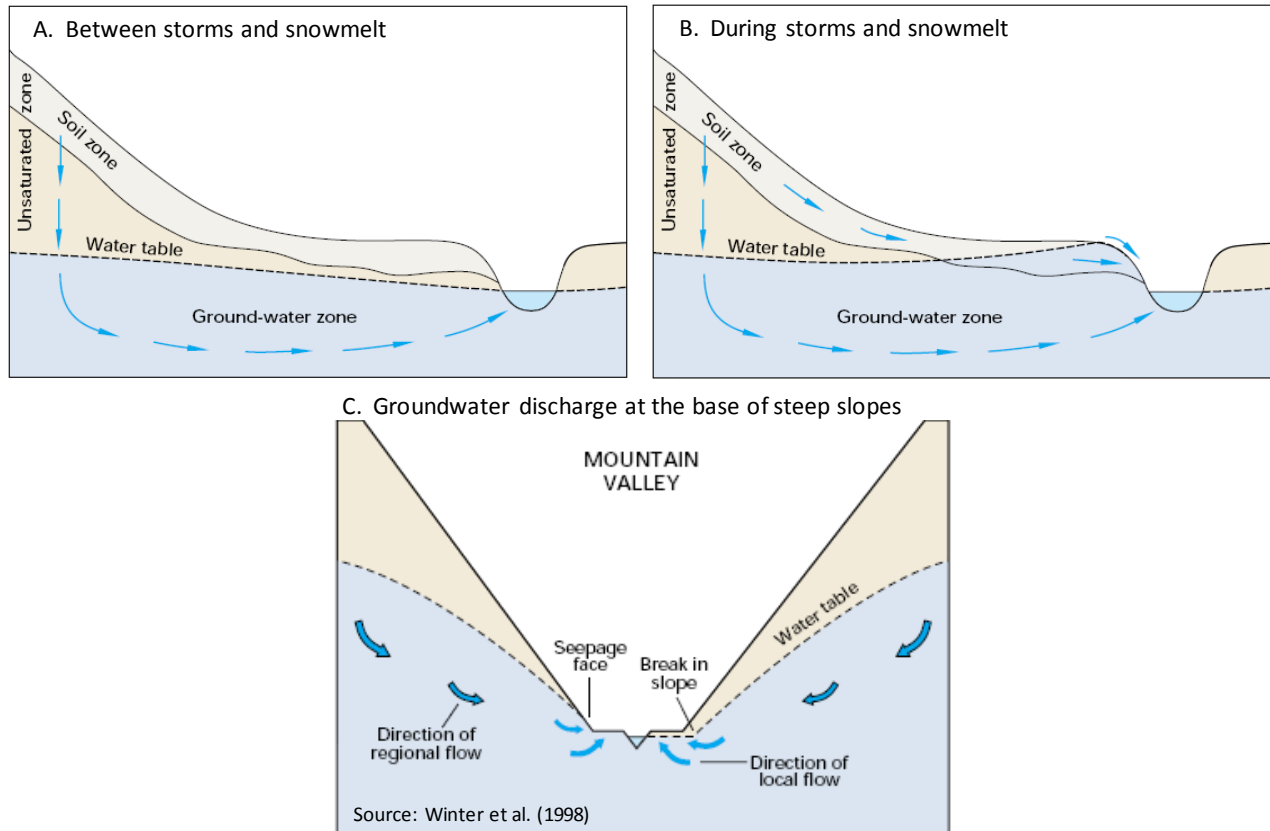
Figure 22   Generalized GW-SW interactions in mountainous terrains (Source: Winter et al. 1998).

SW-GW Interactions in Riverine Terrains: Riverine terrains are river systems and river valleys that have lower gradients and slower velocities than mountainous terrains. Riverine terrains are dominant features throughout B.C. and are a primary focus of management of water rights and EFN assessments. Examples of riverine system include the Fraser River Valley, the Kettle River/Grand Forks aquifer system, and the Okanagan River Aquifer System at Oliver.

Riverine terrains encompass a wide range of sizes, from smaller moderate order rivers to major river systems, bordered by well-developed and broad floodplains (Figure 23). Major river valleys commonly have terraces, natural levees, and abandoned river meanders. Wetlands and lakes are associated with these features.

Aquifers in riverine terrains are usually of glacial or glacial fluvial origin, and range in size from relatively small (e.g., headwater streams) to large systems (e.g., Fraser, Columbia, Skeena rivers). Alluvial deposits range from clays to boulders but sands and gravels dominate alluvial aquifers. The alluvial aquifers are usually unconfined or partially confined and can have strong hydraulic communication with the river system.
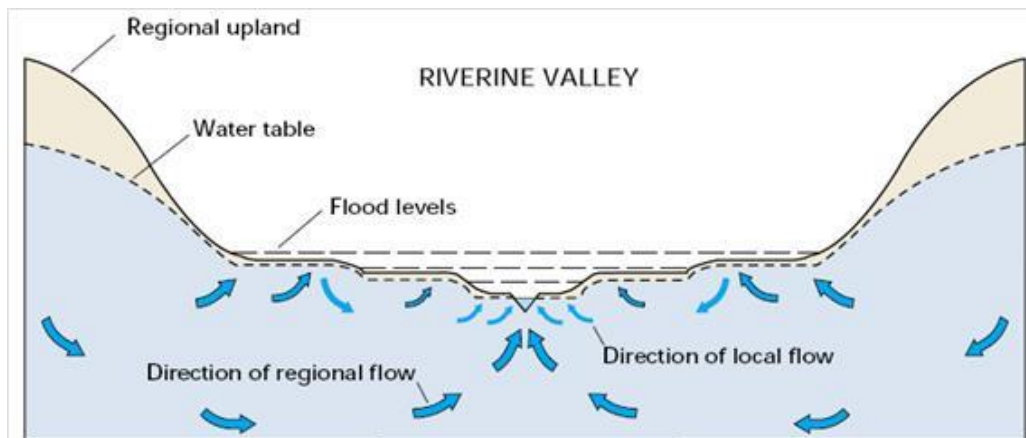
Figure 23   Generalized GW-SW interactions in riverine terrains (Source: Winter et al. 1998).

The following are general characteristics of water movement and SW-GW interaction in riverine terrains (Winter, et al., 1998):

- SW-GW interaction encompasses the interchange of local and regional groundwater flow systems.
- Smaller river systems tend to interact with local groundwater flow systems. The local groundwater systems are usually smaller, have comparatively less storage capacity, and display more seasonally variability. Smaller river systems are more likely to have both gaining and losing reaches that vary seasonally.
- In larger river valleys, both local and regional systems interact with surface waters. Regional groundwater systems discharge to rivers, but may also discharge to lakes and wetlands near the valley walls. Local groundwater flow systems develop and discharge to lakes and wetland along terraces.
- In large alluvial valleys, there may be a significant down-valley component of flow in the streambed and in the shallow alluvium.
- High streamflows from storms and snowmelt promotes aquifer recharge and causes water to move into bank storage and floodplain storage during periods of flooding. Elevated groundwater levels and soil moisture in the unsaturated zone gradually discharges to the river, which supports baseflow.
- During the growing season, evapotranspiration by riparian vegetation can reduce natural groundwater discharges to the stream.

SW-GW Interactions in Plains Terrains: The plains terrain is applicable to the interior plains of northeastern B.C., including the Alberta plains and Nelson lowlands. Winter (2001) defines the plains terrain as having low relief with flat to gently rolling topography, incised by narrow riverine valleys (Figure 24). Surface drainages may be limited or disconnected from the regional stream network, forming areas of wetlands and muskeg.

Flat lying and gently dipping sedimentary rocks underlie the interior plains region of northeastern B.C. Water supply aquifers include bedrock and unconsolidated aquifers. Bedrock aquifers are predominantly fluvial sandstone and fractured shale, with inter-bedded mudstones and siltstones. Buried and isolated channels of sands and gravels within lower permeability surficial materials provide productive sources of groundwater supply in a few areas. Shallow alluvial aquifers of limited extent occur along major river valley, river terraces, and fans.
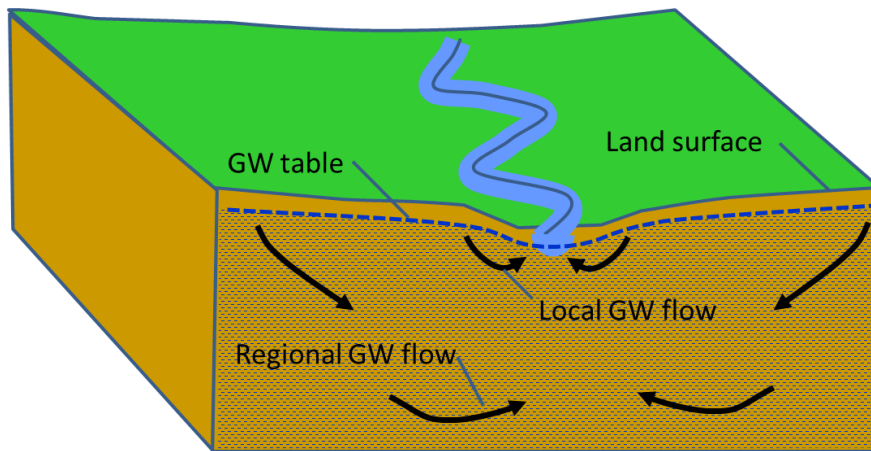
Figure 24   Generalized GW-SW interactions in plains terrains (after Winter 2001).

Water movement and SW-GW interaction in interior plains of northeastern B.C. have the following general characteristics:

- From a broad regional perspective, groundwater flows are generally eastward from highlands in the Rocky Mountains to lowlands in the interior plains. These deeper regional groundwater flows may have restricted connectivity to surface waters from regionally confining aquitards of till, clay, and shale.
- Smaller riverine and mountainous terrains occur throughout portions of the regional interior plains. Where they occur, local shallow groundwater systems can interact strongly with surface waters, typical of riverine terrains. The discharges from local groundwater systems help to sustain baseflow. However, the semi-arid climate and limited and isolated nature of local surficial aquifers can limit the overall baseflow.
- In areas of flat terrain and disconnected drainage networks, groundwater interaction with lakes and wetlands is predominately local-scale in nature (Winter, et al., 1998). Lakes and wetlands can behave as gaining, losing, and flow-through systems. The elevation of the shallow water table relative to the water surface elevation determines the direction of SW-GW exchange. Local geologic conditions and seasonal climatic fluctuations also influence these SW-GW exchanges.

3.2   Relating Surface Water-Groundwater Interactions to Aquifer Type

SW-GW interaction has been studied and characterized in limited areas of the province. Where available, these studies can assist water managers in managing water rights related to groundwater use.

As a first-cut for broadly characterizing SW-GW interactions in the province, the existing aquifer typing system provides a basis for categorizing SW-GW interactions.   B.C. has 12-aquifer types and sub-types, which are illustrated in Figure 25 and Figure 26 for coastal and interior regions of B.C., respectively. The approach used to categorize SW-GW interactions follows the discussion and analysis by (Wei, et al., 2014) and (Allen, et al., 2010). General characteristics of SW-GW interactions in each of the 12-aquifer types are associated with the aquifer properties and the general frameworks for aquifer-stream responses and hydrologic landscapes.   Results are discussed in the following subsections and summarized in Table 5.

Unconfined glaciofluvial aquifer

Confined glaciofluvial aquifer

Unconfined glaciofluvial aquifer

Sedimentary bedrock aquifer

Fractured crystalline bedrock aquifer

Confined glacial/pre-glacial aquifer
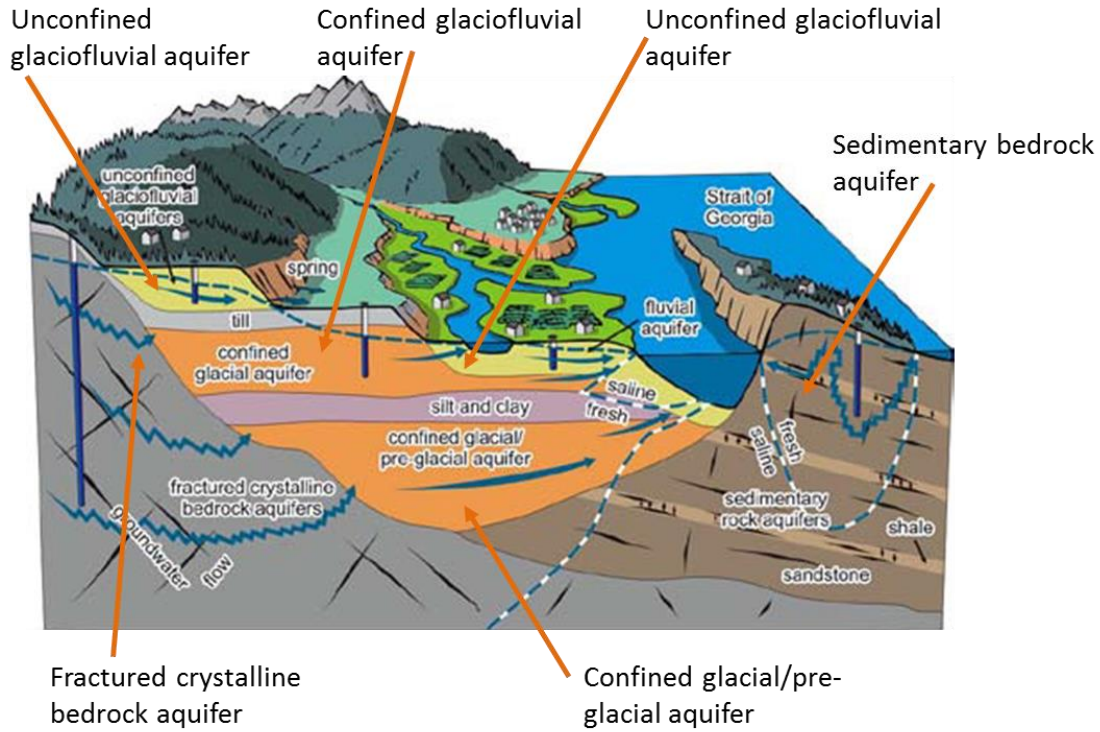
Figure 25   Schematic of aquifer types in coastal regions of B.C. (Source: Wei et al. 2014).

Fractured crystalline bedrock aquifer

Unconfined alluvial fan aquifer

Unconfined alluvial aquifer along low order river

Karst formation

Unconfined alluvial aquifer along high order river

Confined glaciofluvial aquifer

Fractured sedimentary bedrock aquifer
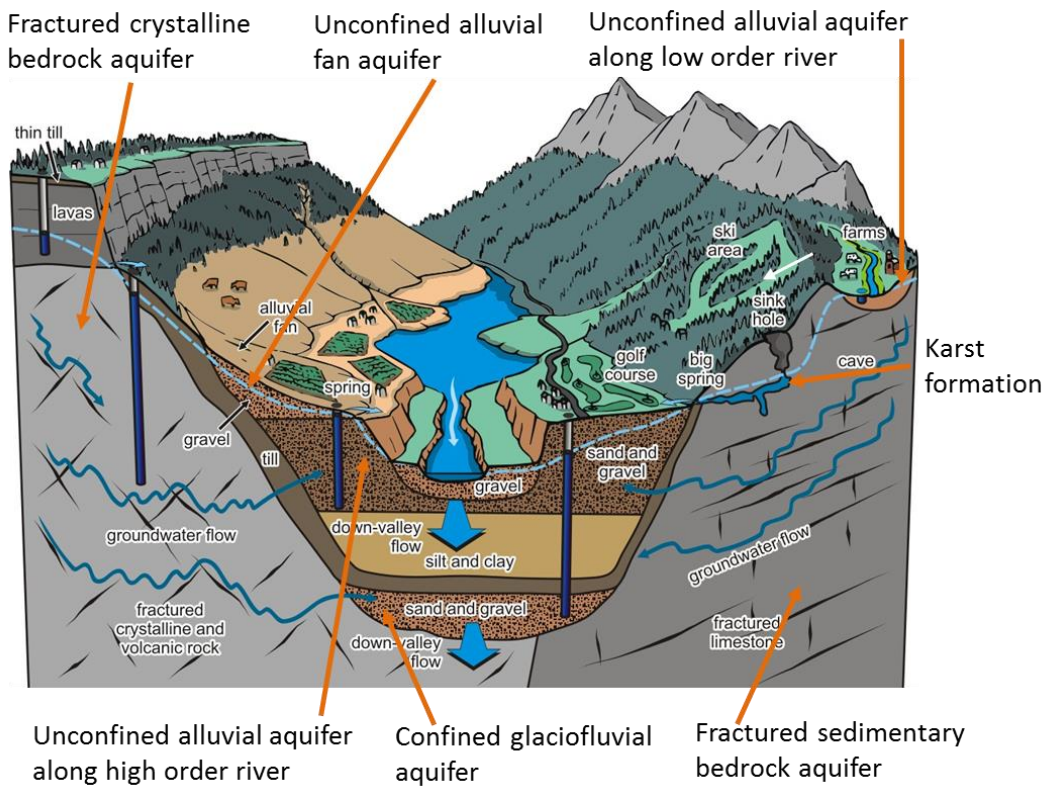
Figure 26   Schematic of aquifer types in interior regions of B.C. (Source: Wei et al. 2014).

Table 5 Aquifer types and associated SW-GW interactions.

Aquifer Type	Description	SW-GW interactions	Examples
1a - Unconfined or partially confined fluvial and glaciofluvial aquifers along high-order rivers	• Rivers have low gradients, low depositional energy • 4% of classified aquifers • Ave. area = 27 km^2 • Ave. well depth = 22 m	• Strong hydraulic communication with river system • Characteristic of large riverine systems • Gaining stream conditions usually dominant • Losing stream conditions may occur in streamflow-driven systems • GW discharges substantially support baseflow • Streamflow depletion from pumping is likely but impacts are likely limited by large river discharge	Aquifers along: • lower reaches of the Fraser River • Columbia River in East Kootenay
1b - Unconfined or partially confined fluvial and glaciofluvial aquifers along moderate-order rivers	• Rivers/streams with moderate and variable gradients • Greater depositional energy than 1a aquifers • 8% of classified aquifers • Ave. area =15 km^2 • Ave. well depth = 22 m	• Similar to 1a aquifers • Strong hydraulic communication with stream system • Gaining stream conditions usually dominant; more variability of gaining and losing reaches than 1a aquifers • GW discharges substantially support baseflow • Streamflow depletion from pumping is likely	Aquifers along: • Cowichan R., Vancouver Island • Kettle River in Grand Forks
1c - Unconfined or partially confined fluvial and glaciofluvial aquifers along low-order rivers	• Streams/creeks with moderate and more variable gradients and greater depositional energy than 1a sub-type aquifers • 2% of classified aquifers • Ave. area = 7 km^2 • Ave. well depth = 19 m	• Variable and dynamic SW-GW interactions, depending on local conditions • Probable hydraulic communication with stream system • SW-GW interactions are characteristic of riverine and/or mountainous regions • Baseflow supported by groundwater discharges from shallow alluvium and possibly underlying bedrock • Probable streamflow depletion from pumping	• Cache Creek aquifer (#135) • Little Fort aquifer (#296)
2 –Unconfined deltaic aquifers formed in river deltas	• Uniform sands and gravels of good hydraulic conductivity • Shallow and small in extent • ~3% of classified aquifers • Ave. area = 5 km^2 • Ave. well depth = 12 m	• Similar to 1a and 1b aquifers • Strong hydraulic communication with river system is likely • Streamflow depletion from pumping is likely	• Scotch Creek aquifer near Chase (#229) • Mesachie Lake aquifer (#189)
3 –Unconfined alluvial fan aquifers	• Coarse grained sands and gravels; at the base of mountain slopes • Shallow and small in extent • ~6% of classified aquifers • Ave. area = 5 km^2 • Ave. well depth = 24 m	• For aquifers located at the base of the mountain or along the valley walls, strong hydraulic communication with stream system and streamflow depletion from pumping is likely • Aquifers elevated above the valley floor may have more variable SW-GW interactions; both losing and gaining conditions may occur	• Vedder River Fan aquifer at Chilliwack (#8)
4a - Unconfined aquifers of glaciofluvial origin	• Shallow alluvial unconfined aquifers of variable extent • ~8% of classified aquifers • Ave. area = 8 km^2 • Ave. well depth = 24 m	• Good hydraulic communication with surface water bodies, where present • SW-GW interactions can be variable depending on water elevations and climatic regime • Aquifers generally support and contribute to baseflow • Streamflow depletion from pumping is likely, where SW-GW connections occur	• Abbotsford-Sumas aquifer (#15) • Hopington aquifer (#35)
4b - Confined aquifers of glaciofluvial origin	• Confined sand and gravel aquifers underneath and in-between till or clay	• Confining aquitards of low permeability reduces and limits SW-GW interactions. • SW interaction with confined aquifers is restricted where confining aquitards are thick, broadly continuous and	• Quadra Sand aquifers in the Georgia Basin • Aldergrove

Aquifer Type	Description	SW-GW interactions	Examples

	layers.
	• ~38% of classified aquifers
	• Ave. area = 13 km^2
	• Ave. well depth = 39 m
		have very low permeability.
		• SW interactions with confined aquifers potentially occur where:
		  - The overlying confining aquitard is somewhat permeable (e.g., silt or a sandy till that can transmit significant quantities of water).
		  - The aquitards are not continuous creating windows or preferential flow paths between the confined aquifer and overlying water table aquifers
		  - The surface waters are in direct contact with confined aquifers such as where streams have incised confining layers, or where confined aquifers intercept lakebeds.
		Pumping from these areas can potentially cause streamflow depletion.
			aquifer (#27)

4c - Confined glaciomarine aquifers	• Located in marine settings near the coast • 1% of classified aquifers	• Not generally significant to EFN assessment due to location in marine settings	• Nicomekl-Serpentine aquifer in Langley (#58).
5a - Fractured sedimentary rock aquifers	• ~11% of classified aquifers • Ave. area = 24 km^2 Ave. well depth = 39 m	• Flow is primarily through fractures and faults of shale, sandstone, siltstone, and mudstones. SW-GW interaction can occur where fracture zones and faults intercept surface waters. • As a rule-of-thumb, bedrock wells have limited influence on streamflow depletion and EFN assessments due to their generally greater depth, lower transmissivity, lower yield, and higher streamflow depletion factors (see Table 2-2) than aquifers comprised of unconsolidated materials. • Strong hydraulic connectivity between bedrock wells and surfaces water is possible and should not be ruled out. Factors indicating potential connectivity are: an overburden thickness that is thin or absent, comparatively high well yield indicating large fracture density or apertures, comparatively shallow wells near surface water features, and shallow water tables in bedrock terrains that sustain baseflow.	• Yellow Point Aquifer (#162) near Ladysmith • Cranbrook bedrock aquifer (#523)
5b - Karstic limestone aquifers	• <1% of classified aquifers • Ave. area = 8 km^2 • Ave. well depth = 75 m	• Karstic aquifers occur in few areas of B.C. and there is little information available. Flow is likely through joints and fissures, and potentially through dissolution channels that may be large and extensive. • There is a potential for strong hydraulic connectivity to surface waters. However, there are few identified aquifers, and they are sparsely developed for groundwater.	• Limestone aquifers in the Canadian Rockies, Sorrento, and Fort St. James
6a - flat-lying or gently-dipping volcanic flow rock aquifers	• 2% of classified aquifers • Ave. area = 484 km^2 • Ave. well depth = 62 m	• Flow is predominantly through joints, fissures and faults, but may also occur through zones of broken and weathered rock. • SW-GW connectivity is likely limited for most cases • Wells in type 6a aquifers should not substantially cause streamflow depletion due to their generally large depth, low transmissivity, low yield.	• Fraser Plateau Lava Aquifer (#124)
6b - Crystalline granitic, metamorphic, metasedimentary, metavolcanic and volcanic rock	• ~17% of classified aquifers • Ave. area = 31 km^2 • Ave. well depth = 71 m	• Flow is predominantly through joints, fissures and faults. • SW-GW connectivity is generally expected to be limited • Wells in type 6b aquifers should not significantly influence streamflow depletion and EFN assessments due to their large depth, low transmissivity, low yield, and the because streamflow depletion factors of type 6b bedrock	• 108 Mile bedrock aquifer (#126) • Lantzville bedrock aquifer (#213)

Aquifer Type	Description	SW-GW interactions	Examples
aquifers		aquifers is comparatively large. • For bedrock regions of higher relief, unstratified fractured crystalline bedrock aquifers can be considered hydraulically connected to headwater or tributary streams within their catchment.	

3.2.1   Type 1 Aquifers: Alluvial Aquifers along Valley Bottoms

Type 1 aquifers are fluvial or glaciofluvial aquifers along river valley bottoms. This group of aquifers is primarily comprised of sands and gravels deposited by rivers or streams in recent times (fluvial origin) or at the end of the last period of glaciation (glaciofluvial origin). Often fluvial and glaciofluvial deposits are mixed due to re-working of the sediments by fluvial processes. Type 1 aquifers tend to be associated with riverine landscapes and typically have strong hydraulic connections with the adjacent river system. Many type 1 aquifers are highly productive and heavily exploited for water and irrigation supply. For these reasons, type 1 aquifers are a primary focus of hydraulic connection to streams and EFNs. There are three subclasses of type 1 aquifers.

Type 1a aquifers are unconfined or partially confined aquifers found along major rivers with high stream order, or in bottoms of major river valleys. The rivers typically have low gradient resulting in deposition of mostly sand and silt. The valley bottoms may include broad floodplains and terraces. Type 1a aquifers are predominantly fluvial in origin, and have comparatively large area and storage capacity, with shallow water tables. They are among the most productive and most developed aquifers in B.C.

Characteristics of SW-GW interactions expected in type 1a aquifers include the following:

- SW-GW interactions in type 1a aquifers are characteristic of riverine landscapes (Figure 23). They usually have strong hydraulic communication with the adjacent river.
- Regional and local GW systems discharge to adjacent streams at various locations. There may be a strong down river or down valley direction of groundwater flow.
- In rainfall dominated coastal regions, groundwater levels generally reflect direct recharge from rain. The regional water table is typically above the river system, supporting gaining stream conditions throughout the year.
- In snowmelt dominated interior regions, groundwater levels may reflect a combination of direct recharge from rain and snowmelt, and recharge from the river during freshet. Gaining stream conditions occur most of the year. Losing stream conditions may occur during and immediately following freshet in response to elevated stream stage. Fine-grained streambed sediments deposited in the low-energy depositional environments, may impede stream driven recharge.
- Groundwater discharges from adjacent aquifer as well as upstream watersheds substantially support baseflow during dry periods.
- Groundwater diversions will reduce groundwater discharges to the stream and potentially induce recharge when wells are in close proximity to streams. Individual wells may have limited effects on streamflow depletion due to comparatively large discharges expected in the high-order streams.

Type 1b aquifers are unconfined alluvial aquifers along moderate-sized river systems and in river valleys. These rivers generally have higher gradients than rivers adjacent to type 1a aquifers. Because the depositional energy is generally higher, aquifer compositions are more likely to have greater proportions of coarse-grained sands and gravels. Aquifers can be fluvial or glaciofluvial in origin, or a mixture of both. They have intermediate area and storage capacity among type 1 aquifers, and shallow

water tables with high productivity. A number of type 1b aquifers substantially support groundwater use for domestic, municipal, irrigation, and fish hatchery water supply.

SW-GW interactions in type 1b aquifers include the following general characteristics:

- SW-GW interactions should be similar to type 1a aquifers; descriptions above generally apply.
- General differences between 1b and 1a aquifers may broadly influence SW-GW interactions in the following ways.
  - There is greater likelihood of both gaining and losing reaches due to, for example, more variable river gradients and discontinuous floodplains in 1b systems.
  - Reduced streambed impedance may occur in 1b aquifers due to scouring of finer-grained sediments in higher energy environments.
  - Where aquifer storage is comparatively small in 1b aquifers, the effects of streamflow-driven recharge in snowmelt-dominated climates may be more pronounced and significant.
  - Streamflow depletion from groundwater pumping is potentially faster and larger in 1b aquifers due to smaller aquifer storage and streamflow, less streambed impedance, and greater transmissivity of coarser-grained aquifer materials.

Type 1c aquifers are unconfined or partially confined aquifers found along lower order (< 3-4) streams in narrow valleys with relatively undeveloped floodplains. The streams can have variable and steep gradients characteristic of mountain systems (Figure 22). The aquifer materials may be fluvial or glaciofluvial in origin, but aquifer thickness and extent are likely limited. The aquifers can have narrow elongated dimensions conforming to narrow river valleys. 1c aquifers are not usually heavily developed, but groundwater can be locally important sources of water supply. Due to their limited size and groundwater development, there has been little characterization and study of type 1c aquifers.

SW-GW interactions in type 1c aquifers include the following general characteristics:

- Greater variability in SW-GW interaction results from smaller and more dynamic aquifer-stream systems. Local conditions, including topography, climate, and hydrogeology are more likely to dictate the nature of SW-GW interactions. SW-GW interactions may have characteristics of both mountainous and riverine landscapes.
- Seasonal recharge and bi-directional (i.e., gaining and losing) SW-GW interactions are common. Losing stream conditions are likely during periods of high runoff from storms and snowmelt. Both losing and gaining stream conditions may occur during low flow periods.
- Groundwater discharges from shallow alluvium and shallow bedrock likely sustain baseflow during dry periods.
- Where groundwater discharges sustain baseflow, streamflow depletion from groundwater withdrawal is likely, particularly given the smaller and narrower extent of these aquifers. The significance of streamflow depletion on EFNs may be limited due to the generally low-levels of groundwater development associated with this sub-type of aquifer.

3.2.2 Type 2 Aquifers: Deltaic Aquifers

Type 2 aquifers are unconfined sand and gravel deltaic aquifers. This group of aquifers is comprised of unconsolidated alluvium deposited in river deltas of oceans and lakes. Type 2 deltaic aquifers are predominantly shallow and unconfined, comprised of sand and gravel, and generally local in extent. The aquifer materials tend to be well sorted by weight and volume, and may display stratification in definite graded layers. Type 2 aquifers have good productivity and are locally important sources of water supply.

SW-GW interactions in type 2 aquifers include the following general characteristics:

- Type 2 aquifers have strong hydraulic connections to streams, and have SW-GW interactions characteristic of riverine landscapes (Figure 23). Type 2 aquifers are also located adjacent to lakes, where strong hydraulic connections may occur with both the lake and stream systems.
- SW-GW interactions in type 2 aquifers should be similar to type 1a and 1b aquifers; descriptions above generally apply.
- Groundwater withdrawal from type 2 aquifers is likely to cause streamflow depletion due to: 1) the strong hydraulic connections with streams; 2) the generally shallow and small size of the aquifers; and 3) the generally high conductivity of the aquifer materials.

3.2.3   Type 3 Aquifers: Alluvial Fan Aquifers

Type 3 aquifers are unconfined alluvial aquifers that occur at the base of mountain slopes, along the side of valley bottoms, and in raised deposits above the valley bottoms. Alluvial fan aquifers form by deposition of sediments from tributary streams as they enter into the main valley. Thus, the streams can have variable gradients and variable interaction with aquifers. Type 3 aquifers are generally shallow and of limited area, and typically comprised of coarse and moderately sorted sands and gravels. Coarser and more permeable sediments tend to occur at the head of the fan, and finer and less permeable sediments are at the distal end of the fan.

Characteristics of water movement in riverine and mountainous landscapes suggest the following general SW-GW interactions in type 3 aquifers:

- Where aquifers are located at the base of mountain slopes or the side of valley bottoms, there likely is a grade-change in the water table, coinciding with surface topography. Where streams traverse these aquifers, strong hydraulic communication with streams and gaining stream conditions are likely. Here SW-GW interactions should be similar to type 1a and 1b aquifers. The extent and duration of groundwater-supported baseflow depend on the aquifer storage and hydroclimatic regime. Because of the generally shallow and local extent of these aquifers, streamflow depletion from groundwater withdrawals is likely in these settings.
- Where aquifers occur above the valley floor, SW-GW interactions may be more variable. Both gaining and losing conditions could occur depending on the relative stream and groundwater elevations and topography. Disconnected losing stream conditions are likely where the stream traverses high permeable sediments near the apex of the fan, and gaining conditions occur along finer grained sediments at the distal end of the fan near the base of the mountain. Consequently, groundwater withdrawals do not necessarily result in streamflow depletion, particularly if there are reaches with disconnected losing stream conditions.

3.2.4   Type 4 Aquifers: Glaciofluvial Sand and Gravel Aquifers

Type 4 aquifers are glaciofluvial sand and gravel aquifers deposited by glacial melt water streams, either directly in front of, or in contact with glacier ice. They include aquifers found near the surface or underneath till or glaciolacustrine deposits. There are three subclasses of type 4 aquifers.

Type 4a aquifers are unconfined and sometimes partially confined sand and gravel aquifers formed by glaciofluvial outwash or ice contact. They are generally shallow and have variable size. Alluvial materials may also have variable composition and conductivity. Type 4a aquifers occur widely throughout B.C. and include some of the most economically important and well-known aquifers in the province (e.g., Abbotsford-Sumas aquifer). Unfortunately, they are also vulnerable to contamination.

SW-GW interactions in type 4a aquifers may be variable and controlled by regional and/or local-scale flow systems:

- Because of their shallow and permeable characteristics, type 4a aquifers will tend to have strong hydraulic connections to surface water bodies, when they are present.
- Low-order streams and small lakes will tend to interact with local groundwater flow systems. These interactions can be variable and may include gaining, losing, and flow through systems. The direction of SW-GW exchanges depends on the surface water and groundwater elevations, and the climatic regime. For larger and higher order streams, both regional and local groundwater flow systems may interact with the surface waters.
- Gaining systems are likely more predominant, similar to interactions in type 1a and 1b aquifers.
- Where SW-GW interactions occur, groundwater discharges will tend support or contribute to baseflow. In this case, pumping from type 4a aquifers would likely contribute to streamflow depletion.

Type 4b aquifers are confined sand and gravel aquifers occurring underneath and in between layers of till, or underlying glaciolacustrine deposits. Because it can be difficult to differentiate materials in confined aquifers, type 4b aquifers include fluvial, alluvial, colluvial, and glaciolacustrine deposits. Consequently, type 4b aquifers exhibit large variability in composition, conductivity, size, and depth. Type 4b aquifers are widely distributed throughout aquifers and the most common type aquifer. Due to the presence of confining and lower permeability strata, they are typically deeper and less vulnerable to contamination than unconfined type 4a aquifers.

SW-GW interactions in type 4b are variable, and include the following:

- A spectrum of connectivity and impacts are possible depending on the continuity, thickness, and hydraulic conductivity of the confining units.
- The hydraulic connectivity between surface waters and confined aquifers is most restricted when the aquifers are deep, the confining aquitards are thick, broadly continuous and have low permeability such as dense clays and tills, and the wells are distant from aquifer boundaries. Under these conditions, it is likely that confined aquifers are effectively isolated from surface waters and pumping is unlikely to cause streamflow depletion.
- As discussed in Section 2.2.2 the presence of confining aquitards generally impedes SW-GW connectivity, but not does necessarily exclude connectivity. Connectivity between water wells in type 4b aquifers and surface waters may occur in several ways.
  - When the overlying confining aquitard are thin and somewhat permeable (e.g., silt or a sandy till) they can transmit significant quantities of water from overlying unconfined aquifers.
  - When the aquitards are not continuous, bridge areas or preferential flow paths occur between the confined aquifer and the overlying water table aquifers. Barlow and Leake (2012) show that pumping from confined aquifers with discontinuous confining layers can both decrease and increase the rate of streamflow depletion depending on the relative locations of the wells, aquitards, and surface waters.
  - When surface waters are in direct contact with confined aquifers such as where streams have incised confining layers, or where confined aquifers intercept lakebeds.

  In these cases, pumping from type 4b aquifers can potentially contribute to streamflow depletion

Type 4c aquifers are confined sand and gravel aquifers that occur within sand, silt and clay deposited under a marine environment near the coast. Because of their location in marine settings, they are not generally thought to be relevant to EFN assessments.

3.2.5   Type 5 and 6 Aquifers: Aquifers in Consolidated Formations

For purposes of categorizing SW-GW interactions, the following four sub-classes of bedrock aquifer have been grouped into a single category for discussion.

Sedimentary rock aquifers:

Type 5a - fractured sedimentary bedrock aquifers
Type 5b - karstic limestone aquifers

Crystalline bedrock aquifers:

Type 6a - flat-lying or gently-dipping volcanic flow rock aquifers
Type 6b - granitic, metamorphic, meta-sedimentary, meta-volcanic, and volcanic rock aquifers

As a rule-of-thumb, bedrock aquifers(except karstic limestone aquifers) are likely to have limited connectivity to surface water and the influence of bedrock wells on streamflow depletion is minor in comparison to wells in unconsolidated aquifers. This assumption is appropriate for bedrock aquifers with the following general characteristics.

- *Deeper aquifers and low permeability overburden properties*: Bedrock aquifers are typically deeper than unconfined aquifers, with average depths of bedrock wells about 50-70 m, compared with average well depths of about 10-25 m in unconsolidated aquifers (Wei, et al., 2014). Overburden of varying thickness and conductivity typically overlie bedrock aquifers. In some areas, the bedrock overburden is comprised of thick layers of low permeability clays and silts that substantially impede flow. Connectivity to surface water is restricted when bedrock aquifers are deep or blanked by low permeability overburden.
- *Discontinuous and heterogeneous fracture zones:* Fracture zones that are the major pathway for groundwater flow are heterogeneous and discontinuous. Bedrock wells immediately next to each other can have vastly different depths and water levels reflecting different fracture zones encountered during drilling (Wei, et al., 2014). The presence of variable well depths and water levels indicates the fracture zones are interrupted and isolated to some degree, suggesting the connectivity to surface water is also likely to be impeded or restricted.
- *Lower well yields and higher streamflow depletion factors:* Bedrock aquifers typically have smaller transmissivity and storativity than aquifers of unconsolidated materials. As a result, median well yields in bedrock aquifers are 0.3 gpm compared with 3-5 gpm for unconsolidated aquifers. In addition, typical stream depletion factors of bedrock aquifers are two- to three orders of magnitude greater than for unconsolidated aquifers (Table 1). This indicates the response time for streamflow depletion caused by pumping from bedrock wells is comparatively long, and the volumetric losses from low yielding wells is be comparatively small.

Although many bedrock wells likely have limited connectivity to surface water, this assumption is not always applicable. Bedrock wells sometimes exhibit strong hydraulic communication with surface waters and pumping from such wells can potentially cause streamflow depletion. Studies by Welch and Allen (2012) and Welch et al. (2012) suggest that unstratified fractured crystalline bedrock aquifers in high relief areas can be considered hydraulically connected to headwater or tributary streams within their catchment. In general, factors that indicate connectivity to surface waters include:

- Bedrock systems that outcrop directly to the land surface and surface waters.
- Shallow bedrock aquifers with thin and absent overburden.
- Shallow bedrock wells or bedrock wells with high yields and large transmissivity.

- Bedrock wells that display strong seasonal water level fluctuations coinciding to stream driven recharge processes.
- Pumping tests that display rapid equilibrium and recovery.
- Pumping schedule corresponding to decrease in stream flow.

Where bedrock wells and aquifers exhibit these characteristics, the hydraulic connectivity should be determined through assessment of site-specific information. Allocation staff should seek assistance from regional hydrogeologists as needed, and where data are limited or there is large uncertainty, it is prudent to assume connectivity.

3.3   Studies of Surface Water-Groundwater Interactions in B.C.

This section describes four site-specific studies of SW-GW interactions in B.C., which illustrate attributes and complexities of SW-GW interactions found in the province.

3.3.1   Coldwater River Study

The Ministry of Environment (ENV) investigated SW-GW interactions within the City of Merritt in response to observations of critically low summer baseflow, elevated water temperatures, and impaired fisheries habitat (Bennett & Caverly, 2009). This study highlights potential habitat impacts from unregulated groundwater withdrawals.

The City of Merritt is located at the confluence of the Coldwater and Nicola Rivers, in south central B.C. (Figure 27). Prior to the study, observed baseflow in the Coldwater River was frequently less than 5% of the mean annual flow (MAF). This is well below the 15% MAF threshold considered adequate for rearing habitat of juvenile salmon and trout. It is also below the 10% MAF threshold considered as short-term survival flows. Measured surface water temperatures were also well above optimum levels for rearing juvenile fish, occasionally exceeding the 25 °C threshold considered lethal for salmon and trout.
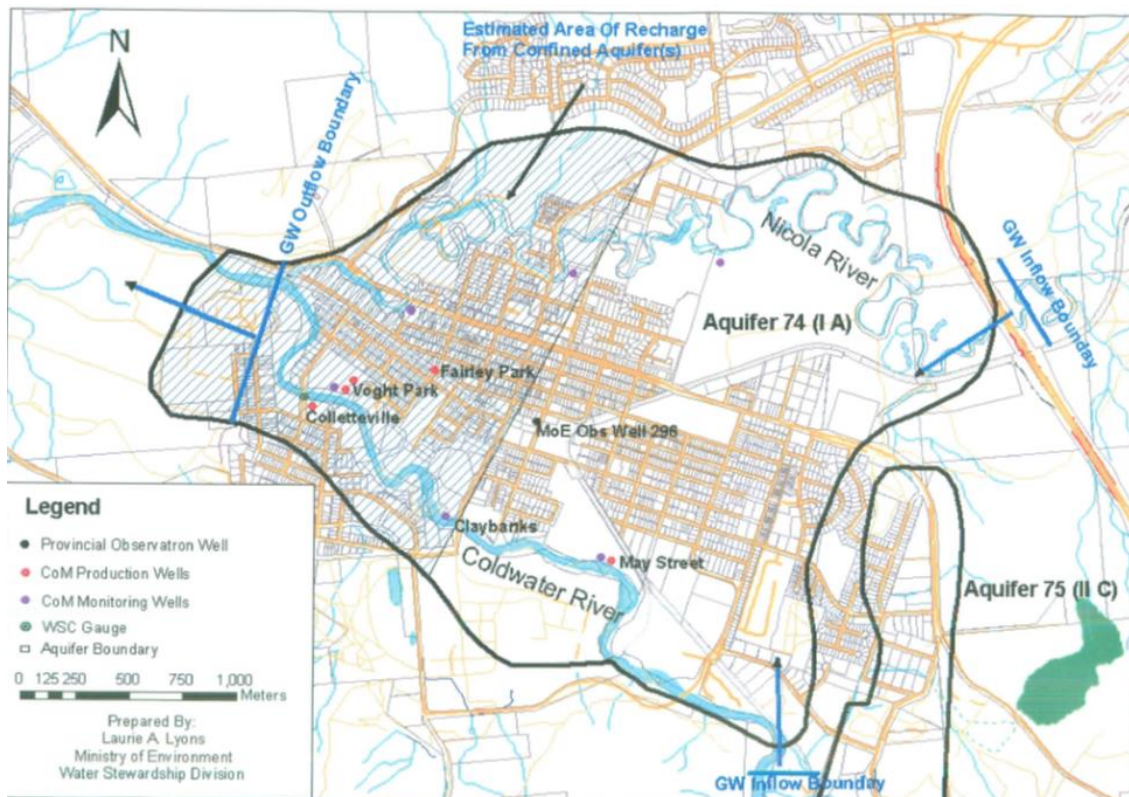
Figure 27   Coldwater River and Merritt aquifer study location (Source: Bennett and Caverly. 2009).

Groundwater withdrawals from the Merritt aquifer appeared to be contributing to diminishing baseflow. The Merritt aquifer is a shallow type 1b unconfined alluvial aquifer located upstream of the confluence of the Coldwater and Nicola Rivers. Climate is characteristic of a snowmelt dominated climatic region, and stream-aquifer interactions are typical of a streamflow driven systems. Figure 28 illustrates the streamflow driven system, showing the response of groundwater elevation in the provincial observation well to increased river flows following freshet.
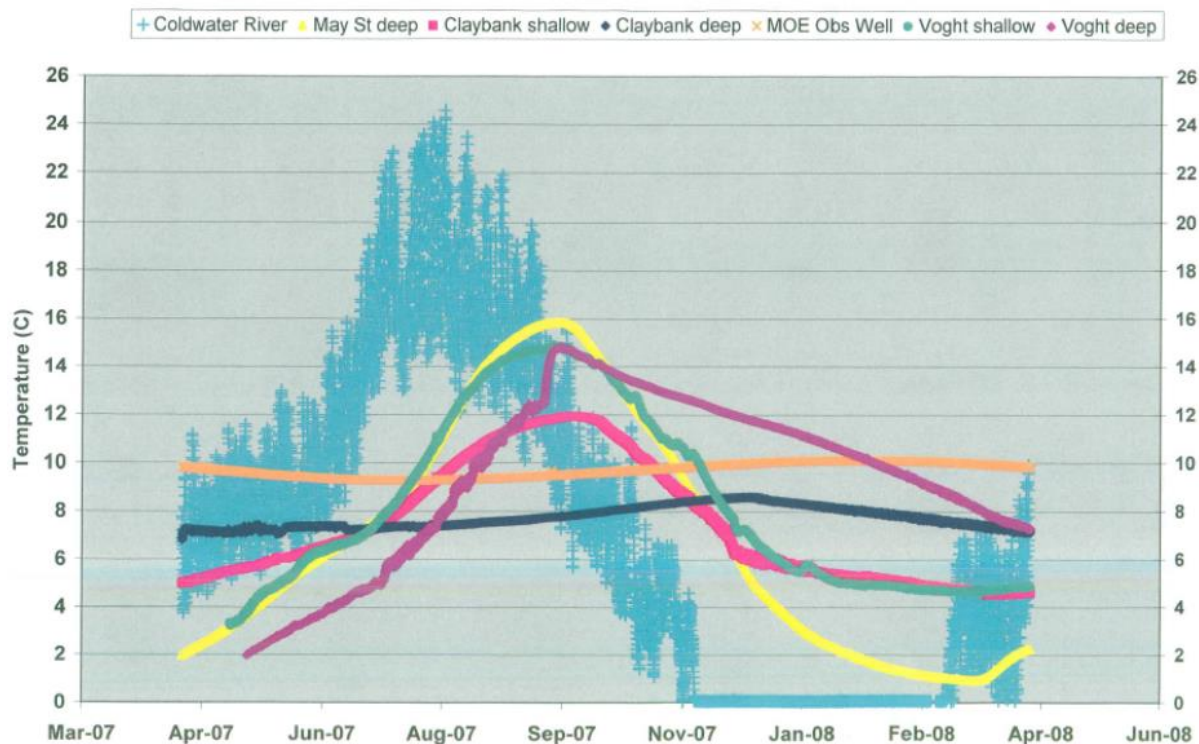
Figure 28   Groundwater levels and river flow versus time near City of Merritt (Source: Bennett and Caverly. 2009).

At the time of the study, the City of Merritt operated four municipal supply wells (Figure 27). These production wells were located in close proximity to the Coldwater River, within 20 to 60 m, with depths between 11 and 45 m. The reported average annual production was 0.1 m^3/sec (8600 m^3/day).

To investigate SW-GW interactions, ENV monitored water levels and temperature at selected observation wells, production wells, and river monitoring locations. ENV also developed a simplified water budget of the Merritt aquifer. The monitoring studies and analyses supported the following findings:

- Losing stream conditions are typical for the Coldwater River reach within the study area for both pre-development and post-development pumping conditions. River losses are the major source of recharge to the Merritt aquifer under both conditions.
- River levels are consistently higher than groundwater levels indicating downward gradients and recharge from the river to the aquifer. Drawdown from the production wells increases the downward gradient, enhancing infiltration from the river and decreasing baseflow. Streamflow is known to be impacted by pumping, indicating a 'connected losing reach' (Figure 3).
- ENV estimated average annual streamflow depletion of 0.07 m^3/sec from an average annual pumping of 0.1 m^3/sec. Pumping from the aquifer almost doubles the amount of infiltration from the river to the aquifer in comparison to pre-development conditions.

- Diminished baseflow has degraded habitat quality and quantity of salmon, trout, and aquatic insects that make up their food supply. Summer low flow was well below short-term survival levels (10% MAF). Water temperature in the Coldwater River low flow exceeded lethal limits for salmon and trout, contributing to degraded habitat quality for these species.

3.3.2   Kettle River and Grand Forks Aquifer Study

The Grand Forks aquifer is among the most economically important and heavily developed aquifers in the province. This study illustrates the application of numerical models to improve understanding of SW-GW interactions, and to quantify effects of groundwater diversions on streamflow depletion.

The Grand Forks aquifer is located at the confluence of the Kettle River and Granby River valleys in south-central B.C. (Figure 29). It straddles the international border, but the vast majority (95%) is in Canada. The aquifer is a type 1b shallow unconfined sand and gravel aquifer, and is a primary source of municipal, domestic, and irrigation supply. Due to its shallow and permeable properties, the aquifer is vulnerable to contamination, particularly nitrates from agricultural activities and domestic septic systems. Climate is primarily a snowmelt dominated, and stream-aquifer interactions are characteristic of a streamflow driven systems as indicated in Figure 30 showing GW level response to increased river stage following freshet.
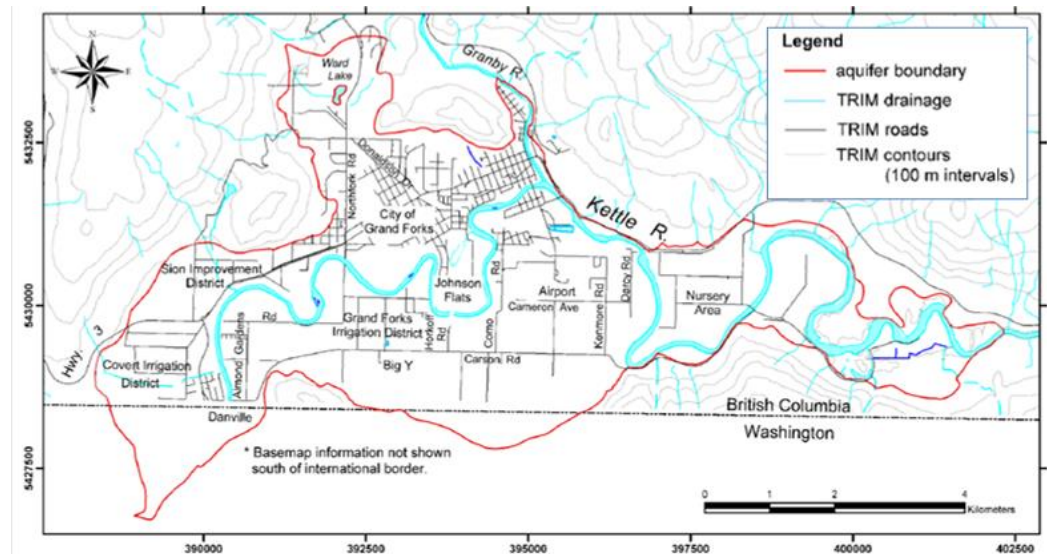
Figure 29   Grand Forks aquifer boundary (Source: Wei et al. 2010).

There are multiple lines of evidence of strong interactions between the river and the aquifer, typical of type 1b aquifers (Wei, et al., 2010):

- Static water levels in wells near the river are similar to the river stage.
- Fluctuations in groundwater levels correspond closely to seasonal fluctuations in river stage.
- Pumping tests in wells close to the river exhibit stabilized water levels in a matter of hours. This suggests the cone of depression had reached the river and the river provides a source of constant recharge to the well.

The magnitude and nature of GW-SW interactions in the Grand Forks aquifer has been studied with numerical groundwater models. The original groundwater model is a three-dimensional steady-state regional flow model with four aquifer units (Allen, 2001). In this model, the Granby and Kettle Rivers are modelled by constant head conditions representative of late summer river stages. This assumption was based on the observation that riverbed sediments are largely comprised of permeable sands and

gravels and do not have extensive fine-grained silts and clays. Model calibration to observed static water levels achieved good results.   Subsequently, the model was updated to refine the hydrostratigraphic representation (Scibek & Allen, 2004b), to incorporate a novel approach for spatial recharge to the aquifer (Scibek & Allen, 2004a), and to include time varying specified head boundary conditions along the rivers (Scibek & Allen, 2003).
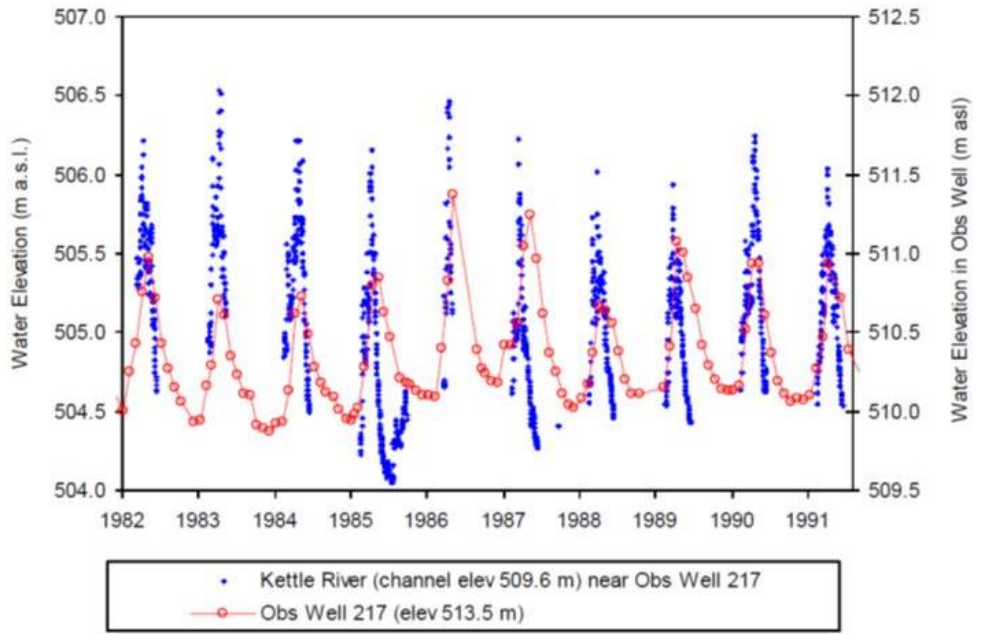
Figure 30   Groundwater levels and river stage versus time near Grand Forks (Source: Scibek and Allen. 2003).

The updated numerical groundwater model provided a means to quantify the SW-GW exchange under both static and pumped conditions (Wei, et al., 2010). In this analysis, the model was used to quantify annual water budgets within each of four distinct aquifer zones (Figure 31). The water budget zones represent stream reaches where either gaining or losing conditions are dominant.
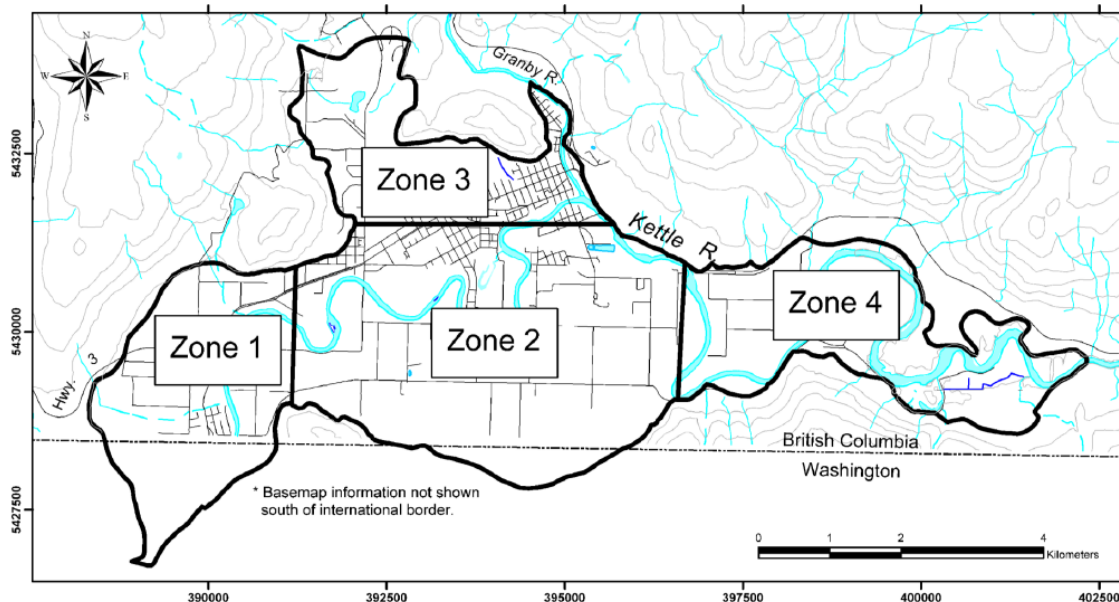
Figure 31   Groundwater model water budget zones for the Grand Forks aquifer (Source: Wei et al. 2010).

The average water budget results for each zone are shown in Figure 32. In these figures, a positive discharge indicates inflow to the aquifer, and a negative discharge indicates outflow from the aquifer. Under static conditions (no pumping) the aquifer gains water from the river in zone 1 (i.e., losing stream conditions). The reverse occurs in the zones 2 and 4 where the aquifer discharges to the river. The gaining-stream conditions are highest in zone 2 due to thinning of the aquifer. There is little net aquifer-river exchange in zone 3.
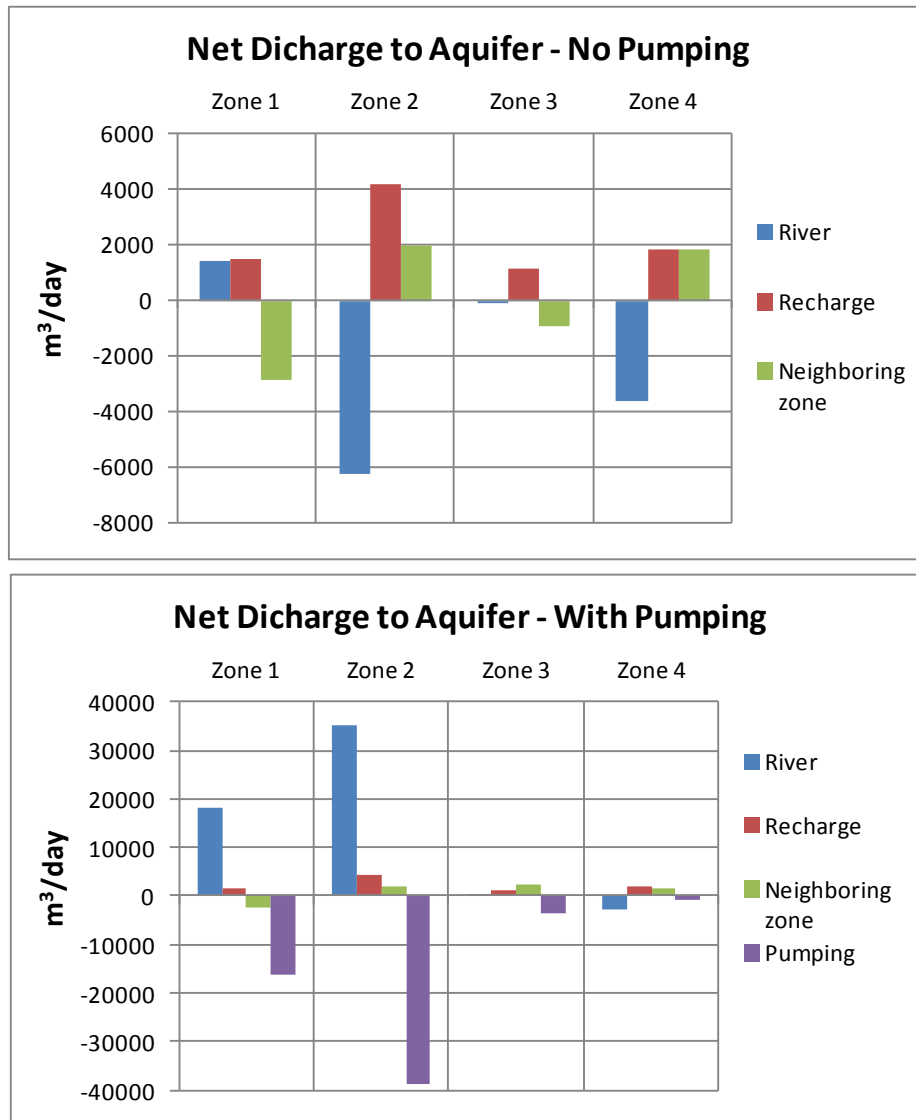
Figure 32   Groundwater model water budget results for the Grand Forks aquifer.

Water budget results for pumping conditions show substantial levels of pumping occur in zones 1 and 2. The effect of this pumping is to substantially increase recharge from the river. In zone 1, the total net discharge from the river to the aquifer increases by more than an order of magnitude due to pumping. In zone 2, pumping causes a net change from gaining-stream conditions to losing-stream conditions, and streamflow depletion accounts for 90 percent of the pumped withdrawals. This illustrates the considerable effect on groundwater withdrawals on SW-GW exchange, and the need to consider both surface and groundwater in water licensing.

3.3.3 Westwold Valley SW-GW Study

The Westwold Valley study was undertaken by the Ministry of Forest, Lands, and Natural Resource Operations (FLNR) as a regional water balance investigation to support water management and water licensing. The results of this study illustrate the dynamic nature of SW-GW interactions.

The Westwold Valley is a riverine valley located midway between Kamloops and Vernon in south-central B.C. The valley bottom encompasses 2,500 hectares, most of which is developed for agricultural use. Steep mountains border the valley to the north, south, and west (Figure 33). The area is characteristic of a snowmelt dominated climatic region.
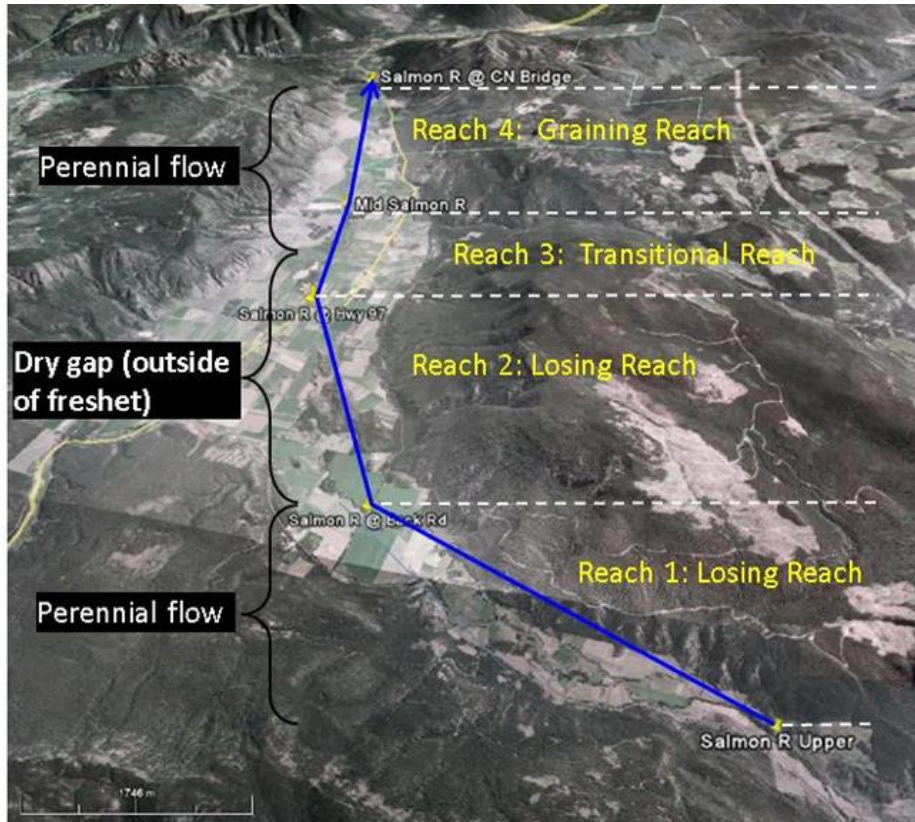
Figure 33 Westwold Valley, view from west to east (modified from Bennett. 2012)

There are two mapped and classified aquifers in the valley (Figure 34). A shallow, unconfined sand and gravel aquifer ranges across the valley floor. The aquifer extends to the surface in the western end of the valley, and is partially confined by surficial silt and clays in the central and eastern portions of the valley. The unconfined aquifer is classified as a type 1b alluvial aquifer, and is typical of a streamflow driven system. ENV has also mapped a deeper, confined aquifer below the shallow aquifer. However, well logs show the confining clay aquitard is not continuous, and the shallow and deep aquifers are likely connected in portions of the valley.

The Salmon River flows through the Westwold Valley from west to east (Figure 33). Flows in the river vary seasonally. Peak flows occur during freshet, usually between April 15 and July 15. During freshet, the Salmon River flows continuously through the four valley reaches shown in Figure 33. Outside of freshet, the river is dry in reach 2 and a portion of reach 3. The river flows year round in reaches 1 and 4. Anecdotal evidence from local residents indicates the dry gap in the middle of the valley (outside of freshet) is characteristic of the river.
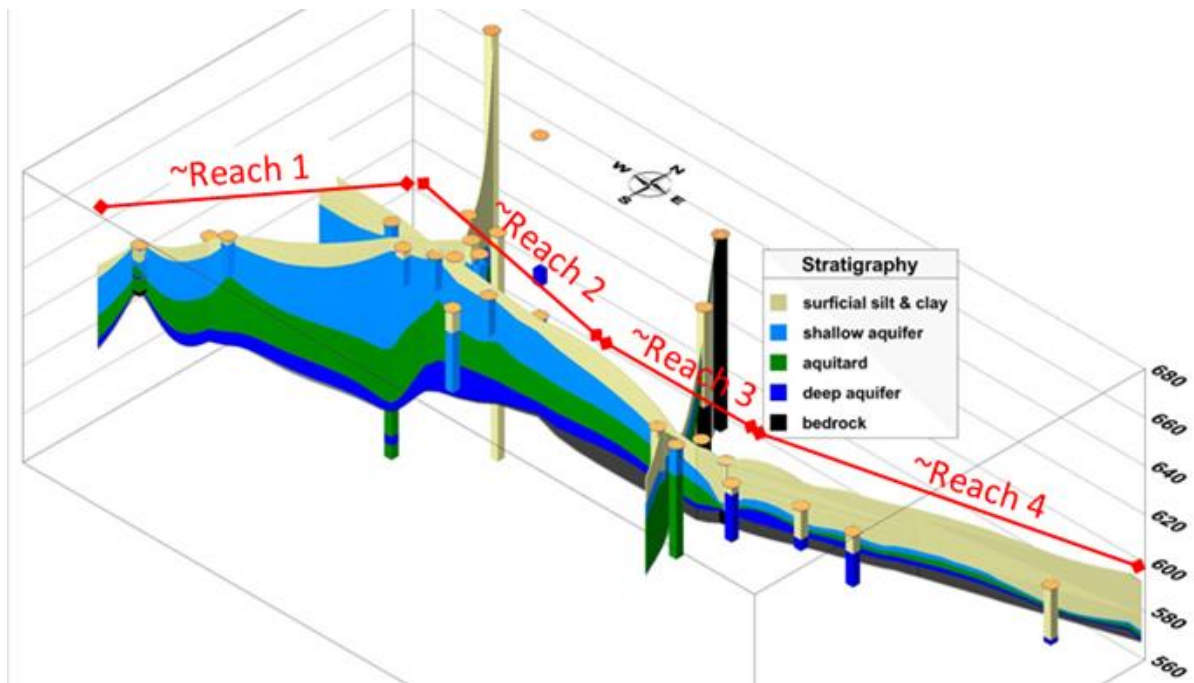
Figure 34 Westwold Valley, hydrogeological cross-section looking from southeast (modified from Bennett, 2012).

The nature of SW-GW interactions in the Westwold Valley has been studied through the collection and analysis of hydrologic and hydrometric data, installation of monitoring wells and collection of groundwater level data, and review of available lithology information (Bennett, 2012). The review and interpretation of these data sources has led to the following findings of SW-GW interaction along the four river reaches:

- **Reach 1 -** Upper Salmon River to Back Road (6.0 km long losing reach). Perennial flows occur along this reach. Hydrometric station data indicate losing stream conditions along this reach during freshet. Outside of freshet, all flows are lost to the aquifer or diverted for irrigation before reaching the downstream boundary at Back Road. Losing stream conditions are thought to occur from a combination of highly permeable streambed sediments, high permeability aquifer materials and increasing aquifer thickness (Figure 34), and reduced streamflow after freshet. A monitoring well adjacent to the river at Back Road showed the presence of an unsaturated zone beneath the streambed. The thickness of the unsaturated zone ranged from 3 m during freshet to 6 m outside of freshet. This suggests disconnected losing stream conditions occur in this reach (Figure 3).
- **Reach 2 -** Back Road to Highway 97 Bridge Crossing (5.1 km long losing reach). The Salmon River flows in this reach during freshet. The river reach is typically dry outside of freshet. Hydrometric data indicate losing stream conditions during freshet for reasons described in reach 1. A monitoring well adjacent to the river at the Highway 97 Bridge Crossing showed the presence of an unsaturated zone beneath the streambed. The thickness of the unsaturated zone ranged from 4 m during freshet to 6 m outside of freshet.
- **Reach 3 -** Highway 97 Bridge Crossing to Salmon River Mid (3.8 km long transitional reach). Hydrometric station data indicate both losing and gaining stream conditions occur along this reach at different times of year. During freshet, the river flows along the entire reach and hydrometric data indicate losing stream conditions during the onset and early portions of

freshet. Outside of freshet, the river is dry in the upper half of the reach, and begins to flow about midway along the reach. At the lower end of this reach, the river flows perennially with all flows derived from groundwater discharge. These gaining stream conditions are thought to arise in part from the gradual thinning of the shallow and confined aquifers from west to east (Figure 34), and the lateral constriction at the downstream end of the valley (Figure 33). The result is a decrease in aquifer storage capacity causing an upward movement of groundwater.

- **Reach 4 -** Salmon River Mid to CN Bridge Crossing (8.1 km long gaining reach). The Salmon River flows year round in Reach 4 with all flow (except during freshet) derived from groundwater. Surface ponding occurs seasonally in the downstream end of the valley following freshet.

This study highlights the need to understand SW-GW interactions when critically assessing water rights. Pumping adjacent to disconnected losing stream conditions in reaches 1 and 2 will not likely contribute to streamflow depletion in these adjacent reaches, even though perennial flow occurs in reach 1. However, groundwater diversions potentially affect the length of the dry gap in reach 3, or potentially affect flows in the reach 4 (Brunner, et al., 2011). Further investigations, long-term monitoring, and/or groundwater modelling is needed to assess such impacts in priority areas.

3.3.4   *Englishman River Study*

GW Solutions, Inc. (2012) conducted the Englishman River Study to characterize and better understand SW-GW interactions in the lower reaches of the watershed. The study documents SW-GW interactions with confined and semi-confined aquifer systems.

The Englishman River is located on the east coast of Vancouver Island and discharges to the Straits of Georgia at the City of Parksville. The watershed encompasses 32,000 hectares, but this study focused on SW-GW interactions in the lower watershed area, along the lower 15 km of the river. Here the river is a fourth-order river with moderate to low gradient. It supports high-quality fisheries habitat that is the subject of several management and restoration studies. Urban development is concentrated along coastal areas in the adjacent terraces and floodplains, and the river and adjacent aquifers are the primary sources of domestic and municipal water supply. Climate is generally rainfall-dominated with seasonal low flow in late summer.

There are several mapped aquifers adjacent to the Englishman River within the study area (Figure 35). Many of these aquifers are type 4b confined Quadra sand aquifers with confining and inter-bedded aquitards comprised of glacial tills.   Geologic cross-sections in Figure 36 illustrate the confined and semi-confined units (GW Solutions, Inc., 2012). Notice the river channel intersects the confined aquifers and the aquifers and aquitards outcrop along the margins of the river channel. In these areas, the confined aquifers are in direct hydraulic communication with the river, and discharges from the aquifers support baseflow. Active seeps observed from aquitards and bedrock outcrops may also significantly support baseflow (GW Solutions, Inc., 2012). Because of the hydraulic connectivity, groundwater diversions from confined aquifers likely contribute to streamflow depletion via interception of groundwater discharges.

GW Solutions (2012) quantified groundwater discharges along three river reaches of the Lower Englishman River. The results are plotted in 'butterfly plots', which show the estimated groundwater discharge from the individual layered aquifers (Figure 37). These plots indicate the confined aquifer contributes significantly to summer baseflow, cumulatively as much as 10% or more of the summer baseflow. Also, notice that deeper aquifers sometimes contribute as much or more than shallower aquifers. The study also found that underlying bedrock systems could contribute as much 30 to 40% of the summer baseflow (GW Solutions, Inc., 2012). However, the bedrock aquifers and discharges are poorly understood and additional work is needed to better characterize these systems.
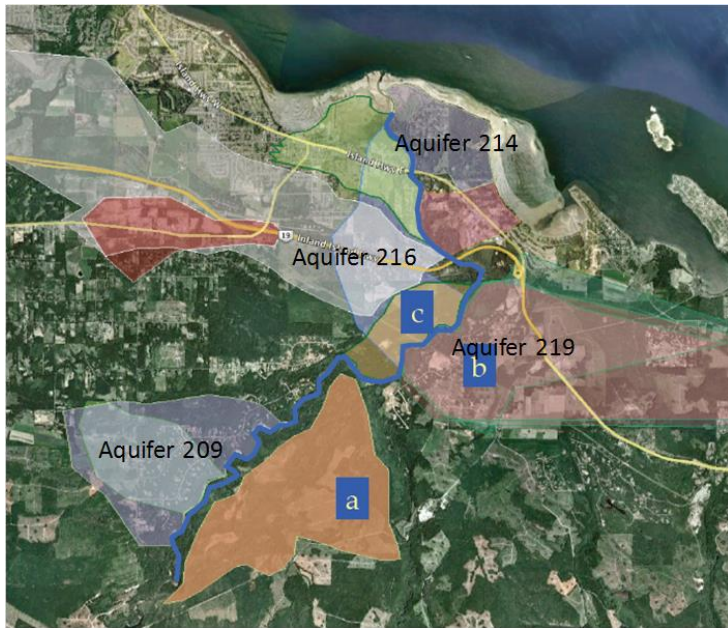
Figure 35 Mapped aquifers adjacent to the Lower Englishman River (Source: Groundwater Solutions. 2012).
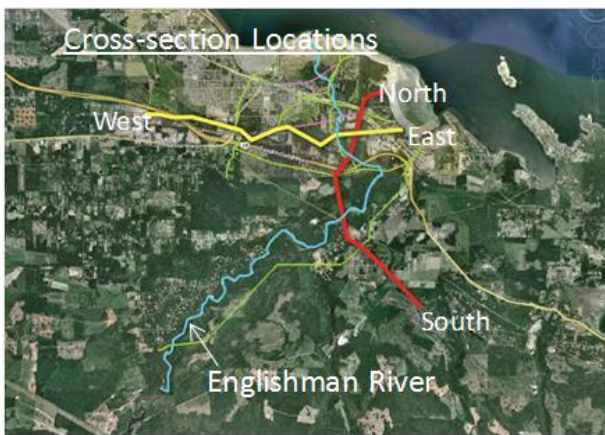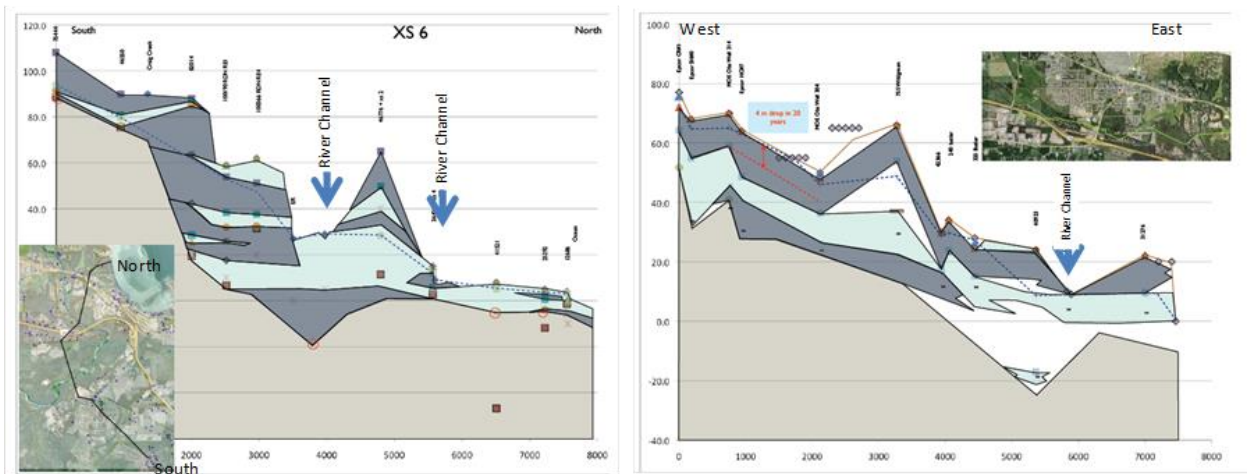
Figure 36   Hydrogeologic cross-sections in the Lower Englishman River watershed (modified from Groundwater Solutions, 2012).

The results of this study illustrate the potential for stream interaction with confined aquifer systems. Groundwater diversions from such aquifers can likely reduce groundwater discharges and affect baseflow. Allocation staff should be aware that confined and semi-confined aquifers are not inevitably disconnected, but in fact can and often are in hydraulic communication with local streams.

Reach	GW discharge (m³/day)	Fraction of summer base flow
10- 16 km	1,900	2%
5 – 10 km	12,000	13%
0 – 5 km	9,500	10%

Modified from Groundwater Solutions (2012)
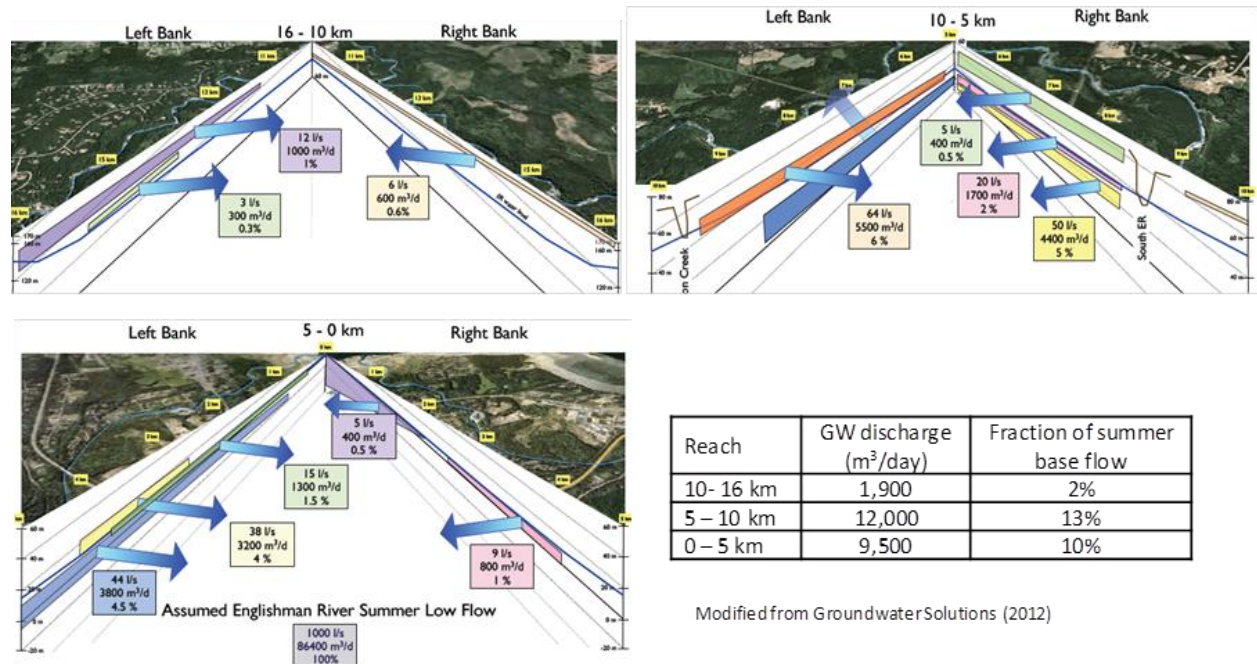
Figure 37   Estimated groundwater discharge to the Lower Englishman River (modified from Groundwater Solutions. 2012).

4. ASSESSING STREAM DEPLETION FROM PUMPING

Water managers require methods for quantifying or appraising the effects of groundwater diversion on streamflow in order to manage water rights. This section describes methods for quantifying streamflow depletion from groundwater pumping, and reviews the approaches adopted by other jurisdictions. The available methods range from easy and cost-effective approaches using arbitrary thresholds or simple estimation methods, to comprehensive site-specific field studies or detailed numerical modelling.

4.1 Analytical Models

Analytical models are simplified approaches for estimating streamflow depletion from pumping, typically at a single well. They generally require basic and limited information about the site conditions, and they usually are easy to implement in spreadsheets or with user-friendly software. For these reasons, analytical models are common methods for simple and quick estimation of streamflow depletion. Historically, some regulatory agencies have adopted the use of analytical models in management of water rights.

Analytical models are essentially solutions of the general unsteady (transient) groundwater flow equation for a prescribed set of simplifying conditions. These conditions or assumptions represent an idealized conceptualization of actual site conditions, which often do not account for complexities of the true system.

A number of different analytical models are available for estimating the effects of pumping on surface water. These models can be broadly grouped into three categories based on the complexity of the aquifer-stream conceptualization.

4.1.1 Analytical Models based on Simple Stream-Aquifer Conceptualization

Glover Model

The well-known Theis equation is among the earliest solutions of the unsteady groundwater flow equation (Theis, 1941). Theis developed this solution for an idealized aquifer-stream system shown in Figure 38, which encompasses the following simplifying assumptions:

- The stream is straight and infinitely long, and stream stage is constant.
- The streambed completely penetrates the entire thickness of the aquifer.
- The streambed materials do not impede flow into the aquifer
- The aquifer materials are homogeneous with respect to transmissivity and storativity
- The aquifer extends infinitely from the stream, such that lateral boundaries do not influence the aquifer response to pumping.
- The aquifer has constant thickness, bounded below by an impervious base. Note the Theis equation is originally developed for confined aquifers with impermeable boundaries on the on top and bottom. However, the Theis equation and associated streamflow depletion models are typically applied to unconfined aquifers. This additionally assumes the water table drawdown due to pumping is small and negligible, such that transmissivity is constant.
- The stream is the only source of possible recharge.
- Pumping occurs from a single well screened over the entire thickness of the aquifer.
- The pumping rate is constant and continuous.
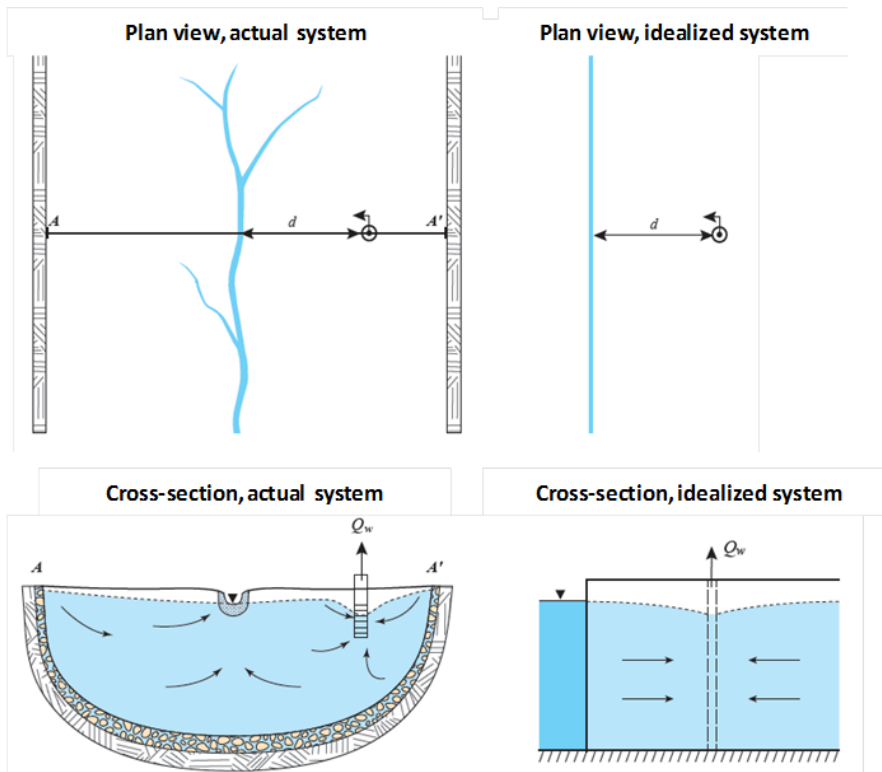
Figure 38   Aquifer-stream conceptualization used in the Glover Model (Source: Barlow and Leake. 2012).

Based on foregoing assumptions, Theis (1941) developed an integral solution of the unsteady groundwater flow equation. Subsequently, Glover and Balmer (1954) expressed the integral solution in a different form that is easier to solve. This solution is known as the Glover model and is expressed as:

$$\frac{\Delta Q_s}{Q_w} = \text{erfc}\left(\sqrt{\frac{Sd^2}{4Tt}}\right)$$

(eq. 1)

where:

ΔQ_s	is change in streamflow caused by groundwater pumping;
Q_w	is the constant pumping rate;
$\Delta Q_s/Q_w$	is the streamflow depletion expressed as a fraction of pumping;
erfc	is the complementary error function;
S	is the aquifer storativity for confined aquifers, or the aquifer specific yield (S_y) for unconfined aquifers;
d	is the distance between the well and the river;
T	is the aquifer transmissivity; and
t	is time since the start of pumping from the well.

The following plot shows example results from the Glover model for a groundwater diversion in a typical unconfined sand & gravel aquifer. Notice the rate at which groundwater pumping causes streamflow depletion increases significantly as the distance from the well to the stream decreases. However, with enough time, all three well locations will eventually derive all water from the stream.
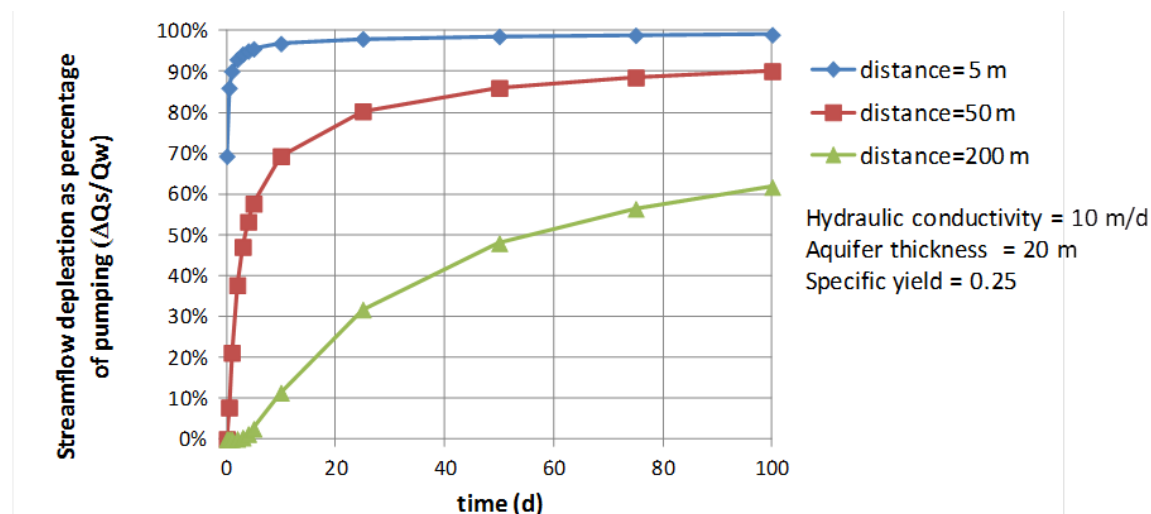
Figure 39 *Example solutions of the Glover model.*

Glover Model with Residual Depletion

The Glover model assumes a constant and continuous pumping rate. Jenkins (1968) extended the Glover model to determine the response of streamflow depletion following pump shutoff. Using the method of superposition, a residual streamflow depletion (i.e., streamflow depletion after pump shutoff) is calculated as the difference between the rate of streamflow depletion from the pumping well (pumping continuously) and an imaginary injection well at the same location. The rate of injection is equal to the pumping rate and begins at the time of pump shutoff (Jenkins, 1968). Mathematically, this is expressed as:

$$\frac{\Delta Q_s}{Q_w} = \text{erfc}\left(\sqrt{\frac{Sd^2}{4Tt}}\right) \quad \text{during active pumping } (0<t \leq t_s) \qquad \text{(eq. 2)}$$

$$\frac{\Delta Q_s}{Q_w} = \text{erfc}\left(\sqrt{\frac{Sd^2}{4Tt}}\right) - \text{erfc}\left(\sqrt{\frac{Sd^2}{4T(t - t_s)}}\right) \quad \text{after pump shutoff } (t > t_s) \qquad \text{(eq. 3)}$$

where t_s is the time at pump shutoff.

Figure 40 below illustrates solutions with the Jenkins approach where groundwater diversion is stopped after 30 days of continuous pumping in the same typical unconfined sand & gravel aquifer used in Figure 39. The plots show streamflow depletion decreases after pump shutoff, but that streamflow recovery does not occur instantly. Rather, streamflow depletion persists after pump shutoff and the duration for streamflow recovery is longer at wells further from the stream. Also notice for the well at 200 m, the duration of streamflow recovery is longer than the duration of pumping, and that streamflow depletion continues to increase after pump shutoff. Wallace et al. (1990) investigated the effects of cyclic pumping using to the Glover model and showed that it is not appropriate to approximate cyclic pumping by an equivalent cycle-average steady pumping rate.
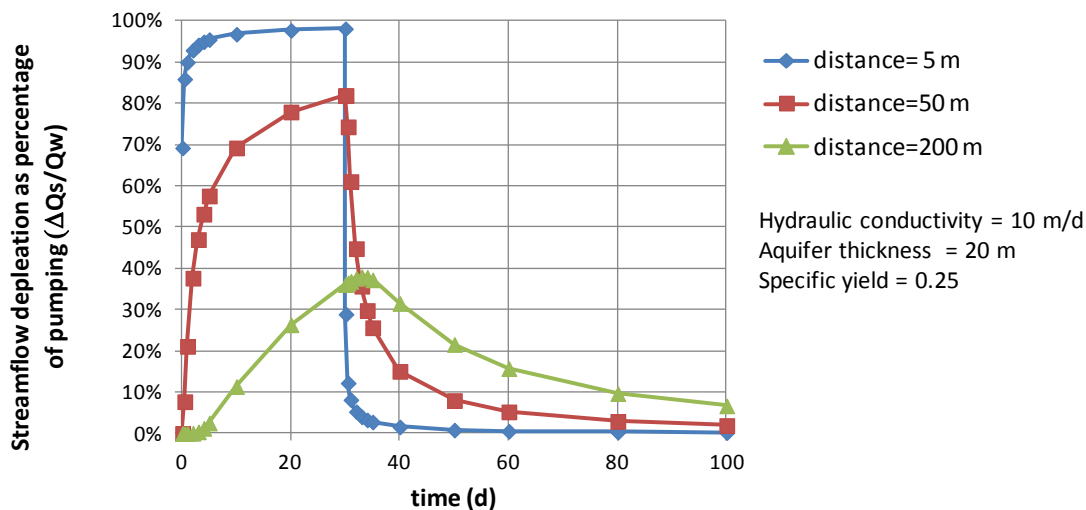
Figure 40   Example solutions of the Glover model with residual streamflow depletion after 30 days of pumping.

Glover Model Extensions

Other extensions of the Glover model examined questions of where streamflow depletion is distributed, and how much depletion is occurring from induced infiltration from the stream.

Newsom and Wilson (1988) and Wilson (1993) developed two-dimensional steady-state solutions for different combinations of aquifer geometry and recharge. Features of these models include: 1) the ability to estimate streamflow depletion occurring in a specified reach; 2) the ability to differentiate and quantify streamflow depletion caused by groundwater capture verses induced infiltration; and 3) the ability to estimate the critical pumping that will induce infiltration from the stream. This information may be useful in groundwater contamination problems where it is necessary to understand how pumping affects the quantity and distribution of groundwater discharge to a stream.

Chen (2003) extended the work of Newsom and Wilson (1988) and Wilson (1993) to include transient effects. Chen developed semi-analytical solutions to estimate the time varying components of

streamflow depletion for induced infiltration and reduced groundwater discharge. An expression for the critical time required to induce infiltration from the stream was derived for a given well distance and pumping rate. Chen (2003) also showed the assumption of steady state conditions significantly overestimate the rate and volume of stream infiltration, especially during early stage pumping. A drawback of this approach is the need for numerical procedures to solve integral expressions, which increases the complexity for its application.

4.1.2   Analytical Models with Improved Aquifer-Stream Representation

Several studies investigated the predictive accuracy of the Glover model through comparison with numerical simulation models, which account for hydrogeological complexities ignored in the Glover equation (Spalding & Khaleel, 1991; Sophocleous, et al., 1995; Chen & Yin, 1999). These studies showed the following simplifying assumptions strongly influence estimates of streamflow depletion:

- Ignoring streambed resistance in the Glover model affects predictions of streamflow depletion. Including low-permeability streambed sediments greatly reduces streamflow depletion at a given time. The Glover model substantially overestimates streamflow depletion in comparison with numerical solutions.
- Representing the stream geometry in the Glover equation as a fully penetrating system (i.e., the stream depth is equivalent to the aquifer thickness) similarly resulted in significant over-prediction of streamflow depletion in comparison to numerical models. The discrepancies were comparable to those of streambed of clogging.
- The Glover solutions assume the aquifer properties are uniform in space and direction. Numerical solutions that included layered conductivity zones resulted in reduced streambed depletion in comparison to the Glover solutions. The ratio of horizontal to vertical conductivity (anisotropy) also influenced the predictions of streamflow depletion.

Of these factors, streambed impedance and partially penetrating streams are the two conditions that most strongly affect prediction accuracy. To address these errors, analytical models were extended to incorporate the effects of streambed impedance and partially penetrating streams. Two of the earliest and well-known models are the Hantush model and the Hunt model.

Hantush Model

Hantush (1965) extended the Glover solution to include the effects of a semi-impervious streambed layer. In this conceptualization, the aquifer-stream system has a vertically aligned layer of low-permeability streambed sediments that separates the fully penetrating stream from the adjacent aquifer materials (Figure 41). All other assumptions in the Glover model are unchanged.
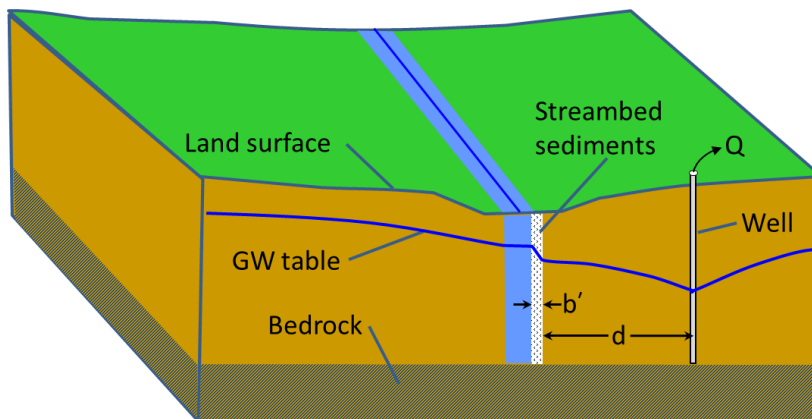
Figure 41   Aquifer-stream conceptualization in the Hantush Model (after Hunt, 1999).

Based on this conceptualization, Hantush developed the following analytical expression:

$$\frac{\Delta Q_s}{Q_w} = \text{erfc}\left(\sqrt{\frac{Sd^2}{4Tt}}\right) - \exp\left(\frac{Tt}{SL^2} + \frac{d}{L}\right)\text{erfc}\left(\sqrt{\frac{Tt}{SL^2}} + \sqrt{\frac{Sd^2}{4Tt}}\right) \qquad \text{(eq. 4)}$$

where all terms are as previously defined in eq. (1), and additionally L is the called the streambed leakance term that represents the effects of streambed impedance. Streambed leakance is evaluated as:

$$L = \frac{K}{K'}b' \qquad \text{(eq. 5)}$$

where K is the hydraulic conductivity of the aquifer; K' is the hydraulic conductivity of the streambed sediments; and b' is the thickness of the streambed. The Hantush and Glover models are equivalent when the streambed leakance term approaches zero. This occurs when the streambed and aquifer conductivity are similar or the streambed thickness is small.

Example results in Figure 42 illustrate the influence of streambed sediments where the conductivity contrast with aquifer sediments ranges up to 3-orders of magnitude. Actual measurements of streambed conductivity are up four or five orders of magnitude lower than the aquifer conductivity, and predominantly range between 0.01 and 100 m/d (Calver, 2001). The comparisons show increasing impedance on the rate of streamflow depletion as the contrast in aquifer and streambed conductivity increases.

Explanation:

Aquifer Properties		Streambed Properties		Conductivity Ratio (K/K')
Conductivity (K) (m/d)	Representative texture	Conductivity (K') (m/d)	Representative texture	
		1	Fine sand	10
10	Coarse Sand	0.1	Silty sand	100
		0.01	Silt	1000
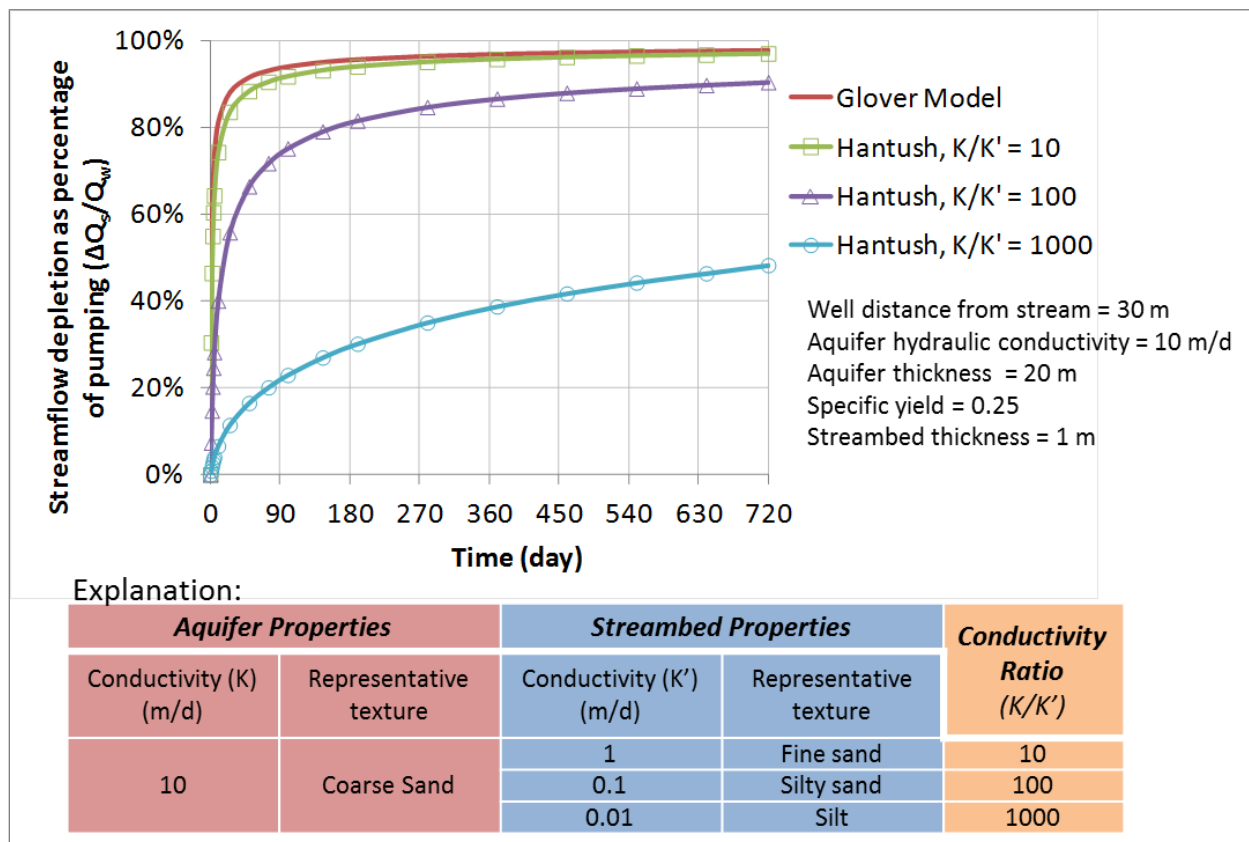
Figure 42 Example solutions with the Hantush Model for different conductivity (K/K') ratios.

Hunt (1999) Model

Hunt (1999) derived a widely used alternative stream depletion model that addresses an aquifer-stream system with both streambed impedance and partially penetrating stream conditions (Figure 43). This approach assumes the vertical dimension of the stream is small in comparison to the aquifer thickness, so that the stream is considered a line source with zero width. Based on this conceptualization, Hunt (1999) derived the following expression:

$$\frac{\Delta Q_s}{Q_w} = \text{erf}\left(\sqrt{\frac{Sd^2}{4Tt}}\right) - \exp\left(\frac{\lambda^2 t}{4ST} + \frac{\lambda d}{2T}\right)\text{erfc}\left(\sqrt{\frac{\lambda^2 t}{4ST}} + \sqrt{\frac{Sd^2}{4Tt}}\right) \tag{eq.6}$$

in which λ is termed the streambed conductance term that incorporates the effects of streambed impedance.
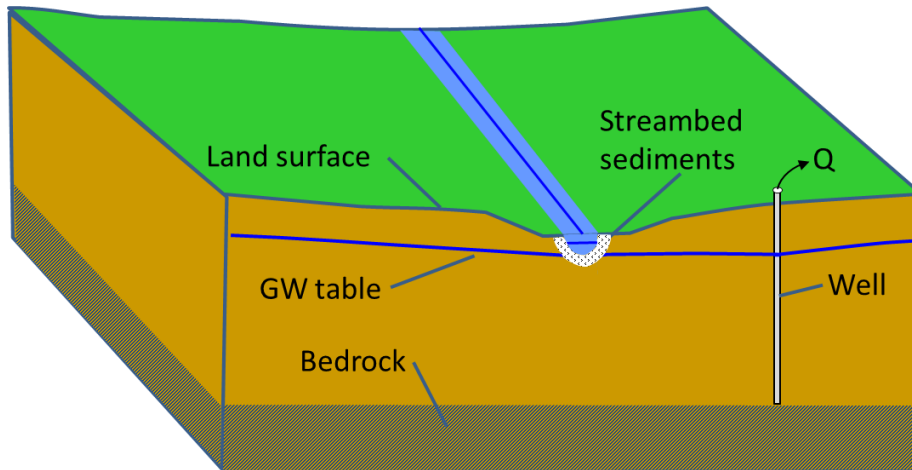
Figure 43   Aquifer-stream conceptualization in the Hunt (1999) Model (after Hunt, 1999)

The stream conductance parameter lacks a degree of physical meaning. Hunt (1999) assumed the stream width is negligible, which is valid for an aquifer of infinite extent. In deriving eq. 6, Hunt expressed the seepage flow through the streambed per unit length of stream as $q_s = \lambda(H - h)$, where H is the water elevation in the river and h is the groundwater elevation below the streambed. Thus, from a mathematical perspective, λ represents the constant of proportionality between the seepage flow rate per unit length of stream and the difference in river and groundwater elevations. In practice, it is common to approximate streambed conductance as a function of stream width and streambed properties, using the expression:

$$\lambda \approx \frac{wK'}{b'} \tag{eq. 7}$$

where w is the stream width, and K' and b' are the streambed conductivity and thickness, respectively. Hunt et al. (2001) state this approximation implies the well spacing from the stream is much greater than the stream width (i.e., $d/w > 1$).

Michigan Screening Tool

The Michigan screening tool (Reeves, et al., 2009) is a practical implementation of the Hunt (1999) Model, incorporating a number of enhancements to improve the model utility and user friendliness. The screening tool is an internet-based program for simplified assessment of potential streamflow depletion impacts.

Assignment of parameters: The Michigan screening tool includes simplifications to aid users in assigning values to the required model parameters. The screening tool uses an alternative method for estimating the streambed conductance term (λ) in glacial deposits:

$$\lambda = \frac{wK_v}{d_s} \qquad \text{(eq. 8)}$$

where w is the average streambed width, K_v is the vertical component of the aquifer hydraulic conductivity, and d_s is the vertical distance from the streambed to the top of the well screen or open interval of the well, which is readily available from the well log or driller. The horizontal component of aquifer conductivity, (K_h) is determined from transmissivity (T) as $K_h = T/b$ where b is the aquifer thickness. A common rule-of-thumb uses a value of 10 for the horizontal to vertical anisotropy ratio (i.e., $K_h/K_v = 10$). Combining these assumptions, the modified streambed conductance in the Michigan screening tool is:

$$\lambda = \frac{Tw}{10bd_s} \qquad \text{(eq. 9)}$$

This form is advantageous because it uses parameters that are readily available from well records, pumping tests, and regional characterization studies. A disadvantage is that eq. 9 is independent of the streambed properties and therefore loses a certain amount of physical significance.

The Michigan screening tool has been applied to both unconsolidated and bedrock aquifers. For application to bedrock aquifers, a statewide map identifies areas where bedrock aquifers are potentially or unlikely connected to surface waters. In areas where proposed wells are connected, a statewide database of bedrock properties provides estimates for the bedrock aquifer properties.

Distribution of streamflow depletion volumes: A second enhancement of the Michigan screening tool is a methodology to distribute streamflow depletion among neighboring catchments. The first generation of the screening assigned the streamflow depletion volume exclusively to the stream within the valley catchment containing the well. However, comparisons to a numerical model found poor agreement. Better agreement with numerical solutions was achieved by distributing the streamflow depletion volume among adjoining catchments. Reeves et al. (2009) evaluated nine different methods to apportion streamflow depletion volumes among neighboring catchments, with the best overall results obtained with an inverse distance weighting procedure.

Variable pumping: A third feature of the Michigan screening tool is the ability to allow users to input variable pumping conditions. The tool uses the method of superposition (Jenkins, 1968) to account for variable pumping effects on the streamflow depletion volume estimates.

Singh (2003) Model

Hunt (1999) showed his model is equivalent to the Hantush equation when $L = 2T/\lambda$. This implies the Hantush solution can model the effects of a partially penetrating stream with an appropriate correction of the streambed leakance term, L. Applying this concept, Singh (2003) modified the Hantush leakance term by adding the following retardation factor (R_p) that explicitly accounts for partially penetrating stream conditions:

$$L = \frac{K}{K'}b' + R_p \qquad \text{(eq. 10)}$$

where,

$$R_p = \frac{b}{\pi}\ln\left(\frac{2e^{v1} - (1 + e^{-v2}) + \sqrt{(e^{v1} - e^{-v2})(e^{v2} - 1)}}{(1 - e^{-b})}\right) - d$$

<div align="right">(eq. 11)</div>

$$v1 = \frac{\pi d}{b} \quad v2 = \frac{\pi w}{b}$$

and b is the thickness of the aquifer, d is the distance from the well to the stream, and w is the stream width.

Substituting L from eq. 10 into the Hantush model (eq. 4) provides an expression that accounts for both streambed impedance and a partially penetrating stream. Conceptually this approach appears more physically based than the Hunt (1999) model because the stream has a finite width and streamflow depletion directly depends on aquifer thickness. However, the Singh model does not appear to be widely cited in the literature.

Other Models Addressing Aquifer and Stream Dimensions

A number of models address implicit assumptions in the Hunt model regarding the infinite extent of the aquifer and the negligible stream width:

- Zlotnik and Huang (1999) derived an analytical model for the case of a partially penetrating stream with a finite width. They divided the problem domain into two regions, one below the stream and one adjacent to the stream, developing governing equations for each region. These equations were solved simultaneously using Laplace transform procedures, providing a means to investigate the significance of stream geometry on aquifer-stream interaction. The authors conclude that stream width plays an important role in aquifer-stream interaction and show wider streams have stronger connectivity with the aquifer.
- Butler et al. (2001) extended the work of Zlotnik and Huang (1999) by developing equations for the case of an aquifer of limited extent and finite stream width. The resulting equations have a complicated form that requires numerical procedures to solve, and is therefore not straightforward to implement. Butler et al. (2001) used the model to investigate the prediction error resulting from assumptions of negligible stream width and infinite aquifer extent. In direct comparisons to the Hunt solutions, they found Hunt's assumption of negligible stream width did not appreciably affect results when the well is more than 5 stream-widths from the stream. However, this was not the case for the assumption of infinite aquifer extent. In comparisons to numerical solutions, they found the aquifer width must be hundreds of stream-widths before the assumption of a laterally infinite aquifer is appropriate.
- Fox et al. (2002) also investigated the influence of finite stream width. They extended the Hunt model to include distributed infiltration across a finite stream width. Similar to the approach of Butler et al. (2001), the model solutions have a complex form that requires numerical procedures to solve. Investigation into the effects of stream-width indicate errors in the Hunt model are small when the well spacing is greater the 25 stream-widths, which is larger than was found by Butler et al. (2001).

4.1.3   Analytical Models for Specific Aquifer Geometry and Flow Conditions

More recent streamflow depletion models address specific hydrogeologic geometries, such as the presence of other water sources, leakage from underlying aquifers, and pumping from semi-confined aquifers. These models provide advances in terms of improved representation of hydrogeologic systems and insights into the specific conditions addressed. However, there are also trades-offs in terms of solution complexity and the need for additional site characterization to determine additional model parameters.

Semi-Confined Aquifers

Hunt (2003) developed analytical solutions for pumping in a semi-confined aquifer where the aquitard forms the top boundary of the pumped aquifer and the stream partially penetrates the aquitard (Figure 44). Similar aquifer conditions occur along the Englishman River on Vancouver Island (see Section 3.3.4), and in areas of the Midwest (Sophocleous, et al., 1988).

The model conceptualization is similar to Hunt (1999) where distance between the well and stream is assumed to be sufficiently large such that the stream width is approximated as zero and the aquifer has infinite extent. However, this model has significantly more information requirements including:

- aquifer and aquitard thickness;
- aquifer and aquitard conductivity;
- aquifer and aquitard storativity;
- streambed thickness and conductivity;
- stream width; and
- well spacing from the stream.
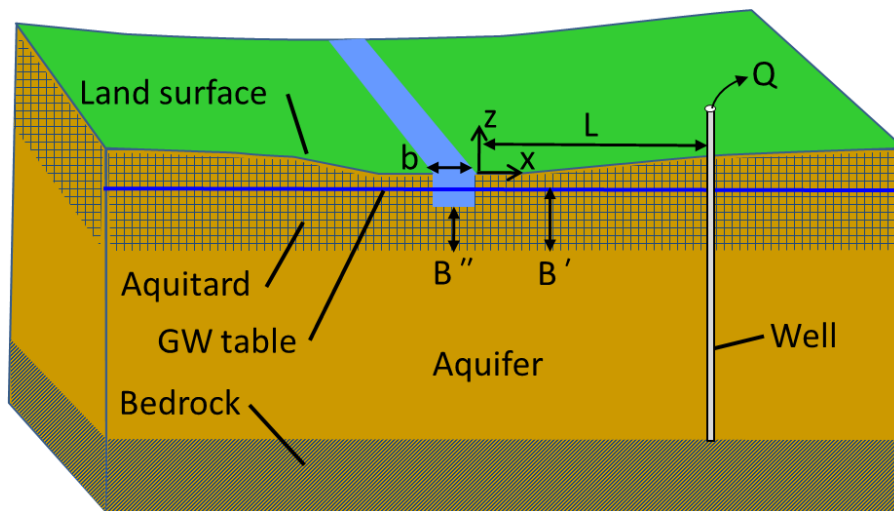
Figure 44   Aquifer-stream conceptualization of a semi-confined aquifer of infinite extent (after Hunt. 2003).

Hunt (2003) plotted stream depletion versus time and found changes in curvature that are characteristic of a delayed yield aquifer response. At early times, the rate of stream depletion is small, as pumped water comes mainly from aquitard storage. The rate of streamflow depletion increases at immediate times as pumped water comes from aquifer storage and the stream. Eventually, streamflow depletion approaches the pumping rate at large times.

Hunt (2008) further extended this work to include the effects of a bounded aquifer system and a stream of finite width, as shown in Figure 45. In this situation, the lateral aquifer boundaries can behave as negative boundaries, which results in greater drawdown and increased rate of streamflow depletion. Such effects are potentially important for thin alluvial aquifers in narrow river valleys found throughout B.C., for example Cache Creek.

The mathematical solutions for the Hunt (2003) and Hunt (2008) models are complex and the resulting solution procedures are not straightforward. However, a spreadsheet solution is available from Bruce's Hunt's research webpage (Hunt, 2012).
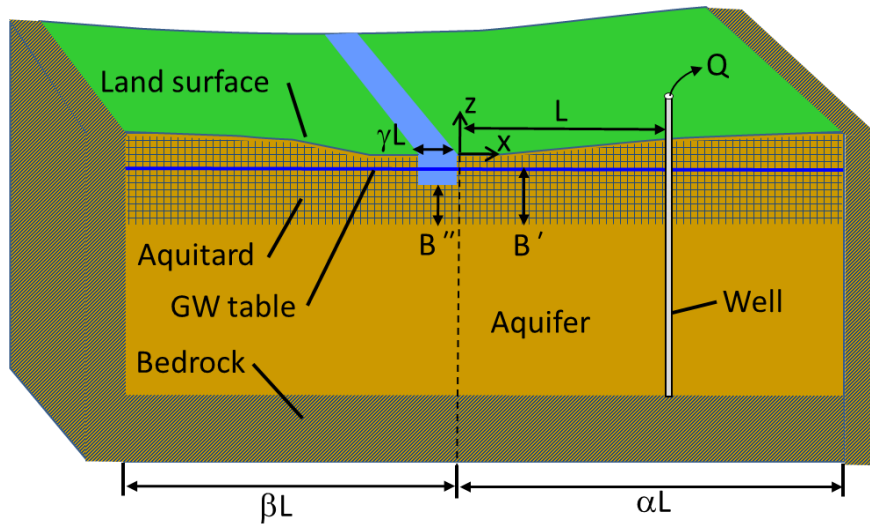
Figure 45   Aquifer-stream conceptualization in the Hunt (2008) Model (after Hunt. 2008).

Connected and Layered Aquifers

Previous models have all assumed an impermeable lower boundary. Another group of models considers the effect of leaky aquifer conditions where pumping occurs from an unconfined aquifer underlain by a semi-confined aquifer (e.g., Figure 46). In this situation, the aquitard separating the aquifers has sufficient permeability to transmit significant quantities of water (i.e. a leaky aquifer), such the unconfined aquifer is in hydraulic communication with the stream and the underlying semi-confined aquifer. Thus, both aquifers are potential sources of water to a well pumping in the unconfined aquifer because pumping stress can induce upward leakage through the aquitard. Leaky aquifer conditions are common in major river valleys of the central plains (Zlotnik, 2004) and occur in B.C. in portions of the Merritt aquifer, Cowichan aquifer, and likely many other aquifer systems.
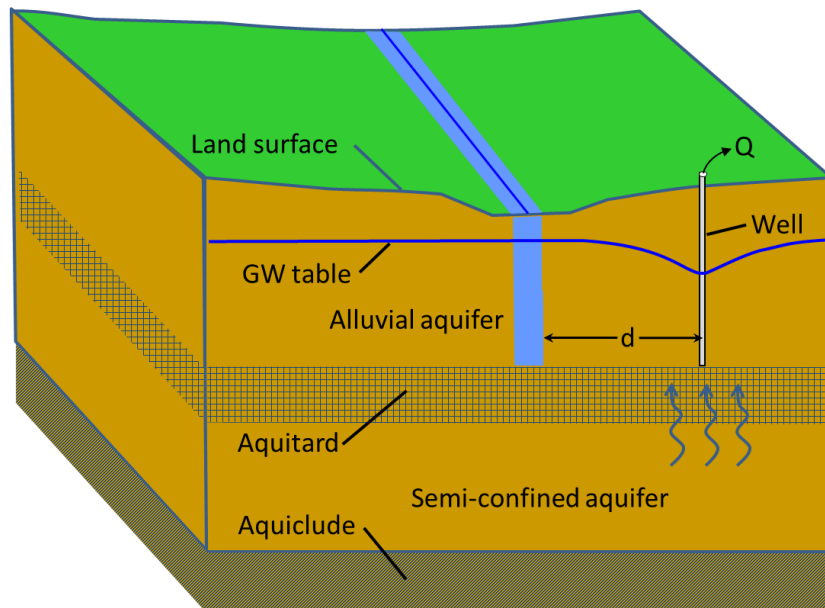
Figure 46   Leaky aquifer-stream conceptualization with a fully penetrating stream (after Zlotnik. 2004).

Zlotnik (2004) developed an analytical model of streamflow depletion in leaky aquifer systems assuming the stream fully penetrates the alluvial aquifer (Figure 46). He also presented solutions for the case of a

bounded aquifer and the case where pumping occurs between two streams. Because the leaky aquifer is a supplemental source of water to the well, upward leakage through the aquitard effectively reduces the magnitude of streamflow depletion during transient conditions. Zlotnik (2004) found the maximum streamflow depletion occurring at steady state is less than the pumping rate, and depends on the aquitard properties, distance from the well, and the distance to the aquifer boundaries. Upward leakage significantly reduced streamflow depletion, even for large conductivity contrasts of 10,000 or more. Application of this model requires information about the aquitard thickness, conductivity, and storativity, which can be difficult to determine.

(Butler, et al., 2007) extended the work of Zlotnik (2004) to include a more realistic representation of the stream and aquifer conditions, including the presence of a partially penetrating stream and streambed sediments (Figure 47). This model, however, is more complex and requires numerical procedures to solve. Aquitard leakage was again shown to significantly influence the rate and magnitude of streamflow depletion, even in the presence of large aquifer/aquitard conductivity contrast.
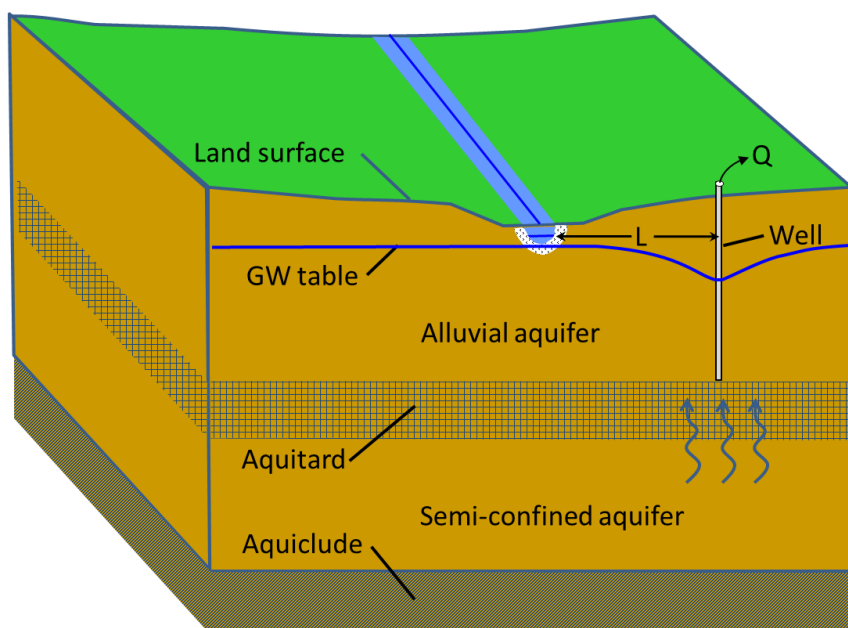
Figure 47   Leaky aquifer-stream conceptualization with a partially penetrating stream (adapted from Butlet et al. 2007 and Hunt, 2009).

In a discussion paper, Hunt (2008b) questioned the work of the previous two papers. He noted the conceptualization and model solutions disregard drawdown in the lower aquifer. This in effect means the lower aquifer provides an infinite supply of water for recharge to the upper pumped aquifer, which does not occur in reality. Consequently, Hunt contends the solutions do not accurately predict streamflow depletion at large times, and the concept of maximum streamflow depletion is flawed. Hunt further states the "solution is in danger of being used, either intentionally or through ignorance, by anyone who wants to justify excessively large well abstractions for a stream depletion problem."

Hunt (2009) extended his previous work to address the problem of the leaky aquitard problem above, taking into consideration the drawdown in the lower aquifer in the solution formulation. Thus, information requirements are extensive including the thickness, conductivity, and storativity of both aquifers and the aquitard, the streambed thickness and conductivity, and the well spacing from the stream. Solutions demonstrated that when storativity of the lower aquifer is considered, streamflow

depletion approaches the pumping rate at large times. These solutions differ substantially from those of Zlotnik (2004). The solution procedure for this model is not straightforward, but a spreadsheet program is available from the researcher's webpage (Hunt, 2012).

Barlow and Moencch (1998) prepared a comprehensive report describing the derivation of analytical solutions to the ground-water flow for ten cases of hydraulic interaction between a stream and a confined, leaky, or water-table aquifer. All aquifer types allow for the presence or absence of a uniform semi-pervious streambank. The report also describes two accompanying computer programs that can be used to evaluate the analytical equations.

Ward and Laugh (2011) extended the model of Hunt (2009) for the situation where pumping occurs in the lower aquifer (Figure 48). Results from this study showed when pumping occurs from a semi-confined aquifer, the effects of streamflow depletion occur more rapidly when there is an overlying phreatic aquifer, compared to the case where there is only an overlying aquitard (e.g., Hunt, 2003). This occurs because pumping stresses produce horizontal flow in the upper phreatic aquifer, which acts as a more direct connection between the stream and the well. Solutions to the model of Ward and Laugh (2011) are also available in the spreadsheet programs developed by Hunt (2012).
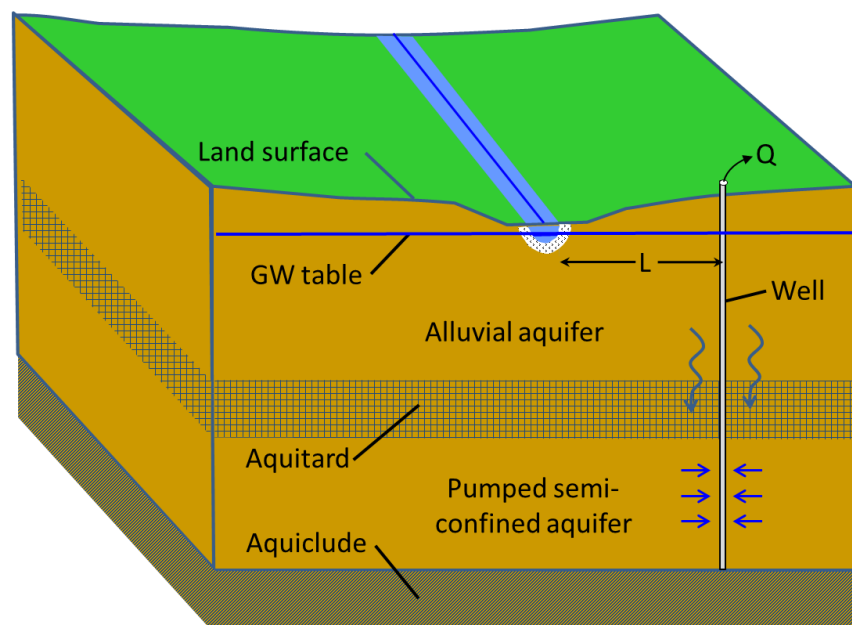
Figure 48   Layered aquifer-stream conceptualization where pumping occurs in the lower aquifer (after Ward and Lough. 2011).

4.2 Numerical Models

Analytical model are useful tools for gaining insights into system behavior and for estimating streamflow depletion under idealized conditions. However, many hydrogeologic complexities affect the magnitude and timing of streamflow depletion including, non-uniform soil and streambed properties, complex stream geometries and stream networks, and non-ideal aquifer geometry (Barlow & Leake, 2012). For these conditions, numerical models are a more robust approach for evaluating the effects of pumping on surface flows.

Numerical groundwater flow models simulate the movement of groundwater by solving the general groundwater flow equation in a discretized domain (i.e., solutions are generated at discrete points). This

provides flexibility for model design and the capability to address complex physical and hydrogeological conditions, including:

- Constrained and irregular aquifer dimensions;
- Heterogeneous soil distributions and multiple aquifer types;
- Complex and variable surface water features, such as meandering streams, stream networks, seasonal streamflow, lakes, springs, and wetlands;
- Distributed and time dependent pumping schedules;
- Distributed and seasonally dependent recharge, evapotranspiration, and irrigation returns;
- SW/GW interactions at different scales, including localized behaviors, basin-wide perspectives, and transient and long-term time scales;

Groundwater flow models are either steady-state or transient models. A steady-state model provides solutions that are independent of time, representing the long-term response to pumping and boundary conditions, assuming they are constant over time. A transient model provides solutions that vary with time, and therefore can simulate the effects of time varying pumping and boundary conditions, as well as time-varying climatic conditions and recharge. Both types of numerical groundwater flow models are useful for supporting management of groundwater basins, for assessing SW-GW interactions, and for evaluating streamflow depletion impacts from groundwater withdrawals.

Integrated surface water and groundwater models are a new generation models for dynamically simulating coupled surface water and groundwater processes. These models simulate all aspects of the hydrological cycle, including rainfall-runoff processes, surface water storage and routing through streams and lakes, evapotranspiration, and the interaction of these processes with subsurface flow systems through infiltration and recharge, unsaturated and saturated zone flow, and groundwater discharge to surface water features. Such models are well suited for simulating SW-GW interaction. Two widely used integrated surface water –groundwater models are MIKE-SHE and HydroGeoSphere.

Numerical models can be developed and applied in many ways. The following describes several applications of numerical models for evaluating SW-GW interactions and conjunctively managing SW-GW resources:

- **Assessment of SW-GW interactions in southwest B.C.:** Starzyk (2012) developed a comprehensive numerical model of the 43 km^2 Bertrand Watershed, near Aldergrove in southwestern B.C. The purpose of the modelling was to improve understanding of SW-GW interactions during base flow conditions, and to assess the dominant controls. The model was developed using HydroGeoSphere, and was calibrated against measured streamflow, groundwater discharge, hydraulic head, soil moisture, and change in surface water levels.

  Model simulations revealed significant seasonal and spatial variability in the direction and magnitude of SW-GW interactions, and these interactions are strongly influenced by topography. Evapotranspiration, particularly transpiration within the riparian zone, is a significant control of base flow in Bertrand Creek. Starzyk (2012) also used the model to assess the effect of a hypothetical well at 150 m from the stream and pumping at a rate equivalent to the largest abstractions of Aldergrove municipal well field. Model results showed the well would cause a 23% depletion of minimum base flow and the addition of about 18 days of dry streambed conditions during the 1-year simulation period.

- **Assessment of SW-GW interactions in the Cowichan Valley Watershed:** Foster and Allen (2015) developed a comprehensive regional scale model of the Cowichan Valley watershed using MIKE-SHE, a comprehensive coupled surface and groundwater modeling system. The calibrated MIKE-

SHE model was used to assess groundwater recharge and discharge, estimate groundwater contributions to streamflow, identify gaining reaches, evaluate the impact of pumping on the system, and assess effects from climate change.

Results of MIKE-SHE model showed the Cowichan River is predominantly gaining in the upper reaches and dominantly losing in the lower reaches. Groundwater diversions noticeably affect exchange between the Cowichan River and the aquifer within the lower valley (near Duncan), and pumping alters the nature of GW-SW interaction from gaining to losing conditions in some locations. Hydraulic conductivity is a main control on the magnitude of SW-GW interaction.

- **Impact evaluation of municipal wells fields:** Eggleston et al. (2012) developed a three-dimensional transient groundwater model to assess streamflow depletion in a complex glacial-sediment aquifer in Massachusetts. The glacial fill sediments include sand, gravel, silt, and clay up to 270 feet (80 m) thick overlying an irregular fractured bedrock surface. Simulation of proposed municipal supply wells show streamflow depletion impacts at a rate about equal to the pumping rates, and that pumping would induce substantial recharge from lakes. Simulations also revealed streamflow depletion decreased rapidly following pump shutoff, falling by about 80 percent within 2 months and by about 90 percent within 4 months. These results supported development of a management plan based on an alternative pumping schedule using reduced pumping rates ahead of critical summertime low flow.

- **Modelling effects of groundwater withdrawals from a semi-confined aquifer:** Nielsen and Locke (2012) developed a three-dimensional steady-state groundwater model to evaluate streamflow depletion from pumping of a semi-confined aquifer in Maine. The buried alluvial valley aquifer is overlain by discontinuous confining units and shallow alluvium of sands, till, and weathered clay. The model provided estimates of the aquifer water budget and rates of streamflow depletion from pumping. The researchers also compared numerical model results to analytical solutions for streamflow depletion. The analytical solutions did not compare favorably and were quite variable depending on the selected setup and parameter values.

- **Optimizing management strategies:** Barlow and Dickerman (2001) describe the use of a groundwater flow model for conjunctive management of surface and groundwater resources. They used a three-dimensional flow model to evaluate streamflow depletion caused by groundwater withdrawal in a highly developed alluvial aquifer in Rhode Island. The numerical model was coupled with an optimization model to evaluate alternative management strategies that would maximize groundwater use during peak demand periods in the summer time, while constraining allowable impacts on streamflow depletion. The authors illustrate the utility of the approach for quantifying trade-offs between groundwater development and streamflow depletion.

4.3 Groundwater Response Functions

A groundwater response function is a means of describing a cause-and-effect relationship between applied stresses to a groundwater system and the resulting response of a condition of interest (e.g., groundwater elevation, water quality, streamflow depletion). Groundwater response functions can be developed and used in many different ways.

For the streamflow depletion problem, response functions describe the relationship between pumping at a particular (single) location in an aquifer and the resulting depletion in a nearby stream. The response function is independent of other pumping or recharge stresses that may be occurring simultaneously within the aquifer (Barlow & Leake, 2012). Such response functions typically express the rate or volume of streamflow depletion that occurs in response to pumping, or the volume of depletion

as a percentage of pumping. Response functions for streamflow depletion are not typically measured, but calculated from analytical models or numerical groundwater flow models. When transient numerical models are used, the response functions reflect time dependent responses. If steady-state models are used, the response functions reflect only steady-state solutions.

The application of response functions to the problem of streamflow depletion is illustrated in a Washington State decision support tool for assessing impacts from groundwater withdrawals in the Fishtrap and Bertrand Creek watersheds south of Langley B.C. (Pruneda, 2007; Pruneda, et al., 2010). In this work, response maps provide a means to quickly view risk levels for streamflow depletion from groundwater diversion.   Using a calibrated regional steady-state groundwater flow model Pruneda (2007) developed discrete estimates of steady-state streamflow depletion response at each node in Figure 49 (left) by individually assigning pumping to each node and running the model sequentially. Interpolating the model results provides a contour map of the steady-state streamflow depletion shown in Figure 49 (right). The map highlights areas of high and low risk for streamflow depletion from groundwater withdrawals. It is the focal point of a decision tool that allows local water rights holders to access whether impacts to base flow can be reduced by switching from surface water withdrawals to groundwater withdrawals.
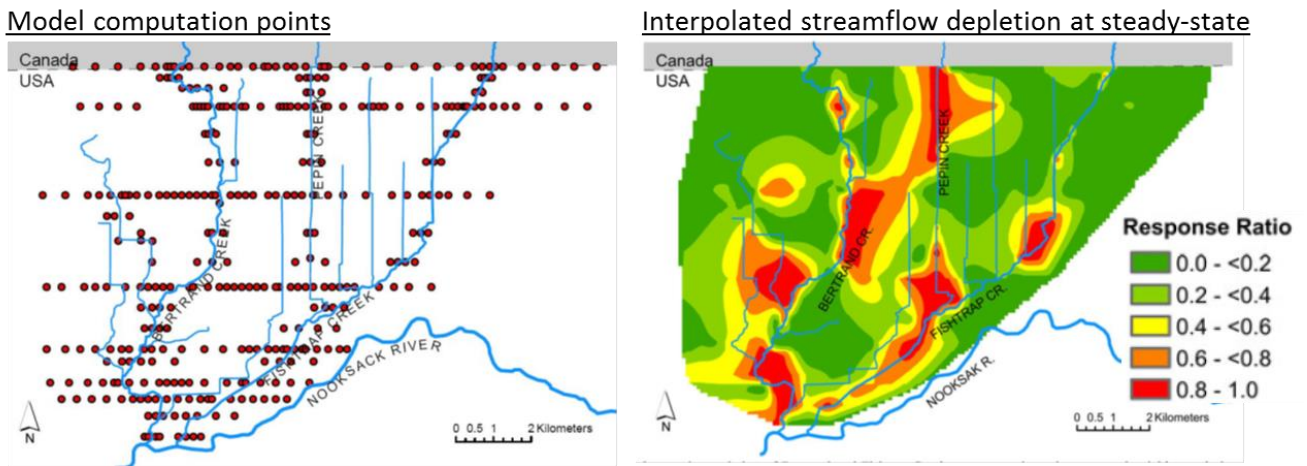
Figure 49   Streamflow depletion response functions for Fishtrap and Bertrand Creek watersheds (Source: Pruneda, 2007).

4.4 Decision Support Tools

Decision support tools are computer based applications that use hydrologic, geologic, geographic information to indicate the risk of streamflow depletion from groundwater pumping. Decision support tools may use a combination of analysis procedures including spatial data analysis with Graphical Information Systems (GIS), statistical analyses of hydrologic information, and analytical models. The goal is assist managers in making decisions that involve complex and dynamic hydrologic systems, such as groundwater licensing decisions, drought declaration and water restrictions, and allocation of monitoring resources.

An example of a decision support tool for streamflow depletion is the 'stream vulnerability assessment framework' developed by Middleton and Allen (2016). This tool provides water managers with a systematic multistep approach for assessing the risks associated with groundwater withdrawals on streams. The framework involves three levels of assessment (Figure 50).

A Level I Assessment is a broad regional scale screening to identify stream-aquifer systems that are potentially vulnerable to impacts from groundwater withdrawal. This is a qualitative analysis using

readily available GIS based information for hydrologic systems, aquifer type and characteristics, groundwater productivity, and groundwater demand. The result of the screening analysis is a stream vulnerability ranking of low, medium, or high based on conservative assumptions. A Level II Assessment is triggered for those stream segments identified with a medium or high risk level.
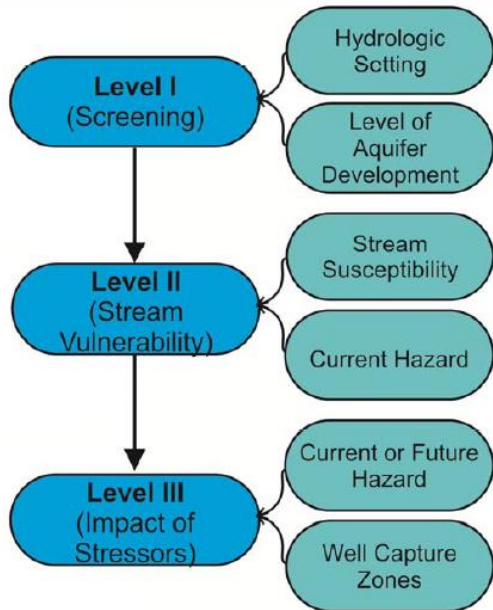
Figure 50   Stream Vulnerability Assessment Framework for Decision Support (Source: Middleton and Allen, 2016).

	Fishtrap Creek	Bertrand Creek	Kettle River	Daves Creek	Mission Creek	Fulford Creek	Cowichan River		Kiskatinaw River
							Aquifer 179	Aquifer 186	
Aquifer #	015	015	158	473	461	722-723	179	186	593
Type	4A	4A	1B	6B	4B	6B	1B	IA	5A
Aquifer Characteristics Rating (A)	8	8	10	3	4	3	10	10	3
Precipitation (mm/yr)[a]	1619.5	1619.5	552.7	313	414.82	997.7	1379.1	1379.1	468.6
PET (mm/yr)[b]	479.5	478.5	579.3	313	538.3	424.1	499	499	355.1
Recharge (mm/yr)[c]	1563.3	1518.3	445.2	566.9	326.3	941.8	1305.2	1305.2	392.2
Area of watershed/aquifer (km²)	37.0	51.0	38.8	37.2	15.1	21.1	7.6	16.9	1150
Q_R (m³/yr) *10⁶	57.8	77.4	17.3	21.1	4.93	19.9	9.9	22.1	45000
Q_S (m³/yr)[d] *10⁶	1.80	0.29	401.	.88	34.8	4.65	683.	683.	14700
Q_s/Q_R	0.031	0.004	23.214	0.042	7.063	0.234	68.854	30.964	0.327
Recharge Ratio Rating (Q_S/Q_R)	6	7	3	6	4	5	3	3	5
Stream Susceptibility (SS)	48	56	30	18	16	15	30	30	15
Q_P(m³/yr) *10⁶	240.	122.	200	128	6.42	8.78	3.54	308	3.56
n (number of wells)	856	828	611	188	57	204	62	222	163
Q_P/Q_R	4.15	1.58	11.58	6.07	1.30	0.44	0.36	13.96	0.01
Hazard Rating (H)	8	8	10	8	8	4	2	10	1
Stream Vulnerability (SV)	High	High	High	High	High	Low	Low	High	Low

Figure 51   Level II Assessment results for nine stream-reaches in B.C. (Source: Middleton and Allen, 2016).

A Level II Assessment is a semi-quantitative analysis that rates the vulnerability of the stream relative to other streams. This analysis uses available information about the aquifer and hydrologic properties (aquifer type, recharge and water budget estimates) to calculate a numeric score for stream susceptibility (SS) and a hazard rating (H) that quantifies the stressors on the aquifer system from pumping. The product of the stream susceptibility score(SS) and the hazard rating (H) defines the overall stream vulnerability (SV), which is ranked as low, medium, or high. A level III Assessment is triggered for stream reaches with a high risk for stream vulnerability. Figure 51 shows example results of Level II Assessments for nine stream segments.
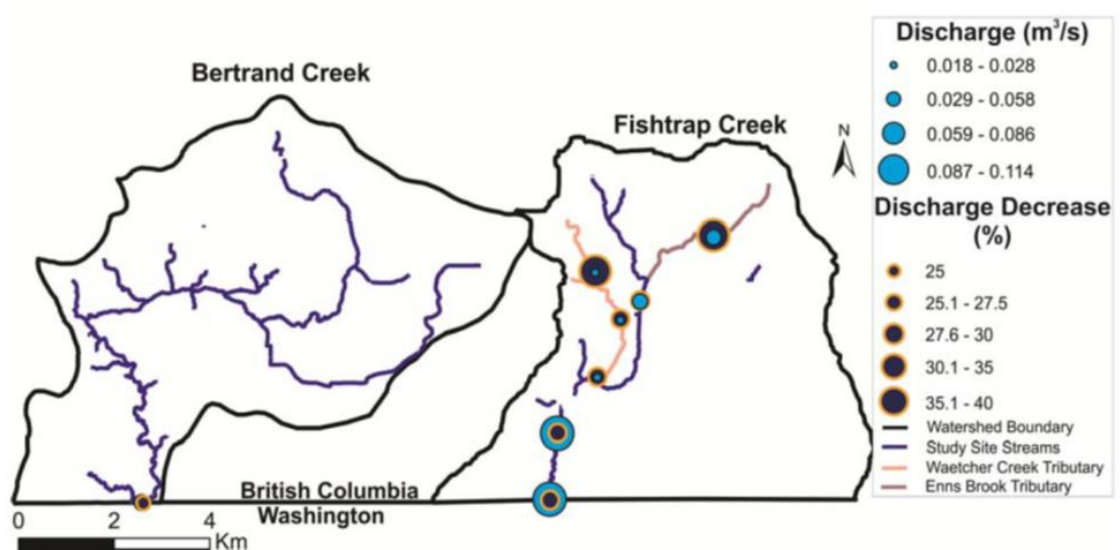
Figure 52   Level III Assessment results for Fishtrap Creek (Source: Middleton and Allen, 2016).

A Level III Assessment is a site-specific analysis for those areas identified with high vulnerability in the Level II Assessment. It uses detailed site-specific information to quantify likely impacts on a stream from stresses on the aquifer, such as from groundwater pumping or land use changes in recharge areas. The intent is to provide decision support for specific management actions such a groundwater licensing and allocation, drought preparedness, water use curtailment, and development approvals. Figure 52 illustrate results from Level III Assessment for Fishtrap Creek. A combination of groundwater modelling and field measurements indicates groundwater pumping impacts streamflow, with greatest impacts to ephemeral reaches. Moreover, field measurements also suggest that reduced groundwater discharge will also affect buffering of high summer stream temperatures. Collectively, the results can support local water management decisions and water license applications.

4.5 Apportioning Streamflow Depletion Among Neighboring Watersheds

Groundwater diversions potentially intercept groundwater flow to different stream segments and neighboring watersheds. Moreover, the distribution of streamflow depletion can be widespread depending on the well location relative to the stream segments and the hydrogeologic conditions. In particular, wells pumping below semi-confining aquitards create a wider distribution of surface water depletion, potentially affecting both local and regional systems (Morgan & Jones, 1999).

When evaluating groundwater license applications in a gaining stream system, water managers must consider the impacts of groundwater diversions on streamflow. However, due to the complex nature of the SW-GW interactions, it is difficult to assess and quantify the distribution of surface water depletion caused by groundwater diversions. The simplest approach is to treat the groundwater diversion as a surface water withdrawal and to assign this withdrawal to the stream segment closest to the well.

However, this is not realistic as it ignores the potential impacts to EFNs and surface water rights holders in the adjacent watersheds.   Alternatively, numerical flow models provide a more accurate and rigorous approach, such as modelling studies of Puget Sound lowlands (Morgan & Jones, 1999). However, use of calibrated flow models is generally not practical, as numerical models are not available for much of the province and they require expertise and training to develop and use.

Reeves et al. (2009) investigated simpler approaches for apportioning the distribution of streamflow depletion among neighboring watersheds. They evaluated nine different methods for apportioning estimates of streamflow depletion calculated from the analytical model of Hunt (1999). The apportionment methods included distance-weighting, transmissivity-weighting, natural neighbor weighting using Theissen polygons, buffer zone methods, and no weighting.

Reeves et al. (2009) evaluated the accuracy of apportionment methods by comparing response functions of streamflow depletion, which are contour plots of estimated streamflow depletion.   Figure 53(left) shows the response function calculated with a transient numerical model that accounts for streamflow depletion in neighboring watersheds.   Because the numerical model accounts for spatial complexity, this plot is considered the best estimate for streamflow depletion distribution. The plot shows the greatest streamflow depletion is concentrated at wells closest to the stream, while low levels of streamflow depletion occur from wells located near boundaries at the top of the watershed.
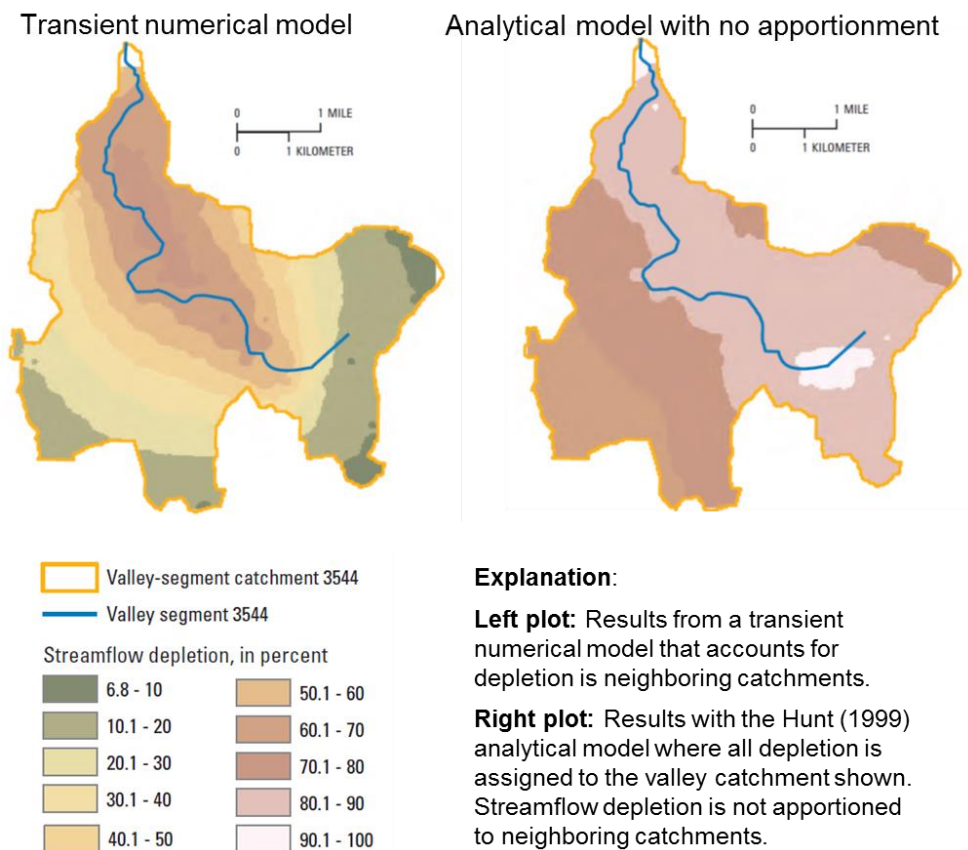
Figure 53   Streamflow depletion response functions for a valley catchment at time = 5 years (Source: Reeves et al. 2009).

The adjacent plot in Figure 53(right) shows the response function calculated with the analytical model of Hunt (1999). The analytical solution overestimates streamflow depletion in comparison to the numerical solution because this model assigns all depletion to the valley catchment containing the well,

neglecting impacts on streams in neighboring catchments. These differences highlight the importance of apportioning streamflow depletion among neighboring catchments.

Figure 54 shows the depletion response functions where solutions from the analytical model were apportioned to neighboring catchments. This figure presents three apportionment methods (Plots B, C, and D) that exhibited the best agreement to the numerical solution (Plot A). Apportioning the streamflow depletion estimates between neighboring catchment provides an improved match with the numerical solution (Plot A) in comparison to the case with no apportionment (Figure 53, right). However, none of the results in Figure 54 was clearly superior in terms of matching the numerical results. Each of three apportionment methods had areas of close agreement and poor agreement in comparison to the numerical solutions, and none produced a statistically significant difference in error characteristics. Reeves et al. (2009) selected the inverse distance method for application in the Michigan Screening tool because it produced a reasonable overall pattern of streamflow depletion compared with the numerical results, and because it is the most straightforward to implement.

Streamflow depletion, in percent

Color	Range	Color	Range
	4.6 - 10		50.1 - 60
	10.1 - 20		60.1 - 70
	20.1 - 30		70.1 - 80
	30.1 - 40		80.1 - 90
	40.1 - 50		90.1 - 100

Explanation:
A) Results from a transient numerical model that accounts for depletion is neighboring catchments.

Solutions with the analytical model where depletion is apportioned to neighboring catchments using:
B) Inverse distance weighting,
C) Inverse distance squared weighting, and
D) Natural neighbor weighting using Theissen polygons

Figure 54 Comparison of streamflow depletion response functions using alternative methods for apportioning streamflow depletion to neighboring catchments (Source: Reeves et al. 2009).

4.6   Regulatory Approaches and Guidance for Assessing Streamflow Depletion

This section presents a survey of regulatory approaches for assessing streamflow depletion in context of groundwater allocation. This survey is not comprehensive as the intent was simply to understand some the strategies and approaches of various jurisdictions. Information on assessment procedures was sometimes difficult to locate, as many jurisdictions apparently have not formalized their procedures, may rely on applicants or proponents to assess streamflow depletion, or they have not yet developed policy statements or guidance documents detailing acceptable procedures and review criteria.

4.6.1   Canadian Regulations and Guidance

A recent report by the Expert Panel on Groundwater on the sustainable management of groundwater in Canada includes five groundwater sustainability goals. One of the goals is the protection of ecosystem viability, which reads: "sustainability requires that groundwater withdrawals do not significantly impinge on the contribution of groundwater to surface water supplies and the support of ecosystems" (Council of Canadian Academies, 2009). It was not within the scope of the report to provide specific guidance on how to assess surface water depletion. Instead, the report offers the following general considerations:

- **Assessment of ecosystem vulnerability to groundwater withdrawal is difficult:** "An assessment of groundwater discharge requirements for ecosystem viability must ensure that relevant surface-water features are incorporated into the groundwater understanding when estimating the discharge of groundwater to surface-water bodies, and that the needs and 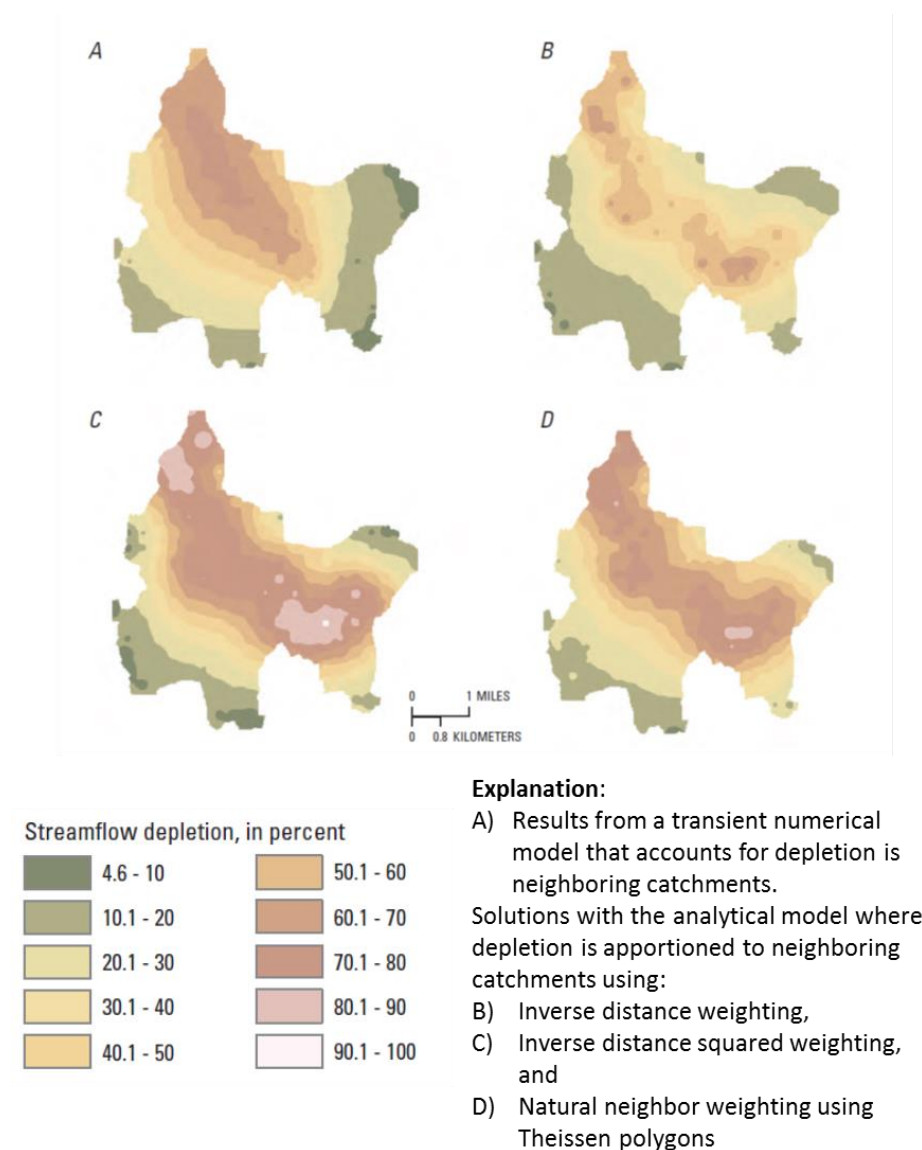vulnerabilities of the aquatic ecosystem are understood. Both of these tasks are technically difficult, making the determination of an acceptable change in groundwater level a major conceptual and measurement challenge."
- **There is no standard assessment approach:** "The most common way for regulators to limit the environmental impact of groundwater withdrawals is through the design of criteria for issuing a groundwater licence or permit. These criteria, however, may reflect only a limited consideration of cumulative impacts and ecosystem protection. There is, to date, no standard methodology for incorporating instream-flow protection into laws and regulations, although a number of provinces are examining ways to address this gap."
- **Iterative or adaptive assessment is prudent: "**Management actions with regard to instream flows may need to be iterative; that is, initially allowing a partial allocation of a proposed groundwater extraction, with follow-up ecological monitoring and evaluation before making modifications to the management decision, consistent with adaptive management principles. This would better account for the slow response time for some groundwater systems and the uncertainty in isolating ecological responses."
- **Expand use of modelling tools in groundwater allocations:** "In most provinces, the use of models by regulatory agencies lags behind state-of-the-art application. Thus, as provincial authorities increasingly seek sustainable groundwater allocation strategies, there is a need to improve their capacity to employ basin-scale groundwater management models."

Other reports voice similar findings on the importance and difficulties of integrating SW-GW management. Recently the Canadian Council of Ministers of the Environment (CCME) reported the results of a survey of Canadian groundwater regulators, consultants, researchers and users with respect to knowledge and knowledge gaps of groundwater in the country (CCME, 2010). Findings included:

> "Uncertainties related to groundwater/surface water interactions were raised as one of the most common understanding gaps, particularly in the context of aquifer sustainability analysis. A lack of stream flow data, knowledge concerning in-stream spatial and temporal flow needs, particularly for maintenance of viable aquatic habitat, and lack of information concerning the

processes related to groundwater/surface water interactions themselves, including the characteristics of the hyporheic zone were identified."

"The use of an in-stream flow needs evaluation in groundwater assessments and the use of groundwater information as part of decisions pertaining to the support of ecosystems and stream flow are limited. Respondents were unsure of what was expected by regulators to demonstrate that there is no significant impact to base flow as all groundwater withdrawals will result in an impact of some kind."

A 2005 study on the state of groundwater management in Canada (Nowlan, 2005) states:

"…the lack of detailed data and information severely hinder the application of best water management practices, in particular practices for water takings and interactions between surface water, groundwater, and aquatic and terrestrial habitats. The limited current knowledge is the main obstacle to improving groundwater regulation."

"Challenges for improved groundwater management include the need to develop better combined GW/SW models and regional-scale indicators of groundwater conditions. In addition to both water resources, aquatic and terrestrial habitats should be examined when dealing with the sustainable use of groundwater as water takings increase."

British Columbia

While the regulation of diversion and use of groundwater in B.C. is new and evolving, it is important to note that hydraulic connection between sources, such as a stream and an aquifer, is recognized in relation to precedence of water rights (e.g., see section 22 of the WSA) and consideration of environmental flow needs of a stream (section 15 of the WSA). The Province of British Columbia (2016a) has also published technical guidance on determining the likelihood of hydraulic connection of an aquifer to a stream and preliminary methods of assigning the fraction demand of groundwater pumping on adjacent streams.

Alberta

The province of Alberta requires a licence for all diversion and use of non-saline groundwater (Alberta Environment, 2011). Applications for groundwater withdrawal greater than 10 m^3/day must also submit a detailed groundwater evaluation report that shall include consideration of long and short-term impacts from pumping on the environment, including impacts to:

- Local sub-basins with sensitive water bodies (i.e., small ratio of contributing area to surface area) or rare biota to be specifically identified and protected.
- Areas adjacent to protected wetlands or "special places" specifically identified and evaluated as sensitive areas.
- Evaluation of effects caused by increased groundwater recharge needed in recharge dominated flow systems or for drought sensitive local water bodies.
- Changes in water quality as a result of the diversion (e.g., increased metal mobility, anaerobic/aerobic changes, salinity increase, etc.).

All projects in sand and gravel deposits adjacent to a water body (river, stream, lake, etc.) are evaluated according to procedures for licensing and approval of surface water works and diversions (Appendix 5, Alberta Environment, 2011). Thus, the province does not specifically evaluate streamflow depletion from pumping, but rather assumes groundwater is fully connected to the stream and all groundwater withdrawals result in an equivalent surface water diversion. The policy does not appear to provide allowances for distance from the stream, the nature of aquifer/stream interactions, or intermediate levels of streamflow depletion due to return flows. Rather the policy places the onus on the applicant

to disprove any streamflow depletion, stating: "the groundwater evaluation guidelines are applicable only if the applicant can prove no hydraulic connection between the sand and gravel deposits and the water body."

Ontario

Ontario requires a Permit to Take Water (PTTW) for surface and groundwater withdrawals greater than 50 m^3/day (Province of Ontario, 2007). There are three categories of groundwater takings: permit renewals (category 1 applications), short-term pumping wells (category 2 applications), and all other wells (category 3). Category 3 and some category 2 applications require hydrogeological investigations by qualified professionals, which must include consideration of the protection of natural ecosystem functions, water availability, and water use. Procedures for assessing streamflow depletion impacts are described in a technical guidance document (Province of Ontario, 2008). However, the guidance does not include prescriptive quantitative procedures for assessing streamflow depletion; rather it outlines the following general steps:

- **Step 1: Evaluate System Isolation:** Consider whether identified surface water features are isolated from the aquifer from which water will be taken. For example, if the aquifer is deep and confined, it is unlikely that pumping water from the aquifer will have measurable impacts on the identified surface water features. System isolation needs to be assessed in the context of the magnitude of the water taking. Large, on-going takings have greater potential to induce unacceptable amounts of leakage through an aquitard compared to small and intermittent takings. If system isolation can be demonstrated, then there is no need to proceed with step 2.
- **Step 2: Assess Potential Impacts to Surface Water:** Predict how the proposed groundwater taking may change ground water flux into the surface water features within the study area. To reduce the uncertainty commonly associated with groundwater-surface water interactions, the use of tracer tests, isotope analysis or installation and monitoring of streambed mini-piezometers and/or near-shore piezometers during pumping tests is encouraged. Additional surface water field studies are likely required if one or more of the following risk factors apply
    - (i) groundwater flux to any surface water feature is predicted to decrease by more than 10% in the zone of influence or 50,000 liters/day, whichever is greater; OR
    - (ii) the maximum predicted reduction of ground water discharge to any 1st or 2nd order river/stream is less than 50,000 liters/day but may exceed 10% of flow at any time (based on conservative calculations or on direct measurements during the taking); OR
    - (iii) the maximum predicted amount of stream depletion in a 3rd or higher order river/stream is greater than 5% of 7Q20 (seven day mean low flow with a recurrence interval of twenty years); OR
    - (iv) groundwater is discharging into a known fish spawning area.

    If the proposed taking is predicted to stay approximately within the limits outlined above within a reasonable degree of uncertainty, and there is an insignificant risk of unacceptable impacts to the natural functions of the ecosystem in the connected water bodies, then there is no need to proceed to Step 3.
- **Step 3: Hydro-ecological Study:** Where the study indicates the proposed taking may cause significant changes in the amount of groundwater flowing between the hydrostratigraphic unit and connected surface water, more detailed field studies performed by Qualified Person(s) with expertise in surface water hydrology and aquatic ecology or biology may be required..

Like Alberta, Ontario places the onus of quantifying streamflow depletion on the applicant. Moreover, the technical guidance is comprehensive and potentially mandates detailed field studies, particularly for shallow unconfined aquifers where surface connections are likely.

Prince Edward Island

For all other areas, the province uses two-step approach to groundwater permitting and assessment of groundwater withdrawals. The province first requires a "Groundwater Exploration Permit" for all proposed high-capacity groundwater wells in excess of 327 m^3/day (50 imperial gallons per minute). The department issues the permit following satisfactory review and confirmation that groundwater exploration will not cause significant impacts on existing groundwater users or the environment. The applicant is required to submit a hydrogeology report detailing the well construction, pumping test, interpretive reports, or other information specified as conditions of the permit. Upon follow-up review, the department issues a groundwater extraction permit if the "test information reveals that the extraction of additional water will not have a significant impact on other groundwater users or the environment."

The province of PEI recently modified its review criteria for assessing impacts of groundwater withdrawal in order to improve protection of ecosystem health (Province of Prince Edward Island, 2013). The policy limits cumulative surface and groundwater states groundwater diversions should not reduce summer baseflow (from August to September) by more than 35 percent. In addition, new groundwater withdrawal applications are initially screened by the proposed pumping rate as a percentage of Normalized Reference Base Flow (NRBF), which has been established individually for each watershed. Based on this screening, regulators pursue one of following three actions:

1. **Proposed groundwater withdrawal is less than 30% of the NRBF:** Groundwater withdrawal is not anticipated to cause significant impacts on streamflow. A groundwater exploration permit is issued and upon satisfactory review of test data and reports, an extraction permit is granted.
2. **Proposed groundwater withdrawal is between 30 to 100% of the NRBF:** Groundwater withdrawal is anticipated to cause significant impacts on streamflow. A conditional groundwater exploration permit is issued that includes specific requirements for a detailed investigation. Depending on review of test data and reports, an extraction permit may be granted.
3. **Proposed groundwater withdrawal is greater than 100% of the NRBF**: Groundwater withdrawal is likely to deplete streamflow below the threshold criteria. The application for groundwater exploration is rejected.

The groundwater policy implicitly assumes stream-aquifer connections, and that streamflow depletion is roughly equal or somewhat less than the groundwater pumping rate. The policy also places responsibility of assessing streamflow impacts on the applicant, similar to other provinces.

Saskatchewan

Similar to PEI, the province of Saskatchewan uses a two-step process for groundwater licensing and assessment of associated ecological impacts, and also places the onus of assessing streamflow depletion on the applicant. The first step is to obtain a "Groundwater Investigation Permit", conduct the investigation, and submit a detailed investigation report to the Water Security Agency. The agency then evaluates the groundwater investigation to "determine if diversion of the requested amount of water will result in negative impacts to existing water users, the watershed, or future water management. And, where necessary, apply mitigation measures or operating conditions to manage or prevent such impacts." Upon satisfactory review, the Water Security Agency issues a water rights licence and an approval to construct and operate works.

4.6.2   U.S. Regulations and Guidance

Rhode Island

The state of Rhode Island Streamflow Depletion Methodology establishes the allowable streamflow diversion as either a direct withdrawal from the stream, or an indirect withdrawal due to groundwater pumping (RIDEM, 2010). Allowable streamflow depletion is determined on a watershed basis taking into account in-stream flow needs, a watershed index, and seasonality. The effect of groundwater withdrawals on streamflow depletion may be calculated in three ways:

1. Assume a 1:1 correspondence between groundwater withdrawal and streamflow depletion;
2. Use the Jenkins (1968) approach, which combines the Glover Model and superposition principle to account for variable pumping; and
3. Use established groundwater flow models (MODFLOW) where available.

In reviewing groundwater withdrawal applications (above 10,000 gpd – 38 m^3/day) regulators evaluate a net effect on streamflow depletion by considering the site-specific conditions and return flows, for example groundwater recharge from septic leach fields. In this way, the methodology is flexible and adaptable to different levels of data availability, site conditions, and watershed sensitivity.

New Jersey

The New Jersey Department of Environmental Quality has taken a simplified approach for quantifying streamflow depletion from groundwater pumping. They simply assume 90% of all groundwater withdrawals from unconfined aquifers are compensated by streamflow depletion. This approach is based on review of direct streamflow measurements and modelling studies that show a decrease in streamflow ranging between 60% and 100% (Canace & Hoffman, 2009). Thus, the 90% rule is considered reasonable and conservative.

Michigan

The state of Michigan prohibits high-capacity groundwater withdrawals (100,000 gpd – 380 m^3/day) from causing detrimental impacts to surface waters. The regulatory framework includes a screening process to help focus agency review on systems with a higher potential for adverse impacts. Applicants for new or increased withdrawals are required to assess the potential for adverse impacts to surface waters with an on-line screening tool called the Michigan Water Withdrawal Assessment Tool (Hamilton & Seelbach, 2011). The groundwater component of this screening tool uses the modified Hunt model as detailed in the report by Reeves et al. (2009).

Output from the screening tool includes the classification of groundwater withdrawals into risk based management zones identified from A through D. This ranking takes into consideration the habitat and stream conditions of the surface waters. Zone A has little risk of causing an adverse resource impact, while Zone D means an adverse resource impact would likely occur in the stream. Groundwater withdrawals in Zone A and in most cases Zone B can proceed with registration with no additional agency review. Proposed withdrawals in Zones C and D is likely to be referred for additional agency review.

Colorado

The state of Colorado strongly regulates surface and groundwater rights, which follows a long history of the first in time, first in right (FITFIR) prior appropriation doctrine (CDNR, 2012). A permit is required for construction of all water wells. All water wells require appropriation of water rights, with exemption for single lot household and small domestic wells in areas where surface water is not over-appropriated.

There appears to be no defined process for assessing streamflow depletion by groundwater pumping. Rather the state places responsibility for demonstrating adequate water supplies squarely on the

applicant, who must show groundwater withdrawals do not cause injury to other well owners and senior water rights holders, including surface water rights. In addition, there are several designated groundwater basins where water rights are over-allocated. Any new application for groundwater withdrawals in these basins requires approval of an augmentation plan to replace groundwater withdrawals. This is only achievable through the retirement of senior water rights and/or identification of new water sources, such as water banking.

Washington

Washington State also has a well-developed regulatory structure for governing surface and groundwater rights based on the FITFIR doctrine. All new applications for non-exempt groundwater withdrawals must demonstrate the availability of water supplies, taking into account senior water rights and EFNs. Environmental flows are protected through the Instream Resources Protection Program, which states:

> "Perennial rivers and streams of the state shall be retained with base flows necessary to provide for preservation of wildlife, fish, scenic, aesthetic and other environmental values, and navigational values" (WAC 173-501-020).

Environmental flows are also protected from groundwater withdrawals as stated by:

> "If department investigations determine that there is significant hydraulic continuity between surface water and the proposed groundwater source, any water right permit or certificate issued shall be subject to the same conditions as affected surface waters. If department investigations determine that withdrawal of groundwater from the source aquifers would not interfere with stream flow during the period of stream closure or with maintenance of minimum instream flows, then applications to appropriate public groundwaters may be approved" (WAC 173-501-060).

In-stream flow requirements are explicitly defined for all major channels and their larger tributaries in the Washington Administrative Code (WAC). However, like Colorado, there does not appear to be a formal process for assessing streamflow depletion from pumping. Rather there appears to be informal case-by-case assessment that occurs during consultation, pre-application, or the application process. The onus is on the applicant to demonstrate water availability and use, and to comply with any availability restrictions.

To help applicants understand and evaluate the availability of surface and groundwater resources, the Department of Ecology has developed a comprehensive water resources inventory assessable on-line. A total of 62 Water Resources Inventory Areas (WRIA's) are defined throughout the state. Each WRIA has an accompanying fact sheet that details the current uses and demands on water resources, and the availability of water for new uses, including a listing of surface and groundwater closures and restrictions.

New Mexico:

DuMars and Minier (2004) present an interesting study that documents the evolution of modelling tools in groundwater allocation using the Rio Grande in New Mexico as a case study. Streamflow in the Rio Grande is fully allocated and a certain quantity of flow must be retained in the river to meet international treaty requirements with Mexico. The city of Albuquerque draws groundwater for municipal supply from the Albuquerque basin, which is hydraulically connected to the Rio Grande. Surface and groundwater are administered by a prior appropriation (FITFIR) doctrine, and the city's wells are junior to surface water rights including treaty obligations. The New Mexico State Engineer regulates groundwater in the basin, and must balance the rights of the senior holders and the City's need to meet municipal water supply.

Various quantitative tools have been used to guide groundwater allocation in the Albuquerque basin. In 1957, the State Engineer denied the City's request for proposed groundwater pumping based on analyses with Darcy's law that showed the basin was hydraulically connected to the river and pumping would deplete streamflow. The Theis equation (Theis, 1941) was used to quantify the projected amount of streamflow depletion, and the City was required to retire an equivalent amount of surface water licences. However, the City refused to comply. The case was resolved in the State Supreme Court in 1963, which agreed with the State Engineer. This established for the first time a principle of coordinated groundwater and surface water management.

The State Engineer initially used the Glover model to quantify the effects of pumping on streamflow depletion beginning in the late 1950's. However, the Glover model (Glover & Balmer, 1954) overestimated the rate of streamflow depletion, which prompted the State Engineer to use numerical models to improve predictions. The first model was a steady-state model developed in the mid 1980's. However, the inability to account for time-dependent streamflow depletion limited the application of this model. A transient model developed in the early 1990s provided a more realistic estimation of streamflow depletion. Still, this model has undergone several revisions in the 1990s and 2000s to incorporate additional hydrogeologic information. After more than 20 years of development, there is still some uncertainty in the numerical model predictions and disagreement in predictions from different available models.

To address uncertainty in the numerical models, the State Engineer does not use the models to quantify the amount of surface water offsets the user must obtain. Instead, the State Engineer limits new groundwater rights to the amount of surface water rights held by the applicant, and there are additional conditions placed on the licence to protect senior water rights. The models are mainly used to assess well interference impacts and to evaluate the timing and magnitude of streamflow depletion.

4.6.3   International Regulations and Guidance

New Zealand

Bekesi and Hodges (2006) describe development of groundwater allocation policies based on a regulatory buffer zone adjacent to streams that have groundwater dependent ecosystems (GDE). Additional regulatory requirements and conditions are mandated for proposed groundwater withdrawals that fall within the regulatory buffer zone, called the GDE interference zone. These conditions include the collection of site-specific data to demonstrate withdrawals do not affect the GDE. This regulatory approach was developed as an interim policy for over-allocated basins where surface and groundwater rights are administered separately. The intent is to protect GDE's until more integrated approaches are developed, such as basin wide numerical models for conjunctive management of surface and groundwater resources.

The GDE interference zone has a variable distance from the stream as a function of the pumping rate (Figure 55). For example, a well with a proposed pumping rate and distance from the stream that falls below the curve in Figure 55 is within the GDE interference zone, and thus triggers additional regulatory requirements. Bekesi and Hodges (2006) use analytical solutions from the Glover model (Glover & Balmer, 1954) to calculate the GDE interference zone. The solution procedure employs a Monte Carlo Probabilistic approach to account for uncertainties in the aquifer properties. In addition, the solution procedure requires regulators to specify of a threshold streamflow depletion, which is the allowable impact to streamflow depletion occurring within a certain timeframe. For example, Bekesi and Hodges (2006) used a depletion threshold of 5 L/s after 30 days as the defining criteria for GDE interference zone. The depletion threshold is arbitrary and adjustable to meet local needs and risks. However, the

threshold criterion is specified on a per well basis and must be adjusted to account for cumulative effects from multiple wells within a groundwater basin.
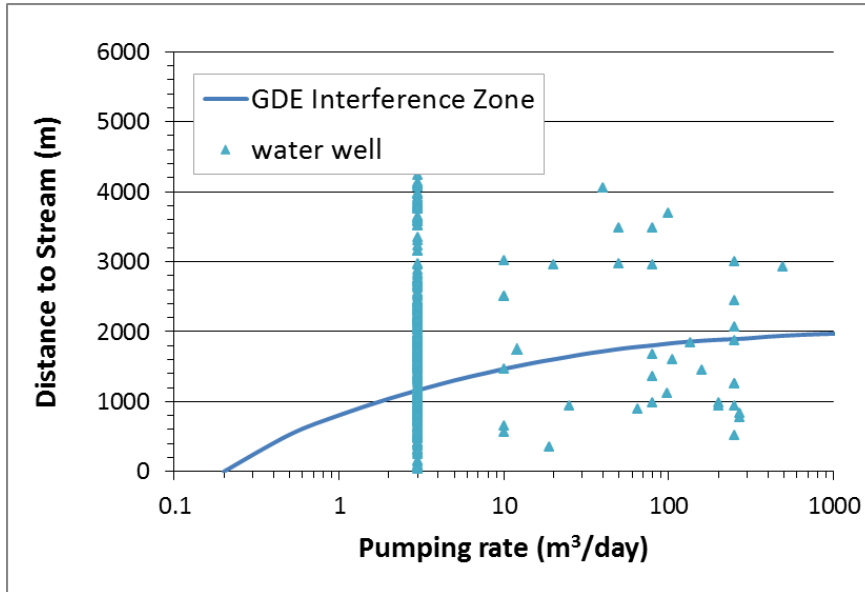

Figure 55   GDE Interference zone concept for groundwater rights allocation (after Bekesi and Hodges. 2006).

Australia

The Australia government has developed a comprehensive and logical framework for adaptive and conjunctive management of surface and groundwater resources (Brodie, et al., 2007). The principles described in this framework are fundamental and comprehensive in nature, and are broadly applicable to any SW-GW system. The goals of the Australian framework include:

- Provide a consistent national approach to conjunctive water management in Australia
- promote decision-making based on an understanding of both hydrological and hydrogeological characteristics of a catchment;
- Provide a common understanding of groundwater-surface water connectivity;
- Raise awareness of the value of numerical models and other predictive tools in setting management targets and options; and
- promote the coordinated monitoring of groundwater and surface water resources

The Australian framework is underpinned by guiding principles that were developed through consensus by national experts. The guiding principles for conjunctive water management are:

- Where physically connected, surface water and groundwater should be managed as one resource.
- Water management regimes should assume connectivity between surface water and groundwater unless proven otherwise.
- Water users (groundwater and surface water) should be treated equally.
- Jurisdictional boundaries should not prevent management actions.

Figure 56 shows the elements of the Australian conjunctive management framework, which encompasses a series of management steps.   However, due to inherent uncertainties in characterizing resources and predicting outcomes, the management steps are iterative and adaptive in nature based on feedback from monitoring and performance review.
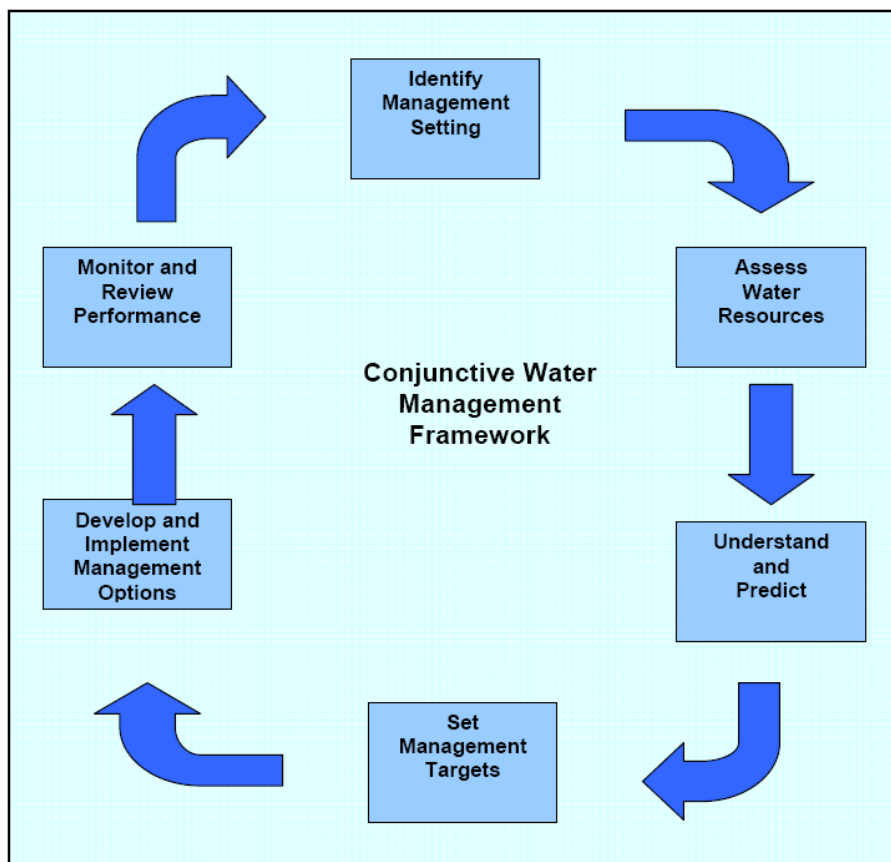
Figure 56   Australian framework for adaptive and conjunctive management of connected GW-SW resources (Source: Brodie et al., 2007).

The report discusses a wide range of analytical and numerical models to support evaluation and prediction of SW-GW interactions, including a comprehensive description of modelling tools and modelling alternatives. In general, analytical models are simplified approaches that can be constrained by assumptions that oversimplify the conceptual model and may not be valid. Analytical models are suited for preliminary investigations and for validating other modelling efforts. Numerical models are better at representing complexities of the system, but are complicated and time consuming to build, and require a robust understanding of the key hydrological processes. When properly constructed and validated, numerical models provide powerful management tools for improving understanding of key hydrological processes, and for assessing impacts of management options.

4.6.4   Summary

Jurisdictions across Canada, the U.S., and elsewhere use a variety of approaches to administer conjunctively SW-GW resources. This reflects the complexity of SW-GW interactions, the regional demands on groundwater resources, the regional importance of groundwater discharges to aquatic habitats, and historical precedents in allocation policies.

Jurisdictions use models of SW-GW interaction mainly as decision support tools. For example, analytical models are used as screening tools in Michigan and New Zealand to help focus agency review of new groundwater pumping permits. Applications that pose a low risk to surface water resources are processed with minimal review, allowing agency resources to be focused on higher risk applications. In only a few cases were jurisdictions found that allowed or described the use of analytical models for assessment of streamflow depletion impacts (Rhode Island, New Mexico, New Zealand).

Many organizations and jurisdictions recognize the potential of numerical models as powerful tools for understanding and assisting in conjunctive management of surface and groundwater resources. However, no jurisdictions were found to use numerical models as management tools to guide policy decisions for groundwater allocation. This likely reflects the intensive time, cost, and data requirements to develop and calibrate numerical models. Even when there is an effort to develop detailed numerical models there may still be enough uncertainty in the model predictions to impede consensus on management policies.

Due to the complexity of SW-GW interactions and the cost and uncertainty of developing detailed numerical models, most jurisdictions take a conservative approach to the conjunctive management of SW-GW resources. This generally entails:

- Assuming all or a very high percentage of groundwater withdrawal is from streamflow depletion, especially when aquifers are strongly connected to surface waters and provide a main source of baseflow. This assumption ignores the time delay response of pumping impacts and sources of groundwater replenishment such as irrigation returns and water banking.
- Using a step-wise or iterative process for groundwater licensing and assessment of associated ecological impacts.
- Placing the onus of disproving the hydraulic connectivity or streamflow depletion impacts on the applicant through requirements for detailed hydrogeologic assessments, detailed ecological impact studies, and/or through an iterative groundwater licensing process.
- Limiting new licences in over-allocated basins by requiring the applicant to possess or retire an equivalent volume of surface water licences (even for exempted uses in some cases).

5. ASSESSING STREAM DEPLETION FROM PUMPING

An evaluation analytical tools was undertaken as a potential means of gaining insights in pumping impacts on streamflow depletion and to support groundwater licensing. Analytical models have advantages in that they are comparatively easier to implement and have manageable data requirements. The evaluation of analytical models encompassed:

- An evaluation of the predictive capabilities of analytical models through comparisons to a solution from an numerical model;
- An evaluation of analytical model solution methodologies; and
- Assessment and guidance for selecting and using analytical models in a variety of aquifer types.

5.1 Analytical Models Selected for Evaluation
ENV selected eight analytical models listed in Table 6 for evaluation as potential screening tools for streamflow depletion. The criteria for selecting these models included:

- Historical and accepted use of the model;
- Ease of use and ability to quantify model parameters;
- Applicability to aquifers found in B.C.; and
- Ability to solve the model equations.

Methods used to evaluate the analytical models are based on three broad criteria:

- **Accuracy:** Do the models provide conservative but reasonable estimates of streamflow depletion volumes? What are the potential errors and their implications.

- **Applicability:** How flexible and adaptable are the models to different aquifer types and aquifer conditions found in B.C.?
- **Implementation:** What is the ease, difficulty, and issues associated with implementing the model solutions? What are the data requirements and data availability?

Table 6   Analytical models selected for evaluation as screening tools for streamflow depletion.

Selected Model	Rationale
Glover model (eq. 1)	Simplest of all models, requires the fewest parameters to implement.
Hantush model (eqs. 4 & 5)	Easy to implement model; accounts for streambed impedance; historical context
Hunt (1999) model (eqs. 6 & 7)	Easy to implement model; accounts for streambed impedance; implicitly accounts for partially penetrating stream conditions; historical context
Singh (2003) model (eqs. 4, 10 & 11)	A simple extension of the Hantush model that explicitly accounts for streambed impedance and partially penetrating stream conditions
Michigan Screening Tool approach (eqs. 6 & 9)	A practical adaption of the Hunt (1999) model that is deployed in a user friendly, internet based tool
Hunt (2008) model	A flexible extension of the Hunt (1999) model for unconfined and semi-confined aquifers of infinite or bounded extent. Many aquifers in B.C. are located in narrow river valleys, and/or may include semi-confined conditions
Hunt (2009) model and model of Ward and Laugh (2011)	These models extend the Hunt (1999) model to include layered aquifer systems where pumping may occur in either the upper or lower aquifer unit. Alluvial aquifers in B.C. can have distinct layered lithology, which can potentially affect streamflow depletion.

5.2 Analytical and Numerical Model Comparisons

In the absence of field measurements, one approach for assessing the accuracy of the analytical models is to compare the analytical solutions against numerical models. The numerical model provides a better representation of the aquifer conditions, as it not constrained to the same degree by simplifying assumptions of the physical system. Thus, model comparisons are relative metrics for gaining insights into the predictability and limitations of the analytical solutions. However, both the analytical and numerical models are approximations and neither model may accurately represent the true aquifer conditions completely. In addition, the comparisons are limited to the modelled conditions of a specific aquifer and do not necessarily extend to other types of aquifers or aquifer conditions.

5.2.1   Grand Forks Groundwater Model

The Grand Forks aquifer is an unconfined alluvial aquifer located in the Kettle River Valley in south central B.C. (Section 3.3.2). The aquifer is highly productive and heavily developed for agricultural and municipal supply. It is among the most economically important aquifers in the province.

Dr. Diana Allen of Simon Frasier University developed a three-dimensional transient groundwater flow model of the Grand Forks aquifer based on the U.S. Geological Survey (USGS) MODFLOW code. It has undergone extensive calibration, testing, and enhancements over a more than 10-year development history. The model is well documented in several reports and applied studies (Allen, 2001; Allen, et al., 2004; Scibek & Allen, 2004a; Scibek, et al., 2007; Wei, et al., 2010). Major features of Grand Forks groundwater model are:

- **Domain and layout:** The model spans an area of about 38 km^2 and has approximately 136,000 active cells (Figure 57). Grid spacing is variable with horizontal spacing ranging from about 12 to 110 m. An extensive analysis of lithology data supported the construction of the

hydrostratigraphic units, which are represented by six model layers in the numerical model (Figure 57). The vertical grid spacing ranges from about 1.5 to 100 m.

- **River-Aquifer Interaction:** The Kettle and Granby rivers are modelled with constant head boundary conditions by assigning a river stage to each of 129 river reaches in layer 1 of the model. For the transient model, the specified river stage can vary in time (i.e., stress periods) in accordance with seasonal changes. Scibek and Allen (2003) used transient hydraulic modelling of the river systems to determine the distribution and seasonal changes in river stage used in the numerical model. By representing the rivers as constant heads, the model is able to capture both gaining and losing river-aquifer interactions. However, this implicitly assumes the river stage is unaffected by flow into or out of the river within any given stress period. In addition, the model assumes there is no streambed impedance, consistent with the prevalence of gravels and lack of fine-grained sediments in the streambed (Scibek & Allen, 2004b).
- **Recharge:** Recharge to the aquifer from precipitation, snowmelt, and irrigation is spatially heterogeneous and time varying. The recharge rates and distribution were determined through extensive modelling using the USEPA HELP model (Scibek & Allen, 2004a).
- **Wells:** The model includes major production wells, such as municipal and irrigation supply wells where information on pumping rates is available. Small domestic wells are not included.
- **Calibrated hydraulic properties:** The aquifer hydraulic properties are uniform in each model layer and have been determined through model calibration to available hydraulic head data. Table 7 shows the calibrated conductivity and specific yield parameters for each model layer.
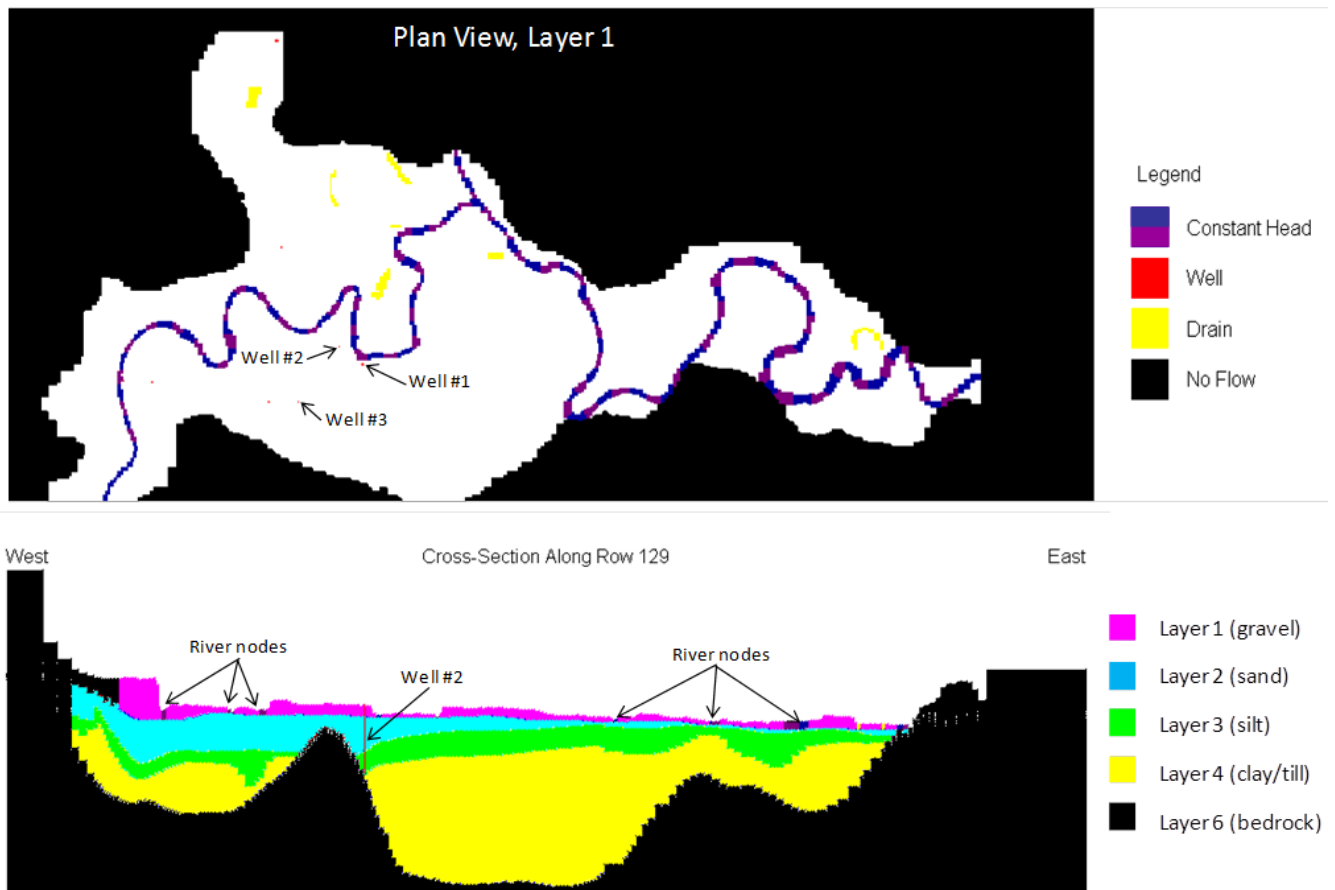

Figure 57   Grand Forks groundwater model domain (note - layer 5 is not visible in the cross-section. It is limited to a small portion of the eastern valley where deeper sand units occur under a thin silt layer).

Table 7   Calibrated aquifer hydraulic properties in the Grand Forks groundwater model.

Layer	Soil Texture	Horizontal Conductivity (K_x ,K_y) (m/day)	Vertical Conductivity (K_z) (m/day)	Specific Yield (S_y) (dimensionless)
1	Gravel	80	30	0.12
2	Sand	20	10	0.12
3	Silt	3	0.5	0.05
4	Clay/Till	0.05	0.01	0.06
5	Deep Sand	20	10	0.12

5.2.2   Simulated Groundwater Pumping Scenarios

Streamflow depletion was simulated for groundwater pumping at three separate well locations shown in Figure 57:

- Location 1: A shallow well (3 m) constructed in close proximity to the river (50 m).
- Location 2: A deeper well (48 m) screened in less permeable sands and located moderately close to the river (167 m).
- Location 3: A shallow (5 m) high capacity well located at a large distance from the river (868 m).

Two pumping conditions were tested:

- Continuous pumping: A constant and continuous pumping rate applied over a total simulation period of 730 days (2 years). The modelled pumping rates are 200 gpm (1090 m3/day) at locations 1 and 2, and 680 gpm (3708 m3/day) at location 3.
- Seasonal pumping: A two-step seasonal pumping schedule: 1) constant pumping rates listed above applied for a period of 65 days, followed by 2) a recovery period with no pumping for 300 days. We modelled two cycles of seasonal pumping for a total simulation period of 730 days.

5.2.3   Numerical and Analytical Model Implementation Methods

Application of the numerical groundwater model for quantifying impacts of streamflow depletion with the numerical groundwater flow model:

- Model implementation: Dr. Allen developed the Grand Forks model using Visual MODFLOW, an integrated modelling package that links the USGS MODFLOW routines to flexible pre- and post-processors. ENV converted the Visual MODFLOW files into Groundwater Vistas, which is a comparable but different modelling package. During this conversion, ENV verified model parameters against documented values (Scibek & Allen, 2004b). ENV implemented the numerical model in Groundwater Vistas using MODFLOW 2000 and the CG2 system solver. We checked model solutions by visual comparisons to plots in the model documentation, and by mass balance calculations, which were consistently below 1%.
- Transient river stage and recharge: For simplification, ENV did not model seasonal changes in river stage, although these capabilities are in the model. We used a constant river stage representative of late summer stage throughout the transient simulation. This provides a more direct comparison with the analytical solutions, which do not account for variation in river stage. However, this simplification potentially influences the predicted streamflow depletion rate.
- Pumping conditions: For purposes of model comparisons, ENV only simulated pumping at hypothetical test wells (see below); all other pumping in the numerical model were set to zero. This removes the potential effects of well interference from the model comparisons.
- Stream depletion calculation: To quantify stream depletion for a given pumping scenario, we first simulated the model conditions in the absence of pumping, calculating the total river flux in the entire domain for each stress period. Next, the specified pumping conditions were included

in a second model run, again calculating the total river flux in the entire domain for each stress period. The difference in total river flux for the pumped and original model conditions yields the simulated stream depletion due to pumping.

Solutions to analytical models were generated in a spreadsheet format using Microsoft Excel 2007 together with Visual Basic macros developed by Hunt (2012). The following table lists the parameters values and data sources in the analytical solutions.

Table 8   Parameter values used in analytical model solution.

Parameter	Source	Location 1	Location 2	Location 3
Model layer with well screen		2	3	2
Distance to river (m)	Model value	50	167	868
Horizontal hydraulic conductivity (m/d)	Model value	20 (layer 2)	20 (layer 2) 3 (layer 3)	20 (layer 2)
Aquifer thickness (m)	Model value at well node	45 (layer 2)	50 (layer 2) 34 (layer 3)	62 (layer 2)
Transmissivity (m^2/d)	Product of horizontal conductivity and thickness of pumped layer	900 (layer 2)	640 (weighted ave for layers 2,3)	1240 (layer 2)
Specific yield	Model value	0.12 (layer 2)	0.09 (weighted ave for layers 2,3)	0.12 (layer 2)
River width (m)	Google Earth	60	60	50
Streambed thickness (m)	assumed	1	1	1
Streambed Conductivity (m/d)	1/10 vertical conductivity in layer 1 (assumed)	3	3	3
Well screen depth (m)	Model value at well node	3	48	5
Vertical hydraulic conductivity (m/d)	1/10 horizontal conductivity	2 (layer 2)	2 (layer 2)	2 (layer 2)
Total aquifer depth(m)	Model value at well node	170	100	155
Lower or Upper Aquifer properties used in Hunt (2009) and Ward and Laugh (2011)	Model values	Lower aquifer K = 3 m/d b = 33 m T = 100 m^2/d S_y = 0.05	Upper aquifer K = 20 m/d b = 50 T = 1000 m^2/d S_y = 0.12	

5.2.4   Model Comparisons for Pumping Location 1

Figure 58 shows model estimates of streamflow depletion from continuous groundwater withdrawals at location 1. Because the well is shallow and in close proximity to the stream, the analytical models predict a rapid response in streamflow depletion, reaching 90% or more of the pumping rate within 30 to 60 days. In comparison, the numerical solutions show a slower streamflow depletion response, reaching the 90% threshold after about 1½ years of continuous pumping. In comparison to numerical solutions, all analytical models overestimate streamflow depletion at early time, with the differences diminishing as steady state conditions are approached after about two years of pumping.

The Singh (2003) model and the Michigan screening tool produced slightly better comparisons to the numerical solution. These models account for partially penetrating stream and well conditions by incorporating the aquifer depth or well screen depth into the solution.
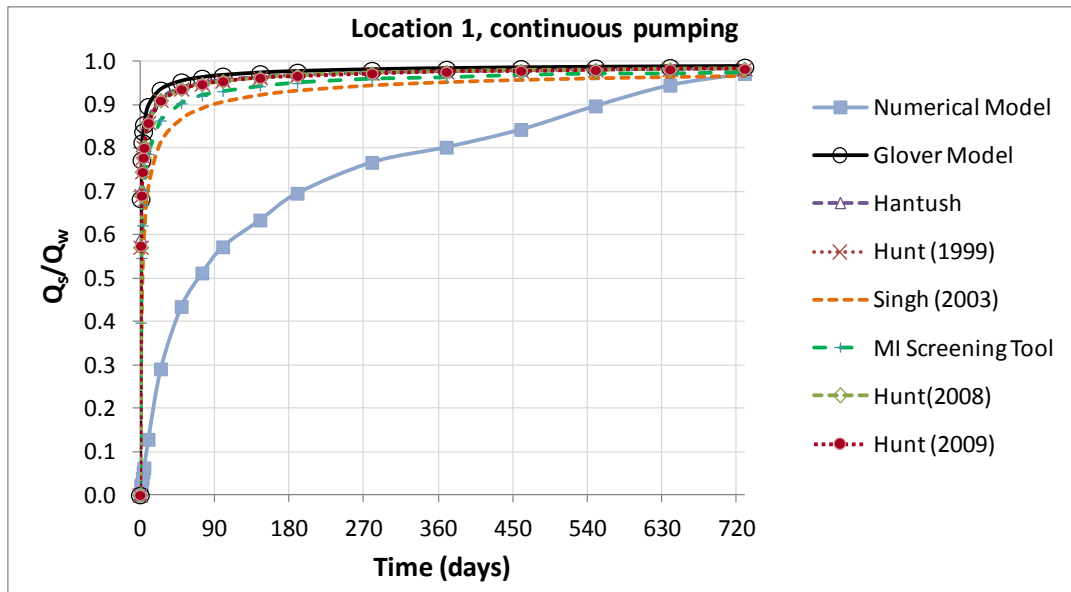
Figure 58   Modelled streamflow depletion from continuous pumping at Location 1.

Interestingly, the layered model of Hunt (2009), which accounts for leakage from underlying aquifer units, did not perform differently than the single layer models. This suggests streamflow is the dominant source of water to the well. Leakage from the underlying silt unit is likely limited by the smaller transmissivity and specific yield of the underlying silt layer, because there was little to no streambed impedance, and because the distance between the well and the stream was small.

Figure 59 shows model results for the case of seasonal groundwater diversion at location 1. Results show poor agreement between numerical and analytical solutions during both the pumping and the non-pumping phases. All analytical models overestimate streamflow depletion during the pumping phase, and underestimate depletion after pumping shutoff.   The analytical models provide conservative estimates of depletion during pumping, but overestimate the rate of streamflow recovery after stoppage of pumping.
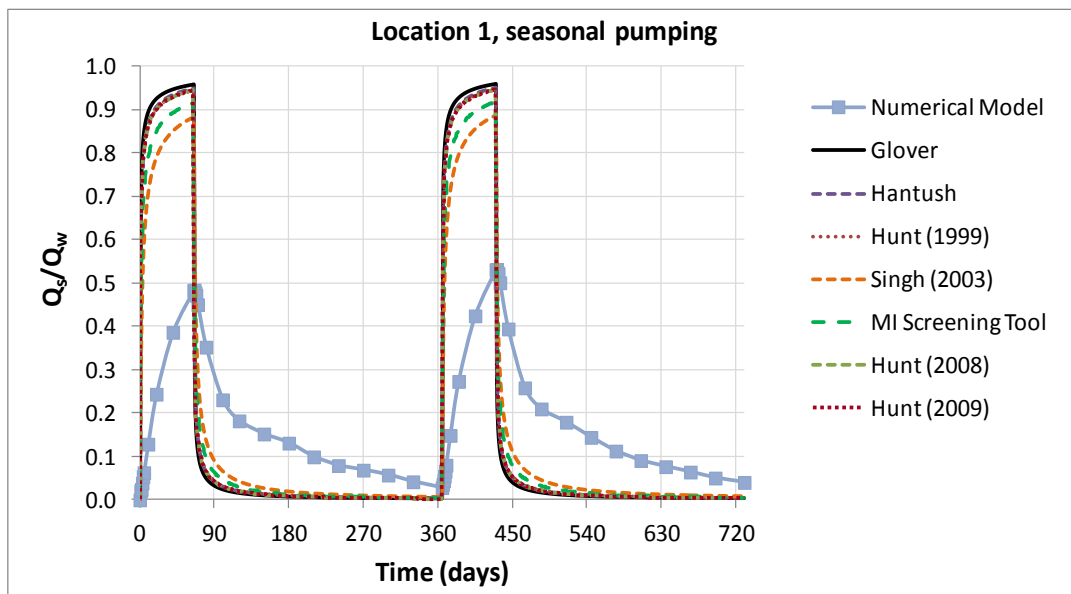

Figure 59   Modelled streamflow depletion from seasonal pumping at Location 1.

5.2.5   Model Comparisons for Pumping Location 2

Model comparisons at location 2 examine the effect of pumping at a lower depth (layer 3) and further from the river, in comparison to location 1.

Figure 60 displays results for the case of continuous groundwater pumping at location 2. The numerical solutions show a streamflow depletion response that is about three times slower than the rate at the shallower and closer well at location 1 (i.e., compare numerical solutions in Figure 58 and Figure 60). Although a lower rate of depletion is consistent with increasing distance and depth from the stream, the overall magnitude of depletion is still substantial, reaching 50% of pumping in about 9 months, and 80% of pumping is about 2 years. Groundwater pumping at location 2 delays the impacts on streamflow, but does not significantly reduce the impacts within the modelled timeframe.
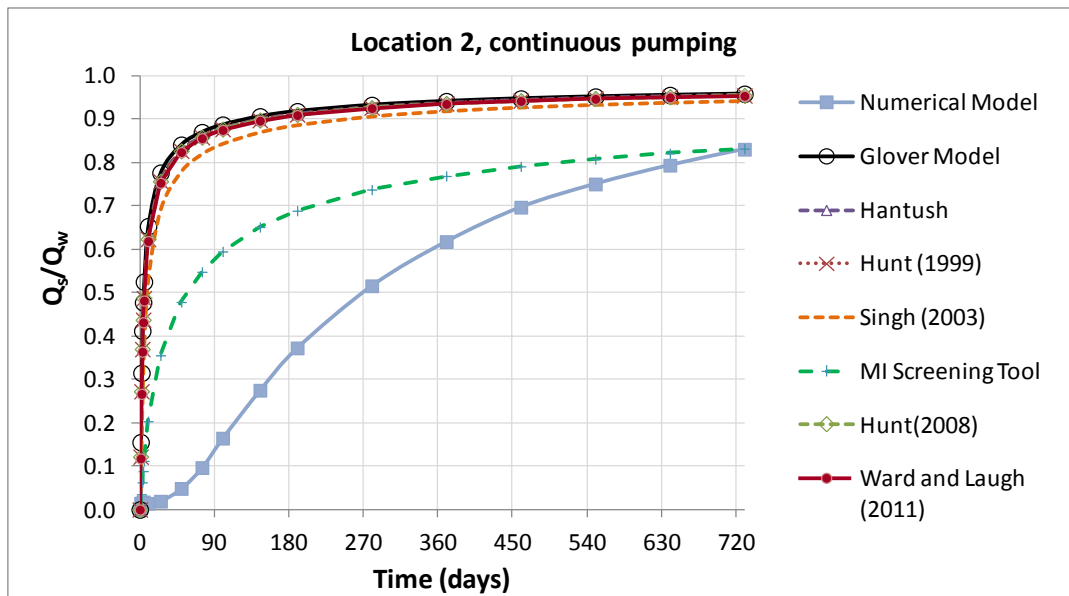

Figure 60   Modelled streamflow depletion from continuous pumping at location 2.

The performance of the analytical model is similar to previous results at location 1. All analytical models overestimate the rate of streamflow depletion in comparison with the numerical model.

The Michigan Simulation Tool shows a slightly better match with the numerical solutions. This model uses a modified streambed impedance term that incorporates the depth of the well screen. The other models, however, assume uniform horizontal flow to the stream.

The layered model of Ward and Laugh (2011), which accounts for pumping in lower aquifer unit, did not perform much differently than the single layer models. This again suggests streamflow is the dominant source of water to the well. The lack of impedance by the lower aquifer conditions may reflect the lack of contrasting aquitard properties in this model application.

Figure 61 shows model solutions for the case of seasonal groundwater pumping at location 2. The numerical solutions exhibit a slow rise in streamflow depletion during pumping, followed by a long gradual recovery period after stoppage of pumping.   The numerical solutions also show streamflow depletion continues to increase after pump shutoff at day 65, and the streamflow does not fully recover prior to the start of pumping in the subsequent pumping cycle. This slow incomplete recovery reflects pumping at depth and within lower permeable units, and at greater distances from the stream.

Figure 61 shows the analytical models overestimate streamflow depletion during the pumping phase, and underestimate depletion after pumping shutoff in comparison to the numerical solution. This is

similar to the results at location 1. In addition, the analytical solutions do not replicate the behavior of increasing depletion after pump shutoff, and incomplete streamflow recovery.
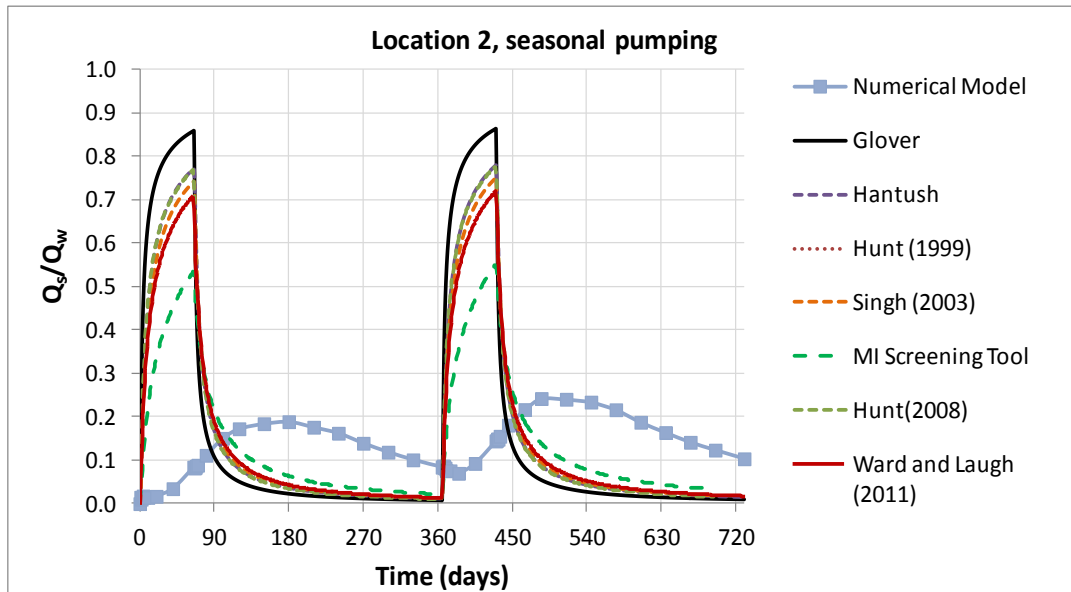

Figure 61   Modelled streamflow depletion from seasonal pumping at location 2.

5.2.6   Model Comparisons for Pumping Location 3

Model comparisons at location 3 examine the effect of pumping from a shallow well located at a relatively far distance from the river (~850 m).

Figure 62 shows model results for continuous groundwater pumping. Because of the larger distance from the well to the stream, the numerical model predicts a very slow initial response in streamflow depletion compared with closer wells at locations 1 and 2. Over time, streamflow depletion gradual increases, reaching about 40% of pumping after two years. With sufficient time, streamflow depletion would eventually equal the pumping rate (i.e., Qs/Qw approaches 1).
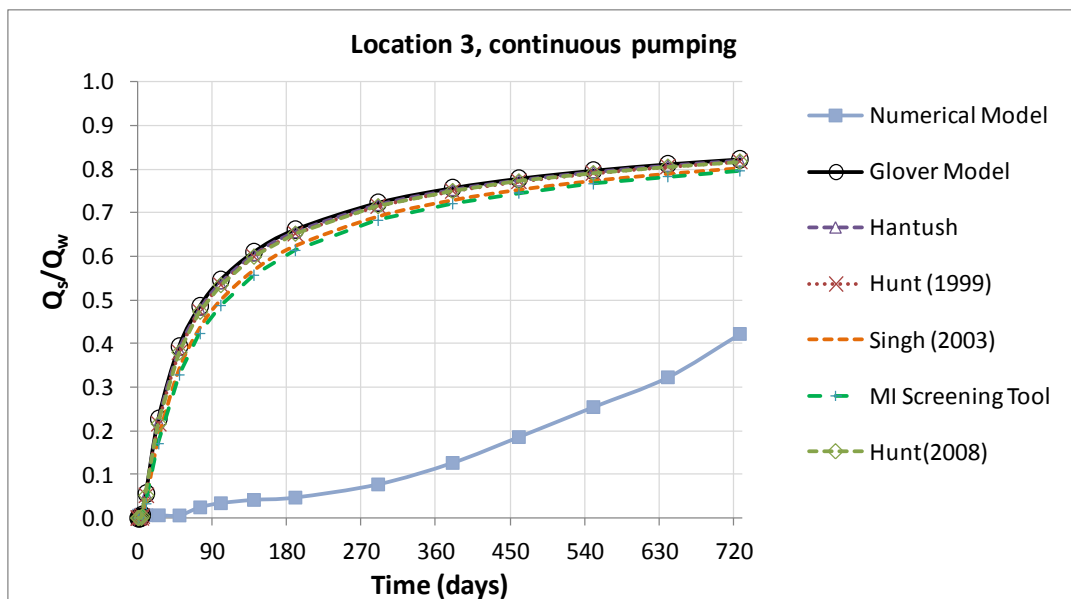

Figure 62   Modelled streamflow depletion from continuous pumping at location 3.

As in the previous locations, the analytical models greatly overestimate streamflow depletion in comparison to the numerical solutions, particularly in the first half of the simulation. The differences diminish in the second half of the simulation. With sufficient time, the numerical and analytical solutions will converge, and are equal at steady state.

These comparisons highlight two points regarding the use of analytical models:

1. Pumping at large distance in a connected aquifer causes a slow response in streamflow depletion. However, over time, the magnitude of depletion is comparable to levels produced at wells that are adjacent to the stream. For groundwater allocation, the long-term depletion is generally of interest to the allocation staff. In this regard, analytical models are useful for gaining longer-term insights into system behavior, but the user must keep in mind the magnitude of depletion is likely overestimated.

2. Analytical models overestimate streamflow depletion at early time after start of pumping operations. Short-term transient behaviors in streamflow depletion would generally be of interest to allocation staff following temporary water use orders, such as curtailment orders during droughts. From a streamflow allocation perspective, the analytical models are conservative in that they overestimate early time streamflow depletion from pumping. Similarly, from the perspective of streamflow recovery after groundwater pumping curtailment, the analytical models overestimate the rate of streamflow recovery. This also is conservative, in the sense that the analytical models would over-estimate the wells that affect streamflow recovery.

5.3 Working with Analytical Models

5.3.1 Solution Methodology and Verification

The primary advantage of the analytical models is the capability to estimate streamflow depletion using closed form equations that have relatively few parameters. However, solving the analytical equations is not always straightforward and errors may occur. It is good practice to verify the accuracy of solutions to the analytical equations. As a means of checking the solution accuracy, ENV compared analytical solutions for the Hantush and Hunt (1999) models using three different solution procedures as follows.

1. **Excel with the Excel supplied erfc function:** Initially we used the Excel supplied function (ERFC) to evaluate terms containing the complementary error function (erfc). The Excel supplied function performed well for most, but not all situations. In some cases, solutions using the Excel function displayed non-smooth behavior as shown in Figure 63. Apparently, there are precision limitations in the way Excel 2007 evaluates erfc, particularly when erfc approaches zero and is multiplied by a large exponential term.

2. **Excel with a calculated erfc function:** In an effort to resolve errors associated with the Excel supplied error function (ERFC), we calculated the erfc using the following series approximation

$$\text{erfc}(x) \approx 1 - (0.255t - 0.284t^2 + 01.421t^3 - 1.453t^4 + 1.061t^5)e^{-x^2}$$
$$t = 1 - \frac{1}{1 + 0.3276x}$$

This calculated error function corrected most of the non-smooth solution behavior shown in Figure 63, but there were still instances where we observed non-smooth solutions.

3. **Excel using Visual Basic macros:** Dr. Bruce Hunt has developed a set of groundwater routines using the Microsoft Visual Basic for Applications (VBA) programming language (Hunt, 2012). These VBA routines are easy to implement as macros in Microsoft Excel. They are available free of charge from Dr. Hunt's research webpage with appropriate credit and reference. The VBA

routines provided an independent check of model solutions developed by ENV. Comparisons in Figure 63 show close agreement between the VBA solutions and the Excel solutions with the calculated error function. This indicates the ENV solutions are correct provided there are no precision difficulties in evaluating the error function.
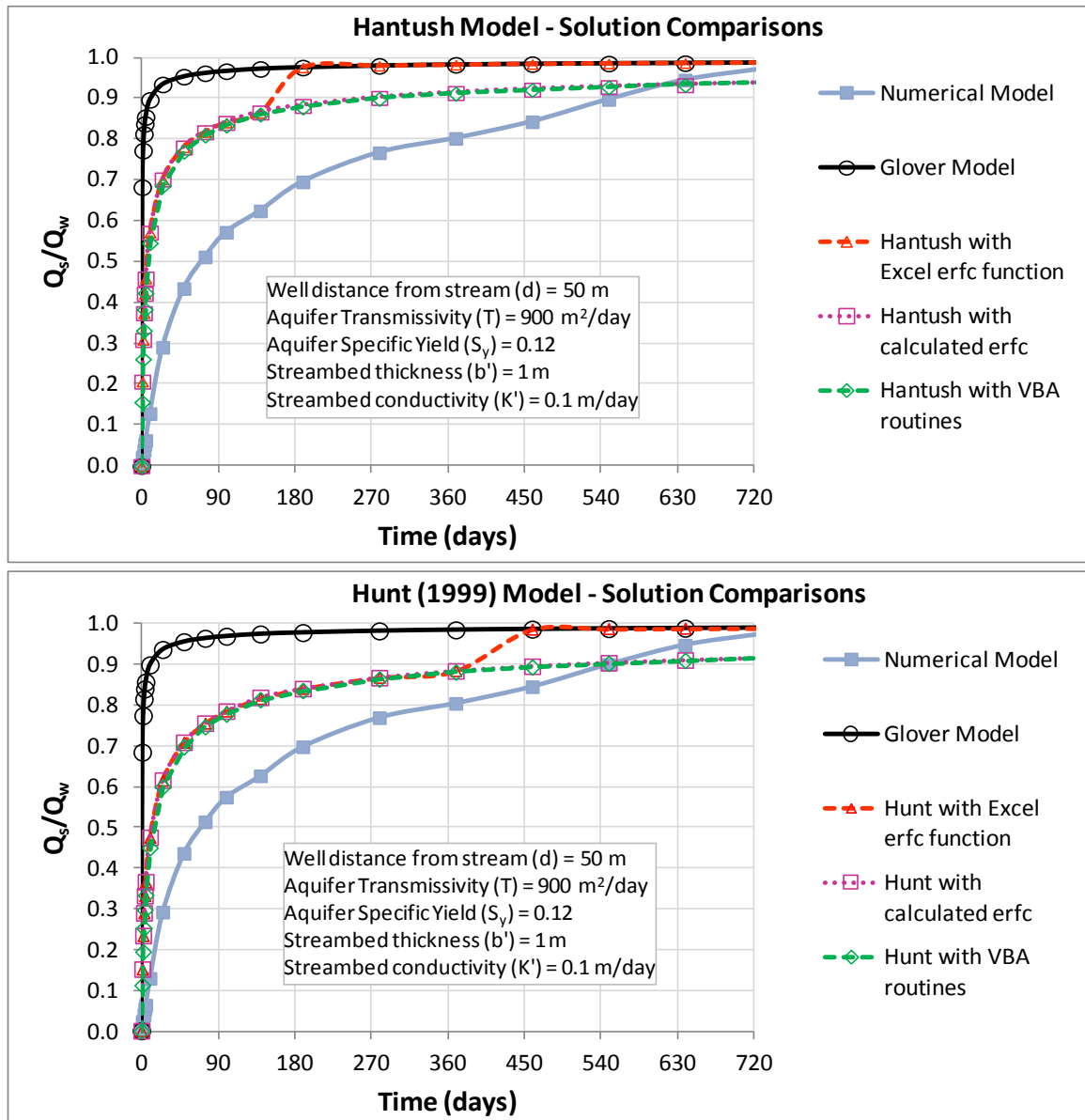

Figure 63   Comparison of analytical model solutions with alternative solution methods.

5.3.2   Using the Hunt (2008) VBA Routine

The VBA routines developed by Dr. Bruce Hunt were the most reliable of the three methods tested for solving the analytical models. They also have several other advantages:

- Accurate and reliable solutions of analytical models for a variety of aquifer systems and configurations, including unconfined, semi-confined, confined aquifers.
- The VBA routines are easy and straightforward to implement with Microsoft Excel. There are no coding requirements and there is only one function call to solve the analytical model.

- Ability to estimate drawdown in the aquifers and aquitards, and to estimate streamflow depletion at specific points or along specific stream reaches.
- Solutions can be generalized and adapted to represent other formulations of streamflow depletion

The Hunt VBA routines are the recommended solution approach for all analytical models (Hunt, 2012). These routines are accurate, flexible and adaptable, and straightforward to implement in Excel. In particular, we recommend use of the VBA routine for the Hunt (2008), as this model can be adapted to represent many common analytical models.

How to Use the Hunt VBA Routines

The Hunt VBA routines are available for download from Dr. Hunt's webpage at:
http://www.civil.canterbury.ac.nz/staff/bhunt.shtml. They are contained in the Excel spreadsheet called 'Function.xls', which must be used to access the VBA routines. Depending on the version of Excel, users may have to select 'enable the macros' in the popup window prior to use. Dr. Hunt's webpage includes implementation instructions and documentation of the available routines.

Figure 64 demonstrates application of VBA routines to solve the model of Hunt (2008). This model describes streamflow depletion due to pumping in the bounded, semi-confined aquifer illustrated in Figure 45. The analytical equations of this model have a complicated form containing integral expressions that require numerical procedures to solve. Hunt (2012) coded the solution procedures into a VBA function called "q_13", which has the form:

$$\frac{\Delta Q_s}{Q_w} = q\_13(t * a_1, a_2, a_3, a_4, \alpha, \beta, \gamma)$$

where, (eq. 12)

$$a_1 = \frac{T}{Sd^2}; \quad a_2 = \frac{\left(\frac{K'}{B'}\right)d^2}{T}; \quad a_3 = \frac{\left(\frac{K''}{B''}\right)d^2}{T}; \quad a_4 = \frac{S}{\sigma}$$

The parameters α, β, γ describe the dimensions of the aquifer and stream system as shown in Figure 45[1], Q_w is the constant groundwater pumping rate from the well, ΔQ_s is the change streamflow due to groundwater pumping, and *t* is time since the start of pumping. Table 9 defines the remaining variables.

The Excel spreadsheet shown in Figure 64 illustrates use of the VBA function "q_13" to estimate streamflow depletion with the model of Hunt (2008). This spreadsheet includes the following elements:

- The user must define the model input parameters, which are specified in cells B2:E16
- From this information, the parameters a_1 through a_4 are calculated in cells H11:H14
- Based on user supplied aquifer and stream dimensions, the parameters α, β, γ are defined in cells E12, E14, and E16, respectively,
- Streamflow depletion is calculated in cells H19:H34 as a function of pumping time listed in cells G19:G31. The solutions are determined by calling the function q_13. For example, the formula bar at the top of the figure shows the functional call for cell H19, which represents the streamflow depletion at time = 0 days. The function q_13 has seven required parameters that are passed to the function by reference to the appropriate cells.
- The adjacent chart shows a plot of the calculated streamflow with time.

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[1] In Figure 45 the distance between the stream and water well is represented by the symbol *L*. For consistency in this report, the well spacing distance is represented by the symbol "*d*".

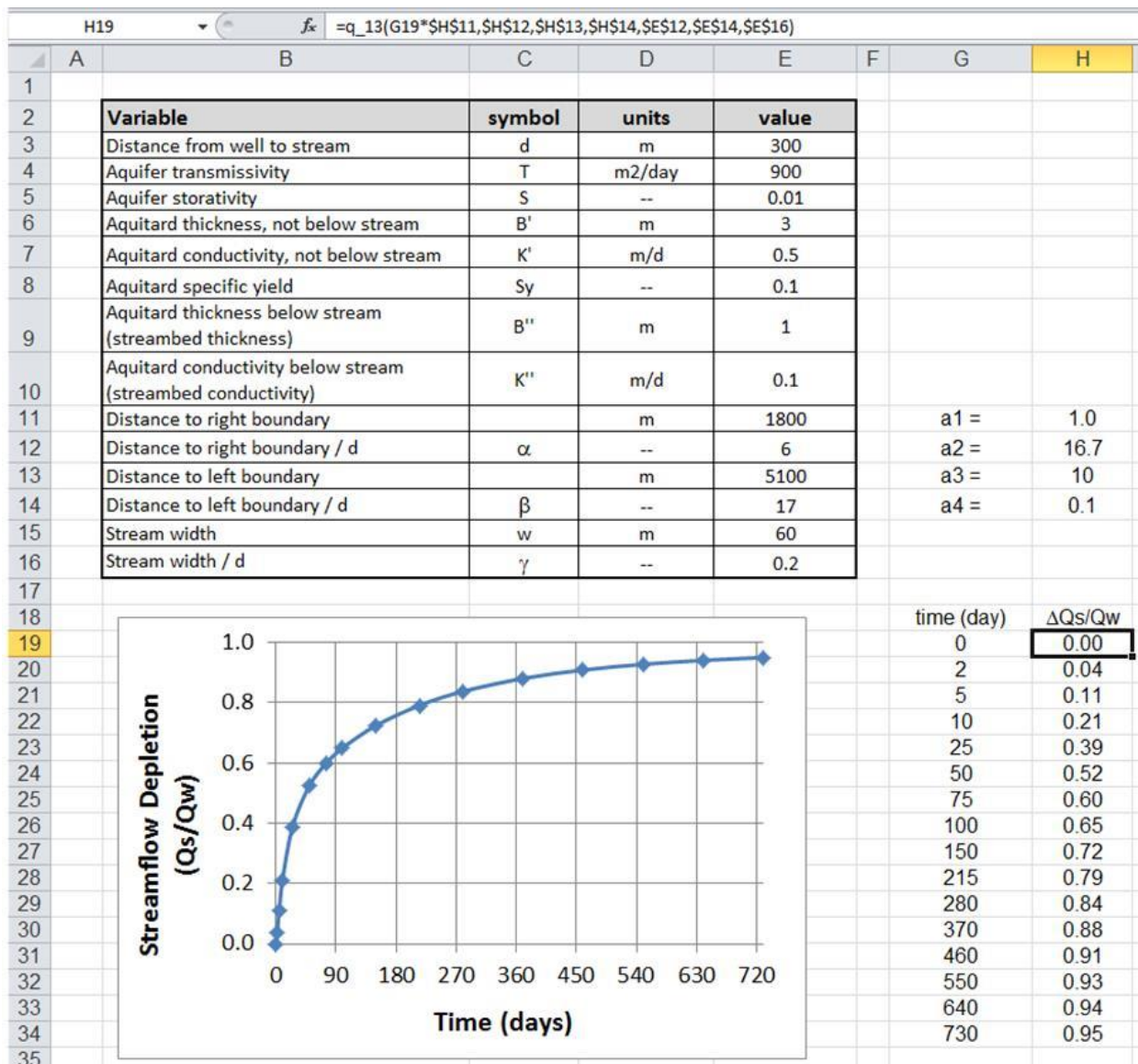|	H19		f_x	=q_13(G19*H11,H12,H13,H14,E12,E14,E16)

Variable	symbol	units	value
Distance from well to stream	d	m	300
Aquifer transmissivity	T	m2/day	900
Aquifer storativity	S	--	0.01
Aquitard thickness, not below stream	B'	m	3
Aquitard conductivity, not below stream	K'	m/d	0.5
Aquitard specific yield	Sy	--	0.1
Aquitard thickness below stream (streambed thickness)	B''	m	1
Aquitard conductivity below stream (streambed conductivity)	K''	m/d	0.1
Distance to right boundary		m	1800
Distance to right boundary / d	α	--	6
Distance to left boundary		m	5100
Distance to left boundary / d	β	--	17
Stream width	w	m	60
Stream width / d	γ	--	0.2

a1 = 1.0
a2 = 16.7
a3 = 10
a4 = 0.1

time (day)	ΔQs/Qw
0	0.00
2	0.04
5	0.11
10	0.21
25	0.39
50	0.52
75	0.60
100	0.65
150	0.72
215	0.79
280	0.84
370	0.88
460	0.91
550	0.93
640	0.94
730	0.95

Figure 64   Example application of the Hunt (2012) VBA routines to solve the model of Hunt (2008).

Solving other Analytical Models with the Hunt VBA Routines

The Hunt (2008) model can be adapted to represent other streamflow depletion models by appropriate adjustment of model parameters. For example, the Hunt (2008) model is able to represent the Glover model by adjusting the following parameters: 1) setting the aquitard conductivity to zero; 2) replacing the aquifer storativity with the specific yield; and 3) setting the streambed conductivity equal to the aquifer conductivity. Table 9 lists parameter adjustments for adapting the Hunt (2008) model to represent other analytical models.

The flexibility of Hunt (2008) model has two useful advantages.

- **Capability to solve different models with a single routine:** With parameter adjustments in Table 9 a single VBA routine is able to solve a variety of models, including some models not available in the set of VBA routines developed by Hunt. For example, the VBA routine for the Hunt (2008) model can be adapted to represent solutions to the Michigan Screening approach.

This simplifies the model application process because the same procedure and functional call is applicable for all models. There is no need to understand or develop separate solution algorithms for different models. Rather the user must only be concerned with the parameter values and appropriate parameter adjustments. This also improves solution reliability because it eliminates potential implementation errors for separately developed models.

- **Capability to extend earlier models to a bounded aquifer setting:** The Hunt (2008) model represents pumping from a semi-confined bounded aquifer system. Thus, when this model is adapted to represent other models, it is possible to include the effects of a bounded aquifer system on streamflow depletion. This provides greater flexibility in adapting the analytical models to bounded aquifer systems found in some parts of B.C.

Table 9   Parameter adjustments for adapting the model of Hunt (2008) to represent other models.

Hunt (2008) Model Parameters		Changes to Hunt (2008) parameters				
		To represent the Glover model	To represent the Hantush model (1965)	To represent the model of Hunt (1999)	To represent the MI Screening tool approach	To represent the model of Singh (2003)
L	Distance from well to stream (signified by 'd' in eqs **)	no change*	no change*	no change*	no change*	no change*
T	Aquifer transmissivity	no change	no change	no change	no change	no change
S	Aquifer storativity	Set to aquifer specific yield	Set to aquifer specific yield	Set to aquifer specific yield	Set to aquifer specific yield	Set to aquifer specific yield
B'	Aquitard thickness	Set to positive value; e.g., 1	Set to positive value; e.g., 1	Set to positive value; e.g., 1	Set to positive value; e.g., 1	Set to positive value; e.g., 1
K'	Aquitard conductivity	Set to 0	Set to 0	Set to 0	Set to 0	Set to 0
B''	Aquitard thickness below stream	Set to 1	Set to streambed thickness	Set to streambed thickness	Set to vertical distance from the streambed to the top of well screen	Set to streambed thickness
K''	Aquitard conductivity below stream	Set to aquifer conductivity; e.g., T/b where b is the water table height	Set to $2TB''/(wL')$ where L' is the leakance term in eq. (5)	Set to streambed conductivity	Set to the vertical conductivity. May be estimated as 1/10 of the horizontal hydraulic conductivity	Set to $2TB''/(wR)$ where R is the modified leakance term in eqs. (10)
σ	Aquitard specific yield	Set to aquifer specific yield	Set to aquifer specific yield	Set to aquifer specific yield	Set to aquifer specific yield	Set to aquifer value
w	Stream width	no change	no change	no change	no change	no change
γ	Stream width divided by L	no change	no change	no change	no change	no change
α	Distance to right aquifer boundary divided by L	Set to large value, e.g., 1000	Set to large value, e.g., 1000	Set to large value, e.g., 1000	Set to large value, e.g., 1000	Set to large value, e.g., 1000
β	Distance to left aquifer boundary divided by, L	Set to large value, e.g., 1000	Set to large value, e.g., 1000	Set to large value, e.g., 1000	Set to large value, e.g., 1000	Set to large value, e.g., 1000

*the pumped well should be one or more stream widths from the nearest stream edge

Calculating Drawdown with the Hunt VBA Routines

The Hunt VBA routines include solutions for determining drawdown in the aquifer and aquitard due to pumping. For example, the VBA routines for the Hunt (2008) model include the following functions to determine drawdown in the aquifer (s) and in the aquitard (η) as a function of position (x, y), the pumping rate (Q_w), and time (t) since the start of pumping:

$$\frac{sT}{Q_w} = \text{W\_13}(\frac{x}{L}, \frac{y}{L}, t * a_1, a_2, a_3, a_4, \alpha, \beta, \gamma) \qquad \text{(eq. 13)}$$

$$\frac{\eta T}{Q_w} = \text{Eta\_13}(\frac{x}{L}, \frac{y}{L}, t * a_1, a_2, a_3, a_4, \alpha, \beta, \gamma) \qquad \text{(eq. 14)}$$

The coordinate location is at the stream edge as shown in Figure 45. These VBA functions allow users to estimate drawdown using simple spreadsheet applications. This can be valuable as it provides a means to estimate model parameters by trial-and-error curve fitting to observation data of groundwater level responses to pumping tests. Lough and Hunt (2006) describe the curve fitting procedures and illustrate the application to field test data.

Generalization of the Hunt Models

The Hunt VBA routines are applicable to general problems of streamflow depletion:

- ***Streamflow depletion from multiple pumping wells***: To determine streamflow depletion from multiple pumping wells, calculate the volumetric streamflow depletion individually for each well using the VBA routines and then sum the results.
- ***Drawdown from multiple pumping wells***: It is possible to estimate the drawdown caused from multiple pumping wells by calculating the drawdown from individual wells, and summing the results. However, a common coordinate system is required when calculating the drawdown from individual wells using the VBA routines.
- ***Evaluation of stepwise variable pumping schedules***: Streamflow depletion caused by stepwise variable pumping schedules is determined with the method of superposition discussed in Section 4.1.1. For example, consider a pumping well with a stepwise pumping schedule:

$$Q_1 \ \text{ for } 0 \ \leq \ \text{time} \ < \ t_1$$
$$Q_2 \ \text{ for } t_1 \ \leq \ \text{time} \ < \ t_2$$
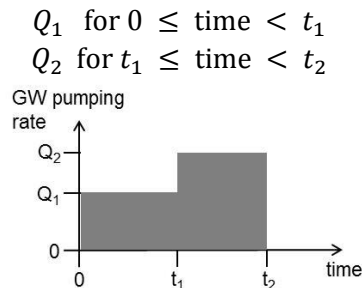
First, determine the streamflow depletion, $\Delta Q_{s1}(t)$, caused by pumping Q_1 beginning at time 0. This time series can be determined with the Hunt VBA routine as

$$\Delta Q_{s1}(t) = Q_1 \cdot \text{q\_13}(t * a_1, a_2, a_3, a_4, \alpha, \beta, \gamma) \quad \text{for } t \geq 0$$

Next, use the VBA routines to determine the time series representing the change in streamflow depletion caused by a stepwise change in pumping from Q_1 to Q_2 at time t_1. This time series is represented as:

$$\Delta Q_{s2}(t) = [Q_2 - Q_1] \cdot \text{q\_13}([t - t_1] * a_1, a_2, a_3, a_4, \alpha, \beta, \gamma) \ \text{ for } t \ \geq \ t_1$$

$$\Delta Q_{s2}(t) = 0 \quad \text{for } t < t_1$$

Notice this time series begins at time t_1. The total streamflow depletion caused by the variable pumping schedule is the sum the two time series:

$$\Delta Q_s(t) = \Delta Q_{s1}(t) + \Delta Q_{s2}(t) \quad \text{for } t \geq 0$$

This approach is extendable to any number of stepwise changes in the pumping schedule.

- ***Streamflow depletion at a specified stream location or stream reach:*** To estimate the streamflow depletion per unit length of stream at any point along a stream, multiply the drawdown beneath the stream at that point by λ, the streambed conductance. The drawdown may be determined with the VBA function in equation 13, and streambed conductance is determined with equation 7.

The cumulative streamflow depletion along a specific stream reach is determined by integrating the streamflow depletion per unit length over the length of the stream reach. A simple way to do this is:

1. Divide the reach in a number of shorter segments such that there is a gradual change in the unit depletion rate between adjacent segments. For example dividing a 1 km reach into 10 segments of 100 m.
2. Calculate the streamflow depletion per unit length at the midpoint of each segment at time t, due to pumping at a rate Q_w. For example, using equation 5-2 the streamflow depletion per unit length at point x_1, y_1 may be calculated by:

$$q_s(x_1, y_1, t)_j = \frac{\lambda Q_w}{T} \, \text{W\_13}(\frac{x_1}{L}, \frac{y_1}{L}, t * a_1, a_2, a_3, a_4, \alpha, \beta, \gamma)$$

where λ is the streambed conductance at the point x_1, y_1.
3. Multiply the streamflow depletion per unit length by the length of the segment (l_j) to determine the volume of streamflow depletion over the segment:

$$\Delta Q_s(x_1, y_1, t)_j = q_s(x_1, y_1, t)_j \cdot l_j$$

4. Sum the streamflow depletion volumes for all segments to determine the total volume of streamflow depletion over the entire reach at time t.

5.4 Analytical Model Selection

Not all models are applicable to all aquifers. Selecting an appropriate analytical model requires an understanding of the aquifer type, the aquifers regional characteristics, the SW-GW interactions, and the ability to quantify model parameters. No single model is applicable to all situations, and there will be some degree of uncertainty in the model selection. Some key questions for model selection are:

- What is the modelling objective? Is a simplified conceptualization and the inherent uncertainties in the model predictions acceptable for the intended use?
- What are the regional hydrogeologic characteristics? Is there sufficient understanding of the hydrogeologic system to confidently use the analytical models?
- Is groundwater pumping occurring from an unconfined, confined, or semi-confined aquifer? If confined or-semi-confined, what is the degree of leakage with the overlying aquifer? Which model conceptualization is consistent with the observed aquifer type?
- What is the nature of the hydraulic communication between the aquifer and surface waters? Are surface waters gaining systems, losing systems, or is the hydraulic communication spatially or temporally variable?

- What is the location of the water well relative to surface waters and aquifer boundaries? Will boundary effects be important?
- What information is available for estimating the aquifer hydraulic properties (T, S)?
- What information is available regarding the nature of the streambed sediments and their potential impedance on streamflow depletion? Is there information available that would assist in estimating streambed hydraulic properties?

Some of these questions are straight forward, while others are difficult to address or have uncertain answers. The subsections below describe general information sources that may assist in addressing some these questions. In addition to the sources of information, consult with hydrogeologists with knowledge and experience of the area.

Table 10 provides general guidance for model selection for common aquifers types and aquifer conditions in B.C. There are two main drivers for model selection: matching site conditions and model conceptualization, and capturing key processes controlling streamflow depletion. However, the guidance cannot be comprehensive, as site-specific conditions will not conform to model conceptualization to varying degrees, and the data limitations constrain the ability to characterize key processes at a given site. Given this uncertainty, a rule-of-thumb is to select models that correspond to the basic aquifer type and characteristics, and require the fewest model parameters. It is important for model users to keep in mind that analytical models are based on idealized conceptualization of complex physical systems, and that results from these models should be used appropriately to gain insights into the system behavior and not as deterministic prediction tools.

Table 10   Guidance for Analytical Model Selection for Aquifer/Stream Conditions

Aquifer and Stream System	Site Conditions & Model Selection Considerations	Aquifer Conditions and Aquifer Types	Recommended Models & Rationale
Basic unconfined aquifer system	• Groundwater pumping occurs in a broad unconfined aquifer where gaining conditions are dominant • Aquifer boundaries are far from the stream, and do not significantly influence the rate streamflow depletion • Streambed impedance is not significant due to coarse-grained streambed sediments, or effects of impedance are ignored due to lack of data, recognizing results will overestimate depletion rates.	• 1a & 1b, unconfined aquifers along high and moderate order rivers • 2, unconfined deltaic aquifers provided aquifer boundaries do not affect depletion rates • 3, unconfined alluvial fan aquifers, provided SW-GW connectivity is established. • 4a, unconfined aquifers of glaciofluvial origin where SW-GW connectivity is established	Glover model (1957): • Model conceptualization represents an idealized unconfined aquifer discharging to a gaining stream • Simplest model requiring only aquifer hydraulic parameters • Information about the streambed properties is not needed
Unconfined and bounded aquifer system	• Same as the basic unconfined system, except the aquifer boundaries are close to the water well such that the aquifer boundaries are likely to increase the rate streamflow depletion (negative boundary)	Smaller unconfined aquifers in narrow riverine valleys, or near the base of mountains and valley walls: • 1c, unconfined aquifers along low order rivers • 2, unconfined deltaic aquifers • 3 & 4a, where SW-GW connectivity is established.	Glover model (1957), but solved with the model of Hunt (2008) using parameter adjustments in Table 9. The dimensions of the bounded aquifer are represented by the parameters α and β, illustrated in Figure 45.
Unconfined aquifer system with	• Same as basic unconfined system except streambed impedance is significant due to fine-grained	• 1a & 1b, unconfined aquifers along high order and moderate-order rivers	Hantush model or Hunt model (1999): • Both models are applicable and recommended because streambed

Aquifer and Stream System	Site Conditions & Model Selection Considerations	Aquifer Conditions and Aquifer Types	Recommended Models & Rationale
streambed impedance	streambed sediments. • There is information available to estimate streambed properties, such as visual observations or quantitative measures of grain size of the streambed sediments.	with low depositional energy • 1c, 2, 3, 4a, where the presence of fine grained streambed sediments is established.	impedance is modelled directly. The Hunt model is easier to implement with the VBA routines. Singh (2003) model: • This model accounts for partially penetrating stream conditions through specification of the aquifer thickness. Recommended for deep unconfined aquifers where data are available to estimate thickness. Michigan Screening Tool Approach: • This model implements an alternative expression for streambed impedance (eq. 8), which ignores streambed hydraulic properties. Therefore is not appropriate for modeling effects of streambed impedance.
Semi-confined aquifer system	• GW pumping occurs from unconsolidated sediments bounded above by an aquitard and bounded below by impermeable or very low permeable materials • The aquifer is hydraulically connected to a stream, where the streambed is located within the aquitard. • There is adequate information to estimate hydraulic properties of the aquifer and aquitard, the streambed properties, and distances to aquifer boundaries	• 1a, 1b & 1c, where semi-confined conditions are established • 4b, where SW-GW interactions are established .	Hunt model (2008): • Model conceptualization is consistent with the site conditions. • Model is able to address effects of streambed impedance, when data are available to estimate streambed thickness and conductivity • Model is able to address effects of bounded aquifers. • The model has significant data requirements, including hydraulic properties of the aquifer, aquiclude, and possibly streambed.

Layered aquifer system	• A layered aquifer system with the following units from top to bottom:
	  - An unconfined alluvial aquifer that is connected to a stream
	  - An aquitard comprised of unconsolidated sediments, but with capacity to transmit significant leakage.
	  - A semi-confined aquifer of unconsolidated sediments
	  - Impermeable layer of clay or bedrock
	• There is information available to estimate the hydraulic properties of all aquifer units and the streambed properties
	• GW pumping occurs from either the unconfined aquifer or the semi-confined aquifer
		• 1a, 1b & 1c aquifers with underlying semi-confined aquifers
		• 4a and 4b layered aquifer systems
			Hunt model (2009):
			• Applicable for the leaky aquifer condition where pumping occurs from the upper unconfined aquifer
			Ward and Laugh model (2011):
			• Applicable for the case where pumping occurs from the lower semi-confined aquifer
			
			• Both models can be solved with VBA routines available from Hunt (2012)
			• Both models have significant data requirements, including hydraulic properties of the two aquifers, aquiclude, and possibly streambed.
			• Neither model can address bounded aquifer conditions

Determining General Aquifer Characteristics

Knowledge and understanding of the hydrogeologic conditions supports the model selection, model application, and interpretation of model results.   Potential sources of publically accessible hydrogeologic information include:

- The B.C. Ecological Reports Catalogue (EcoCat), a publically assessable repository of natural resources reports for BC. The database contains information on regional aquifer characterization studies, and detailed information for particular wells such as construction reports and aquifer.an online mapping tool that is publically available to access and view spatial information including:
- Provincial aquifer database, provides information on the location, size, and characteristics of mapped aquifers
- Provincial WELLS database, a database of voluntarily submitted well construction reports and hydrogeologic information

Assessing Aquifer Connectivity to Surface Water Bodies

As a first approximation, Table 5 provides evaluations of SW-GW connectivity based on aquifer type. For detailed site-specific evaluations, various desktop and field methods are available to assess stream-aquifer connectivity and to quantify SW-GW fluxes. Desktop methods include:

- *Hydrograph analysis:* If multiple streamflow gauging stations are present on a stream reach, the difference in measured hydrographs is attributable to contributions from groundwater discharge and interflow (i.e., lateral flow through the unsaturated zone). This assumes no other streamflow inputs or withdrawals are present, or hydrographs for any such inputs or withdrawals are available and included in the analysis.
- *Hydrograph separation:* Hydrograph separation is the process of separating a streamflow hydrograph into a direct runoff component from periodic storms and snowmelt, and a baseflow component from groundwater discharge and interflow. The procedure is inexact and may use precipitation and temperature data in addition to the streamflow hydrograph. The estimated baseflow contribution represents the net groundwater discharge to a gaining stream at the regional scale. However, the results do not provide information about the spatial distribution of the groundwater fluxes.
- *Hydrogeological assessments and Darcy law calculations:* This approach applies Darcy's law to calculate the GW flux to SW. It requires sufficient information to estimate the aquifer hydraulic conductivity, and sufficient borehole data to map the groundwater surface in order to determine the GW gradient adjacent to the SW.
- *Decision Support Tools:* Decision support tools, such as the stream vulnerability assessment framework developed by Middleton and Allen (2016), make use of readily available geographical information to infer potential connectivity between mapped stream and aquifer systems.

Various field methods are available to infer or measure GW-SW connectivity and fluxes. Guidance is available from Rosenbury and LaBaugh (2008) and Brodie et al. (2007). The field methods include:

- *Seepage meters:* Devices that directly measure GW flux into the surface water body across a small area streambed or lake bottom.
- *Piezometers:* Devices to measure the hydraulic head in the aquifer relative to the surface water elevation. This information establishes the hydraulic gradient between the groundwater and surface water, which allows calculation of the GW flux from Darcy's law.

- **Artificial tracers:** Dyes or soluble tracers added to surface water or groundwater to infer or measure SW-GW interaction based on visual observation or quantitative measurements.
- **Temperature monitoring or profiling:** Temperature measurements to infer contributions and distribution of groundwater discharge to surface waters.
- **Environmental tracers:** The use of naturally occurring chemical constituents, such as salinity, to infer or quantify GW contributions to SW.
- **Field and biological indicators:** Visual indications of groundwater seepage such as differences in water colour and clarity, springs, chemical precipitates, or concentration of plants and animals known to thrive in places where groundwater discharges to surface water.

Two recently completed studies in the Bertrand Creek and Fishtrap Creek watersheds in southwestern B.C. illustrate use of multiple measurement methods to infer and quantify of SW-GW interactions (Starzyk, 2012; Middleton, et al., 2015).

5.5 Determining Model Parameters

All analytical models require specification of input parameters that define the aquifer and streambed properties. This is a challenge for poorly characterized aquifers, or aquifer systems that greatly deviate from the idealized system conceptualization. Meaningful predictions, however, depend on the ability to determine representative parameter values.

Estimating Aquifer Hydraulic Properties

All analytical models require an estimate of the aquifer transmissivity (T), which represents the ability to transmit water horizontally such as to a pumping well. Transmissivity is the product of the horizontal hydraulic conductivity (K_h) and the aquifer thickness (b):

$$T = K_h b$$

The analytical models assume the hydraulic conductivity, aquifer thickness, and transmissivity are spatially uniform.

Aquifer thickness is determined from available lithological information. For confined aquifers, the thickness is the distance between confining units. For unconfined aquifers, the thickness is the water table height above the lower confining unit, assuming the regional water table is relatively flat.

Methods for estimating K and T vary. In the absence of laboratory or field measurements, literature values provide an estimate of conductivity. These estimates can be as simple as relating aquifer lithology descriptions to characteristic values of the geologic materials available in standard groundwater reference books. Textbook information is also useful as a reasonableness check on available field measurements.

Another approach to estimating T is to use characteristic values based on aquifer type. Wei et al. (2014) compiled transmissivity data from across the province and categorized these data by aquifer type. More comprehensive assessments have been conducted for selected regions in the province including the Okanagan Basin (Carmichael, et al., 2009), the Regional District of Nanaimo (Carmichael, 2013), the Cowichan Valley Regional District (Carmichael, 2014), and the Gulf Islands (Allen, et al., 2003). An objective of these studies was to compile all available pumping test data and to reinterpret these data with a consistent analysis approach. Table 11 summarizes and categorizes the available hydraulic property information by aquifer type.

Various laboratory methods are available to measure K from core sample, or to estimate K from measurements of grain size distribution. Measurements of grain size distribution are not routinely available, and the correlation between grain size and K is subject to uncertainty.

Table 11 Summary of measured aquifer hydraulic parameters reported in B.C.

Aquifer type	Type 1a	Type 1b	Type 2	Type 3	Type 4a	Type 4b	Type 5a	Type 6b
Province Wide[1]								
Transmissivity (m²/d)								
Range	350-22,000	1-36,000	960-2,400	25-5,600	2-89,000	2-120,000	0.1-480	0.2-400
Geometric mean	4,500	1,300	1,500	710	690	250	4	9
Okanagan Basin[2]								
Transmissivity (m²/d)								
Range (N samples)		70-38,000 (13)		20-24,000 (12)	6-6,500 (49)	0.3-39,000 (88)	0.4-39 (3)	0.01-30 (51)
Geometric mean		1,800		420	650	340		0.4
Median		5,400		530	900	500	7	0.3
Conductivity (m/d)								
Range (N samples)		13-4,200 (13)		7-2,600 (12)	3-1,400 (33)	0.3-1,800 (84)	0.2-34 (3)	0.002-8 (45)
Geometric mean		360		130	170	60		0.1
Median		610		130	200	100	7	0.1
Storativity (-)								
Range (N samples)		0.05-0.18 (4)		0.015-0.024 (2)	4E-4 -0.08 (11)	6E-5 - 0.1 (15)		3E-4 - 1.5E-3 (2)
Geometric mean		0.11			0.005	1.2E-3		
Median		0.14		0.02	0.04	4.4E-4		8.5E-3
Regional District of Nanaimo[3]								
Transmissivity (m²/d)								
Range (N samples)		2,300-5,400 (3)	170-3,700 (5)		16-11,300 (4)	4-1,600 (74)	1-18 (8)	1.1-1.4 (2)
Geometric mean			1,000		260	110	3	
Median		4,600	1,500		490	120	3	1.3
Conductivity (m/d)								
Range (N samples)		320-940 (3)	30-900 (5)		1-70 (3)	0.2-380 (74)	0.04-3.1 (8)	0.2-0.3 (2)
Geometric mean			200			18	0.3	
Median		680	260		2	16	0.3	0.25
Cowichan Valley Regional District[4]								
Transmissivity (m²/d)								
Range (N samples)		230-170,000 (13)	9-900 (9)		20-4,900 (7)	0.5-240,000 (58)	0.03-12 (5)	0.2-100 (18)
Geometric mean		9,300	100		260	220	0.3	
Median		23,000	140		200	250	0.2	3.1

Aquifer type	Type 1a	Type 1b	Type 2	Type 3	Type 4a	Type 4b	Type 5a	Type 6b
Conductivity (m/d)								
Range (N samples)		140-28,000 (13)	1.2-230 (9)		1.5-1,300 (7)	0.1-23,000 (56)	0.007-9.5 (5)	0.05-27 (18)
Geometric mean		1,700	20		30	20	0.1	5
Median		1,900	40		30	20	0.04	1
Storativity (-)								
Range (N samples)		0.002-0.056 (4)	3E-4 - 0.17 (3)		0.006 -0.12 (3)	1E-5 - 0.003 (16)		2E-6 - 0.004 (3)
Geometric mean		0.008				2E-4		
Median		0.006	0.07		0.01	2E-4		2E-5
Gulf Islands (Gabriola)[5]								
Transmissivity (m^2/d)								
Range (N samples)							0.03-4600 (64)	
Arithmetic mean							2.0	
Conductivity (m/d)								
Range (N samples)							0.0002-70 (62)	
Arithmetic mean							0.007	
Storativity (-)								
Range (N samples)							2.4E-7 – 0.036 (9)	
Arithmetic mean							0.007	

[1] Wei et al. (2014)   [2] Carmichael et al. (2009)   [3] Carmichael et al. (2013)   [4] Carmichael et al. (2014)   [5] Allen et al. (2003)

Determining Streambed Properties

The hydraulic properties of the streambed sediments (hydraulic conductivity and thickness) affect the rate and distribution of streamflow depletion, and accordingly, many analytical models include effects of streambed impedance. Unfortunately, the hydraulic properties of streambed sediments are not routinely measured and are subject to large variability.

The approaches for measuring and estimating streambed conductivity include correlations with grain-size measurements, laboratory measurements on core samples, and field-based measurements such as in-stream seepage meters, slug tests, and pumping test data (Landon, et al., 2001; Hunt, et al., 2001; Fox, 2007). However, it is prudent to keep in mind that values of streambed conductivity can vary greatly depending on the measurement or estimation approach (Song, et al., 2009), or due to inherent heterogeneity of streambed sediments.

Streambed conductivity information will likely be limited or not available for most modelling applications. To apply analytical models in this situation it is necessary to either:

- Use textbook estimates of streambed conductivity based on visual observations and general descriptions of streambed lithology and thickness;
- Ignore streambed impedance by using models that do not account for these processes (e.g., Glover model), or
- Assume streambed impedance is negligible by setting the streambed properties equal to the aquifer properties (i.e., set the streambed thickness to 1, and set the streambed conductivity to the aquifer conductivity).

When streambed impedance is significant, the consequence of ignoring or assuming negligible streambed impedance is that model predictions will be conservative in the sense they will overestimate the timing of streamflow depletion.

5.5.1   *Estimating Model Parameters from Pumping Test Data*
Analysis of drawdown and recovery data collected from pumping tests is a common approach for estimating site-specific aquifer hydraulic parameters. Allen (1999) provides a comprehensive overview of methodologies for analyzing hydraulic test data, particularly focusing on procedures applicable to bedrock aquifers.

It is also possible to obtain representative estimates of both aquifer and streambed parameters by curve fitting to site-specific pumping test data. Several researchers describe case studies involving field measurements of aquifer and streamflow response to long-term pumping tests (Hunt, et al., 2001; Fox, 2004; Lough & Hunt, 2006; Fox, et al., 2011). These response data permit the simultaneous estimation of aquifer and streambed parameters by fitting predictions from analytical models to the measured groundwater level and streamflow data, analogous to standard pumping test procedures for drawdown data. This curve fitting is typically through a trial-and-error process, systematically varying the model parameters until there is an acceptable match with measured response data.

Parameter estimation based on inverse analysis of pumping test data has produced favorable results. Researchers report good agreement in model predictions with independent observations (i.e., field measurements not used for parameter estimation), and similarity of parameter values with other independent measurements such as grain size analysis (Hunt, et al., 2001; Fox, 2004; Lough & Hunt, 2006; Fox, et al., 2011).

There are, however, significant limitations with parameter estimation from pumping test data. Estimated parameter values are non-unique, varying significantly with changes in field conditions, test conditions, or with the model to which they are fit (Nyholm, et al., 2002; Kollet & Zlotnik, 2007).

Moreover, the pumping test requirements are significant. They must be of long enough duration to affect streamflow depletion response, and must include simultaneous measurement of streamflow and drawdown data at one or more observation wells.

Use of pumping test analysis to support streamflow depletion modelling is unlikely to be practical for most studies. However, these methods are potentially useful for major aquifer characterization studies and licensing of high capacity or controversial production wells that warrant comprehensive assessment.

6. <u>SUMMARY AND RECOMMENDATIONS</u>

This report has addressed the following three objectives:

1) Investigate and improve understanding of SW-GW interactions in B.C. and the effects of groundwater withdrawals on surface waters;
2) Evaluate modelling approaches for assessing impacts of groundwater withdrawals on EFNs, particularly analytical models that are simple to implement ; and
3) Recommend modelling tools for assessing impacts from groundwater withdrawals.

6.1 Surface Water-Groundwater Interactions in B.C.

6.1.1   General Characteristics
Surface water and groundwater are closely linked in the hydrologic cycle. Groundwater moves continuously from recharge areas to discharge areas in streams, lakes, springs, wetlands, and oceans. This movement occurs over a broad range of spatial and temporal scales, from tens of metres and days to hundreds of kilometres and centuries. Because of this range in scales, the connection between recharge and discharge areas is not always evident.

Groundwater discharges comprise a high percentage of surface flows in streams. For many streams and rivers in B.C., groundwater contributions account for high percentage of the total annual flows, ranging from 20 to 80 percent. However, during seasonal dry periods, the groundwater contributions can be much higher, accounting for the vast majority of baseflow in streams, up to 100% depending on local conditions. Due to B.C.'s diversity of climatic and topographic conditions, groundwater-dominated low flow periods occur at different times of the year. Northern and eastern areas of B.C. see low flow periods in the winter and early fall. In western and coastal areas of B.C., low flow periods occur in the summer and early fall.

The movement of water between surface water and groundwater is spatially heterogeneous and temporally dynamic. Groundwater interaction with surface water bodies, including streams, lakes, and wetlands, occurs in three general regimes: 1) gaining systems where surface waters receive water from groundwater discharges; 2) losing systems where surface waters discharge water to groundwater through infiltration; and 3) flow-through systems where surface water receive groundwater at up-gradient boundaries, and simultaneously discharge to groundwater at down-gradient boundaries. These interactions are variable and can be highly localized and transient. Each of these interactions can occur simultaneously on the same surface water body at different locations. Small-scale to regional-scale heterogeneities in aquifer and stream properties strongly influence the spatial distribution of SW-GW interactions. SW-GW interactions also change over different time scales, from short-term responses to precipitation events or diurnal fluctuations, to seasonally variations and long-term trends.

Groundwater is integral to numerous aquatic ecosystems in B.C. Many aquatic habitats are dependent on groundwater discharges. Mixing between surface and groundwater in the sediments of

streams helps to supply and retain nutrients and solutes that are essential to aquatic organisms and the overall ecological health of the stream.   In particular, there is a focus on sensitive fisheries. Fish populations depend on groundwater discharges for adequate flows and habitat, temperature refuge during hot summer and cold winter low flows, and for supply of nutrients and oxygen. Groundwater discharges to streams can substantially influence the distribution, movement, behavior, and reproduction success of fisheries in B.C. streams.

6.1.2   *Effects of Groundwater Pumping on Surface Waters*

When aquifers and surface waters are hydraulically connected, groundwater diversions can significantly influence the quantity and quality of surface waters. The following are general relationships between groundwater pumping and surface water responses in hydraulically connected systems.

Groundwater pumping reduces surface water flows and surface water levels in two ways.
- **Induced Infiltration***:* Water wells constructed sufficiently close to surface waters can capture water directly from surface water bodies, i.e., pumping induces water to flow from the surface water to the well intake. The ability to capture water directly from surface waters depends on the location, size and depth of the well.
- **Interception:** Interception reduces the available groundwater that flows to surface waters without directly capturing surface water, i.e., pumping withdraws groundwater that would eventually discharge to a surface water body in the absence of pumping. Interception does not depend on distance between the well and the surface water body. Water wells located at large distances from surface waters can cause reduction in surface flows by interception.

There is a time delay between changes in pumping conditions and the response of surface water flows or surface water levels in a hydraulically connected SW-GW system.

- **The effects of pumping on surface water are not immediate but increase over time.** Following initial startup of pumping from a well, there is transient period during which the effects of groundwater pumping on surface waters increase over time. This occurs because the initial source of groundwater to the well is from aquifer storage. Over time, the amount of water removed from storage decreases as the cone of depression around the well stabilizes. Correspondingly, induced infiltration and interception gradually increase as the source of groundwater flow to the well.
- **There can be a large time delay between pumping and surface water response.** Water wells located at large distances from surface waters can cause reduction in surface flows from interception, but there is a time delay between the time of pumping and the surface water response. The time delay increases with distance between the well and the surface water. Even wells that are located at considerable distances from surface water can cause depletion of surface waters, but the time delay can be large, up to years. Streamflow depletion over the long-term is an important consideration in allocation of groundwater for use.
- **With sufficient time, all groundwater pumped from a well is derived from surface water sources.** A well pumping at a constant rate in an alluvial aquifer will eventually develop an equilibrium condition where the cone of depression and aquifer storage are stable. At this point, all groundwater pumped from the well is from induced infiltration and interception, which eventually manifest as a reduction is surface water flows or levels.
- **Depletion of surface water flows and levels continues after pumping stops.** After stoppage of groundwater pumping, there is a recovery period when the natural groundwater levels are re-established. Depletion of surface water continues during this recovery period because groundwater that would otherwise discharge to surface waters is instead replenishing aquifer storage. In taking action during a drought, the transient response during recovery is an

important consideration so action is taken on those junior groundwater right holders that will likely result in streamflow recovery.

- **Time-varying pumping patterns cause time varying responses in surface waters.** Cyclical changes in groundwater pumping rates cause a corresponding change in reductions of surface water flows and levels. However, the magnitude and persistence of streamflow depletion depend on the distance between the well and the surface waters. Wells close to streams produce cyclical and more seasonal responses in streamflow depletion, corresponding to pumping patterns, and with larger maximum depletion rates that approach the seasonal pumping rate. Wells located far from streams produce smaller, less variable, but more persistent response in streamflow depletion, with maximum depletions that approach the long-term average annual pumping rate.
- **The effect of multiple pumping wells on surface waters is the additive response of individual wells.** Although impacts to surface waters from individual wells may be small, the cumulative impact of pumping from a well field or the collective wells in a watershed can be significant. The cumulative effect of pumping on surface waters is a key consideration in groundwater allocation decisions.

6.1.3   Relating Surface Water-Groundwater Interaction to Aquifer Type

Geologic and climatic conditions strongly influence the nature and timing SW-GW interactions. B.C. is geologically and climatically diverse and SW-GW interactions in B.C. reflect this diversity. There are few studies on SW-GW interactions in the province, and many areas of the province do not have adequate streamflow and groundwater monitoring information. Consequently, it is not possible to characterize SW-GW interaction throughout the majority of the province.

The existing aquifer typing system provides a basis for broadly categorizing SW-GW interactions in province. Table 5 summarizes attributes of the 12-aquifer types and sub-types, and the associated aquifer-stream interactions.

- Most types of unconsolidated surficial aquifers in the province are strongly to variably connected to surface waters. Groundwater pumping from these aquifers is likely to impact surface water flows or levels.
- Confined and semi-confined aquifers have variable connectivity to surface waters depending on the properties of the confining geologic units (aquitards). Groundwater withdrawals from confined aquifers do not necessarily eliminate the possibility of streamflow depletion.

    Limited connectivity between confined aquifers and surface waters occurs where the aquitards are continuous with low permeability, such as aquitards formed by thick deposits of dense clay and till that effectively restrict the vertical movement of water. Groundwater diversion from these types of confined aquifers is more likely to have a low risk of impacts on surface waters.

    Hydraulic connectivity between confined aquifers and surface waters occurs where: 1) the aquifers outcrop directly to surface waters; 2) where the confining geologic units have sufficient permeability to transmit significant quantities of water; and 3) where the confining geologic units are discontinuous and windows to the underlying surficial aquifer. Groundwater pumping from these types of confined aquifers is likely to impact surface water flows and levels.

- Bedrock aquifers have variable connectivity to surface waters that is difficult to assess because flow occurs through heterogeneous fracture zones and faults that are difficult to characterize. In general, SW-GW interaction and pumping impacts are limited in comparison to unconsolidated aquifers due to the typically low conductivity and greater depth of bedrock aquifers. Groundwater pumping can potentially affect surface waters if wells intercept fracture

zones and faults that outcrop to surface waters and springs. Bedrock aquifers that are shallow and highly productivity also have the greatest risk to effect streamflow depletion.

6.1.4   Recommendations Related to Surface Water-Groundwater Connectivity

Because of the generally complex and dynamic nature of SW-GW interaction it is not always possible to fully understand the nature of SW-GW interactions and the degree to which groundwater withdrawals will impact surface waters. Water managers and allocation staff will face uncertainty in water licensing decisions. Practices to support allocation staff in furthering goals of sustainable management and informed licensing include:

- **Promote awareness and dialogue of SW-GW connectivity and potential impacts.** Staff should bear in mind the inherent connection between surface and groundwater during licensing, and the potential for groundwater withdrawals to affect surface water availability for existing and future water rights holders, as well as for meeting critical EFNs.   Moreover, the potential impacts are not diminished by distance between wells and surface waters, rather the impacts are delayed. To promote the understanding of the SW-GW connectivity, managers and staff should pursue ongoing dialogue to increase awareness and education of SW-GW connectivity, to assist staff in licensing decisions and problem solving, and encourage assessment of licensing protocols.
- **Support studies and monitoring activities to improve understanding of SW-GW connectivity.** Managers should continue to support studies of SW-GW interactions as well as monitoring activities to assist these efforts, particularly the collection of hydrometric and groundwater level data. Aquifer water budgets can assist allocation staff in understanding the connection between groundwater withdrawals and surface water impacts, and in quantifying the availability of groundwater for allocation. Such efforts are essential in high priority areas where there is a high demand on surface and groundwater resources, where there are existing surface water allocation restrictions, or where there are high value aquatic habitats.
- **Use more conservative approach in high priority, high impact areas.** To minimize potential conflicts in water rights and impacts to aquatic resources, a more conservative approach should be used in high priority areas, areas with large uncertainty in SW-GW interactions, or high risk areas with a potential for significant surface water impacts. Licensing decisions should be based on defensible technical studies, should include a sufficient factor of safety in available allocation quantities, and should consider groundwater allocation restrictions in areas with existing surface water allocation restrictions.

6.2 Modelling Surface Water-Groundwater Interaction

6.2.1   Modelling Tools for Managing Groundwater Diversion and Use

Canadian and international regulatory agencies use modelling tools to evaluate SW-GW connectivity or to support management of water rights in connected SW-GW systems. Three broad modelling approaches support this:

- **Analytical Models:** Analytical models use idealized conceptualization of the stream-aquifer system to develop simplified procedures for estimating surface water response to groundwater pumping. Analytical models require limited information about the site conditions and are comparatively easy to implement. Solutions from analytical models provide insight into system responses, but do not capture the hydrogeologic complexities and tend to overestimate actual surface water responses.
- **Numerical Models:** Numerical models are a comprehensive approach to modelling groundwater flow and surface water response. Although constructed in many ways, they have the ability to capture relevant hydrogeologic complexities, providing a means for comprehensive

basin-scale groundwater management. Numerical models are time consuming, costly and difficult to construct and calibrate.

- **Response Functions:** Response functions use analytical or numerical models to describe the relationship between groundwater pumping and surface water response at a particular location. Response functions provide the ability to map the spatial distribution of surface water responses to pumping. This allows easy visual inspection of surface water responses to groundwater pumping. However, this approach assumes the response at each location is independent of other pumping that may occur simultaneously in the aquifer.

A review of the use of groundwater models in water allocation found that regulatory jurisdictions rarely use models alone to establish allocation decisions, as there is always a degree of uncertainty in modelling results. Regulatory agencies use groundwater models as support tools; for example, several jurisdictions use analytical models to screen the review of groundwater licensing applications. Some jurisdictions also encourage or require the use of models to assess impacts from groundwater pumping.

6.2.2 Assessment of Analytical Models

Assessment of analytical models for aquifer-stream systems is a primary objective of this study. A large number of analytical modelling approaches are available in the literature spanning a range of complexity and applicability. Analytical models fall into three general categories.

- **Models with simple conceptualization of aquifer-stream systems:** These include the earliest analytical models developed for stream-aquifer systems based on the Glover Model (Glover & Balmer, 1954) and subsequent extensions. These models derive from a highly idealized representation of the aquifer-stream system. However, they require the fewest parameters and are the easiest to implement.
- **Models with improved aquifer-stream representation:** A second generation of analytical models sought to improve the aquifer-stream representation by including effects from streambed impedance and partially penetrating streams. These models require two additional parameters (streambed conductivity and aquifer thickness) that can be difficult to establish. Key models are those of Hantush (1965), Hunt (1999), and Singh (2003).
- **Models that address specific aquifer geometries:** Researchers have developed complex analytical models that address specific aquifer geometries, including pumping from semi-confined aquifers, layered aquifers, and bounded aquifers. These models have additional parameter requirements for aquifer properties and geometries, and have difficult solution procedures.

Evaluation of Model Predictions: Eight analytical models were tested and evaluated through inter-model comparisons. A calibrated numerical model of the Grand Forks aquifer provided estimates of streamflow depletion and recovery in the Kettle River from groundwater pumping at three individual pumping locations. We assessed the accuracy of the analytical models by comparing model prediction to the numerical model solutions. Each of the analytical models overestimated the rate of streamflow depletion and streamflow recovery in comparison to the numerical model, providing conservative estimates of surface water impacts from groundwater diversion. No analytical model substantially outperformed the others.

Evaluation of Solution Procedures: We evaluated alternative methods for solving the analytical expressions for the Hantush model in a spreadsheet format. The Visual Basic Applications (VBA) routines developed by Dr. Bruce Hunt (Hunt, 2012) are easy in use in Excel and provide reliable solutions. In comparison, solutions obtained through direct coding in Excel were generally in close agreement to the VBA solutions, but occasionally displayed non-smooth behavior. These errors stem from precision limitations when the complementary error function (erfc) approaches zero.

Solving Analytical Model with the Hunt VBA Routines: The VBA routines developed by Bruce Hunt provide a number of advantages for estimation of aquifer-stream interactions using analytical models:

- The routines and documentation are available free of charge from Dr Hunt's webpage.
- The routines have undergone extensive development and testing, and peer review.
- They are easy and straightforward to implement in Microsoft Excel.
- Analytical models are available for a variety of aquifer configurations including unconfined semi-confined, confined aquifers, and bounded aquifer systems.
- The routines provide the ability to estimate drawdown in the aquifers and aquitards, and to estimate streamflow depletion at specific points or along specific stream reaches.
- Solutions can be generalized and adapted to represent other formulations of streamflow depletion models.

6.2.3   Recommendations Related to Groundwater Modelling
Groundwater models provide a means for assessing the behaviour of groundwater movement and the response of SW-GW interactions to groundwater pumping. Because groundwater resources are costly and difficult to characterize, modelling tools are widely used in groundwater investigations and resource development. Modelling studies will most likely be used to support groundwater licensing applications where technical studies are required by the province. Recommendations for promoting the use and appropriate review of groundwater models in investigations related to SW-GW interactions are:

- **Support groundwater modelling training for government staff.** Use of groundwater models by government staff lags behind industry use, yet government staff often review modelling studies in Environmental Assessment reviews. In the future, it is likely that staff will also review models developed in support of groundwater licensing applications. Ongoing groundwater modelling training for groundwater staff will support the development and use of groundwater models within government as well as the appropriate review of models submitted to government. This training should address both analytical and numerical modelling approaches, including the limitations and proper use and documentation of these models. The Edumine groundwater modeling course (Wels, et al., 2014), developed with support from the province, is a good example of resources available to provincial staff.
- **Use the Hunt VBA routines for analytical modelling of SW-GW interactions.** Analytical models provide simple tools for assessment of stream depletion. These models are appropriate for general purposes where quick and broad assessment of stream depletion potential is useful, such as to support review of licensing applications, or preliminary screening of licence applications and groundwater curtailment. The Hunt VBA routines provide broad capabilities for analytical modelling applications to varying aquifer conditions. The use and application of VBA routines is described in this report.
- **Promote selected use of numerical models for assessing groundwater allocation strategies.** Researchers have previously developed regional groundwater flow models for priority areas in the province, including the Grand Forks aquifer, the Abbotsford-Sumas aquifer, and the Cowichan Basin. There are potential conflicts in these priority areas between surface water rights, groundwater rights, and objectives for EFN protection. A numerical model is potentially a comprehensive management tool for informing the development of sustainable groundwater and surface water allocation strategies. Considerable effort has gone into the development of existing models and their availability affords an opportunity to develop and test the use of these models as groundwater management tools. However, additional resources and cooperation between researchers, groundwater staff, and allocation staff would be needed to develop and test a detailed groundwater model for applications to groundwater management.

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APPENDIX A: ABBREVIATIONS, NOTIATIONS AND GLOSSARY

Abbreviations and Acronyms

EFN	Environmental flow need
ET	Evapotranspiration
FITFIR	First in time, first in right
FLNR	Ministry of Forest, Lands, and Natural Resource Operations
GDE	Groundwater dependent ecosystem
GW	Groundwater
MAF	Mean annual flow
Mgpd	Million gallons per day
MODFLOW	Modular Three-Dimensional Finite-Difference Ground-Water Flow Model
ENV	Ministry of Environment
NRBF	Normalized reference baseflow
SW	Surface water
USGS	United States Geological Survey
VBA	Visual Basic for Applications
WRIA	Water resource inventory area
WSA	Water Sustainability Act

Notation

b	Saturated thickness of the aquifer [L]
b'	Streambed thickness [L]
B'	Aquitard thickness [L]
B''	Aquitard thickness below a stream [L]; see eq. 12
d	Distance from a water well to a river/stream [L]
d_s	Vertical distance from the streambed to the top of the well screen or open interval of a well [L]; see eq. 8 and eq. 9.
D	Hydraulic diffusivity, defined as T/S [L^2/t]
erfc	Complementary error function
K	Aquifer hydraulic conductivity [L/t]
K_h	Horizontal component of the aquifer hydraulic conductivity [L/t]
K_v	Vertical component of the aquifer hydraulic conductivity [L/t]
K'	Streambed hydraulic conductivity [L/t]; also aquitard conductivity in eq. 12
K''	Aquitard conductivity below a stream [L/T]; see eq. 12
$L = \frac{K}{K'} b'$	Streambed leakance term in the Hantush model [L]; see eq. 5
Q_s	Stream discharge [L^3/t]
Q_w	Pumping rate from a well [L^3/t]
ΔQ_s	Change in streamflow due to groundwater pumping (streamflow depletion) [L^3/t]

$\Delta Q_s / Q_w$	Streamflow depletion expressed as a fraction of pumping [dimensionless]
R_p	Retardation factor in the Singh (2003) model to account partially penetrating stream conditions [L]; see eq. 10 and eq. 11
s	Water table drawdown in an aquifer due to pumping [L]
S	Aquifer storativity [dimensionless]
S_y	Aquifer specific yield [dimensionless]
T	Aquifer transmissivity [L^2/t]
t	Time [t]
t_s	Time at pump shutoff [t]
w	Streambed width [L]
λ	Streambed conductance term used in the Hunt (1999) Model [L/t]; see eq. 7. The Michigan screening tool uses an alternative formulation for λ; see eq. 8.

Glossary

Baseflow: The portion of streamflow hydrograph that derives from subsurface seepage from saturated zones (aquifers) and unsaturated zones (bank storage).

Confined aquifer: An aquifer bounded both below and above by beds of considerably lower permeability than that existing in the aquifer itself (aquitards). Groundwater in a confined aquifer is under pressure greater than atmosphere pressure, such that the water level in a well will be above the upper confining layer. Pumping from a confined does not dewater the pore spaces. Pumping releases water from storage by reducing the pressure exerted on the water and porous matrix causing the water to expand and pore space to consolidate.

Environmental flow needs (EFNs) – The volume and timing of water flow in a stream required for the proper functioning of the aquatic ecosystem of the stream.

Gaining stream: A stream reach where groundwater discharges maintain or contribute to a net gain in streamflow.

Groundwater recharge: water infiltrates into the ground and joins the zone of saturation.

Hydraulic conductivity: A measure of the ease with which a fluid can move through the pore spaces or fractures or a porous medium. Hydraulic conductivity depends on the size, shape and interconnectedness of the pore spaces or fractures, and the density and viscosity of the fluid.

Hydraulic diffusivity: Ratio of transmissivity to storativity (*T/S*). It is a measure of the rate at which pumping stresses prorogate through the aquifer. Larger values of hydraulic diffusivity indicate groundwater levels or hydraulic head will change more rapidly in response to pumping.

Hydraulic head: The level to which water rises in a well with reference to a datum such as sea level.

Losing stream: A stream reach where seepage through the streambed causes a net loss in streamflow.

Semi-confined aquifer: Confined aquifers where the confining layers are not continuous, or the confining bed materials are semi-permeable; i.e., the permeability of the aquitard is comparatively lower than the adjacent aquifer, but large enough to transmit significant water between adjacent geologic units.

Specific yield: Also known as the drainable porosity, the specific yield is the volume of water released from an unconfined aquifer when it is allowed to drain under the forces of gravity.

Storativity: The volume of water released from storage by a confined aquifer per unit surface area of aquifer per unit decline in hydraulic head normal to surface. It is equal to product of specific storage and saturated thickness, $S=S_s b$. Storativity is also referred to as the storage coefficient.

Streamflow depletion: The reduction in streamflow caused by groundwater withdrawals.

Transmissivity: The product of hydraulic conductivity and saturated aquifer thickness (Kb). It is a measure of the rate at which water can flow through the aquifer per saturated thickness.

Unconfined aquifer: The aquifer close to the land surface in which the water table forms the upper boundary of the aquifer. Pumping from an unconfined aquifer releases water

Water table: The water surface of unconfined aquifer at which the pressure is atmospheric.