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Screening Tool for Guiding Short-Term Groundwater Curtailment during Water Scarcity

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Photograph of wells adjacent to the Lower Cowichan River, by FLNR West Coast Regional Operations Division.

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EXECUTIVE SUMMARY

During periods of water shortage, the *Water Sustainability Act* provides statutory decision makers and regional water managers with authority to order short-term curtailment of surface and groundwater diversions in order to protect critical environmental flow needs. However, short-term curtailment of groundwater diversions will not necessarily produce the desired streamflow recovery due to the variable time lag between pumping and surface water response. To address the variable response of groundwater curtailment, a suggested groundwater curtailment approach is to take action on users in accordance with the first-in-time, first-in-right (FITFIR) water allocation system, but to apply FITFIR only where it is likely to result in a benefit to the stream within the short term curtailment period of interest.

This report describes a spreadsheet based screening tool to support statutory decision makers and regional water managers in guiding groundwater curtailment and data collection activities. The screening tool is intended as a support tool that the decision maker may want to consider as part of their toolkit during times of scarcity. The screening tool does not hinder the decision maker from the option of curtailing all groundwater users in a particular area during times of scarcity.

The screening tool calculates a setback distance from a stream wherein the curtailment of groundwater users is most likely to have a positive influence on streamflow recovery during a specified short-term curtailment period. This setback distance is referred to as a 'curtailment envelope.' The spreadsheet calculates the curtailment envelope from the user specified pumping rates, distance between the well and the stream, and the aquifer hydraulic properties. The calculations are based on a number of simplifying assumptions about the aquifer-stream system.

The screening tool can be used to help prioritize drought planning, data collection efforts, and curtailment evaluation to those wells within the curtailment envelope, while committing less resources to wells that are outside of the envelope. An example application of the screening tool is presented for aquifers in the Lower Cowichan River watershed. Results from this case study indicate:

- Blanket curtailment of groundwater use based solely on well proximity to streams or on well location within mapped aquifer polygons does not ensure groundwater curtailment will have a positive benefit on streamflow recovery.
- To improve confidence that short-term groundwater curtailment will benefit streamflow recovery requires an assessment of aquifer lithology, hydraulic connectivity to surface waters, and pumping rates on an individual well basis.
- Groundwater curtailment planning is prudent in high priority areas where water restrictions are likely. Curtailment planning should focus on major and medium users, and include the identification and verification of well locations and groundwater pumping volumes, and the assessment of hydraulic connectivity to surface waters.

<u>**CONTENTS**</u>

1. GROUNDWATER CURTAILMENT - AN APPROACH

1.1 *Water Sustainability Act* and Groundwater Curtailment

Use of non-domestic groundwater in British Columbia (B.C.) requires an authorization under the *Water Sustainability Act* (WSA). The WSA provides a precedence of water rights for both surface water and groundwater based on the first-in-time, first-in-right (FITFIR) scheme. However, the WSA modifies FITFIR by giving precedence to essential household needs and critical environmental flow needs (EFNs), followed by senior rights holders for both surface water and groundwater.

Prior to the WSA, the allocation of surface water did not consider the effects of groundwater pumping on the availability of surface water. However, experience in B.C. shows groundwater in many aquifers exists in hydraulic connection with water in streams, particularly where groundwater occurs in unconfined sand and gravel aquifers near streams and lakes. The WSA recognizes the connectivity between surface and groundwater resources. During periods of water shortage, the WSA provides statutory decision makers and regional water managers (decision makers) with authority to order short-term curtailment of surface and groundwater diversions in order to protect critical EFNs. Specifically, section 22 (1) of the WSA requires decision makers to consider the precedence of water licences on both the stream and aquifers that are hydraulically connected to the stream when taking action to curtail water use.

When curtailing surface water diversions during droughts, there is an immediate response in streamflow recovery. In contrast, the recovery of streamflow following stoppage of groundwater pumping is delayed and variable; streamflow may recover over a period time that can span minutes to years depending on the well location relative to the stream and the aquifer hydraulic properties. Because groundwater curtailment has variable effects on streamflow, the decision maker is faced with the question of how to effectively and equitability curtail both surface and groundwater use during times of drought in accordance with section 22(1) of the WSA. This report proposes one possible approach for taking collective action on surface water and groundwater users when there is water shortage in a stream. The report also presents a spreadsheet based screening tool to help identify focus areas for temporary curtailment of groundwater pumping during droughts. The screening tool does not hinder the decision maker from the option of curtailing all groundwater users in a particular area during times of scarcity.

1.2 Hydraulic Connectivity between Wells and Streams

Groundwater and surface waters are linked in the hydrologic cycle. In many areas of B.C., groundwater discharge to surface streams can comprise a high percentage of baseflow, particularly in smaller streams during critical low flow periods. A stream reach that receives groundwater from an adjacent water table aquifer is a “gaining stream” (Figure 1A) and the aquifer and stream are hydraulically connected.

Pumping groundwater from hydraulically connected aquifers reduces surface flows in adjacent streams as shown in Figure 1. Groundwater diversions cause streamflow depletion by the combined effects of groundwater interception (Figure 1C) and induced infiltration from the stream (Figure 1D). The effect of streamflow depletion does not necessarily depend on the distance between the well and the stream. Wells located far from streams (km’s) can cause a reduction in streamflow, however, there is a time delay between the start of groundwater pumping and the observed streamflow depletion. The time delay can be very large, up to years, depending on the distance between the well and the stream and the aquifer properties (Barlow and Leake, 2012).

Similarly, curtailing groundwater pumping does not immediately stop the effects of streamflow depletion. There is a recovery period following pump shutoff during which the cone of depression gradually fills and the natural groundwater levels are re-established (Figure 1E). Streamflow depletion continues after pumping stops because groundwater that would otherwise discharge to the stream is going into aquifer storage. Over time, the natural groundwater gradients are re-established (Figure 1F).

A) Prior to pumping, groundwater discharges to gaining streams under natural gradient conditions.

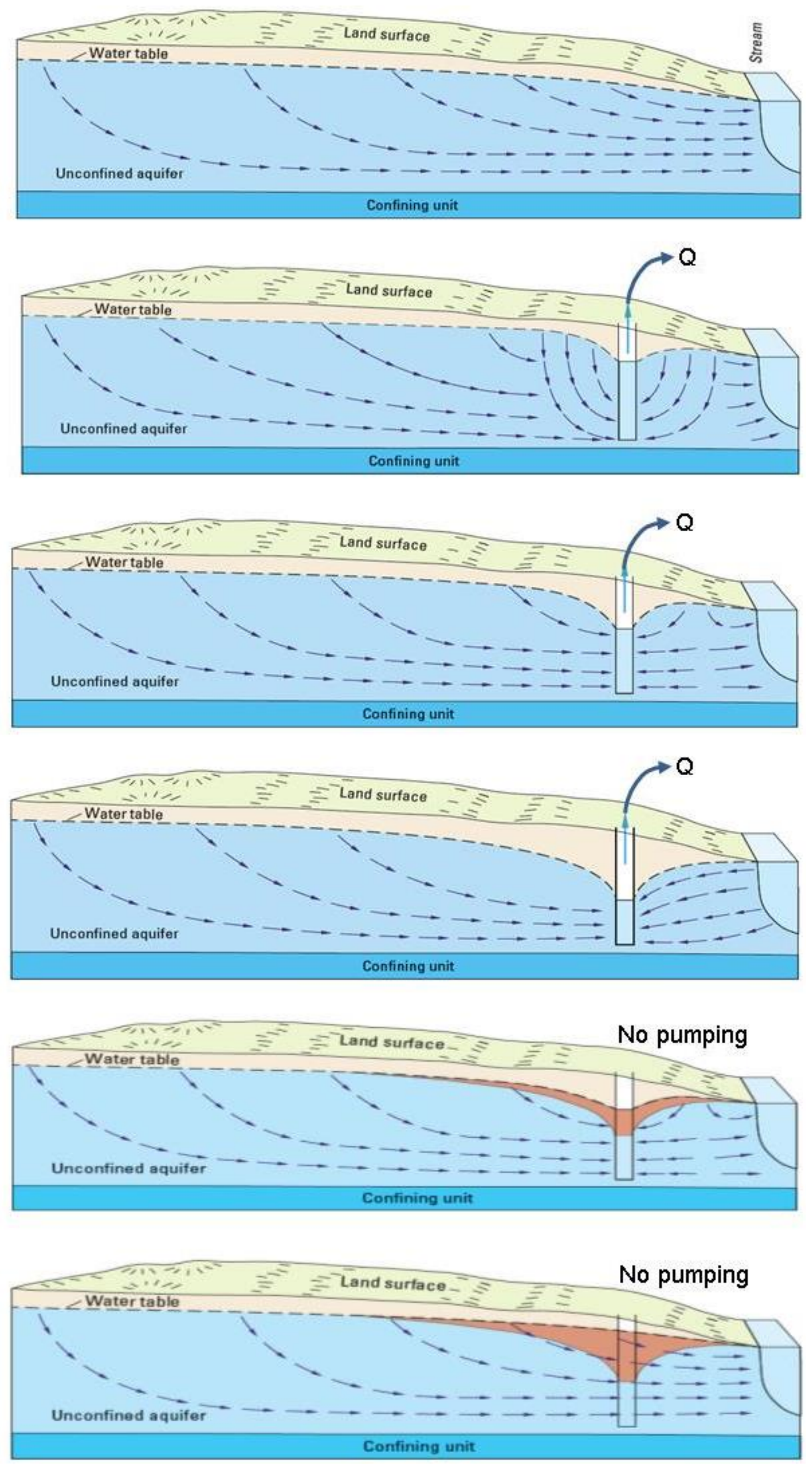
B) After start of pumping, the well initially draws water from aquifer storage, which does not affect streamflow.

C) Over time, the drawdown cone of depression stabilizes and the well draws water that would flow to the stream in the absence of pumping. Pumping reduces streamflow by intercepting groundwater flow.

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.

E) When pumping stops, groundwater levels begin to recover as aquifer storage increases. Streamflow depletion diminishes but continues after pumping stops.

F) Eventually, groundwater levels and streamflows recover to pre-pumping conditions.



EXPLANATION

Volume of cone of depression refilled since pumping stopped

Source: Barlow and Leake (2012)

FIGURE 1 Effects of groundwater pumping in a connected aquifer-stream system.

The rate at which streamflow recovers after pumping is stopped depends on the location of the well relative to the stream and the aquifer hydraulic properties (transmissivity, hydraulic conductivity, and storativity). Comparisons in Figure 2 show streamflow recovery is faster when wells are comparatively closer to streams, and aquifer hydraulic conductivity is comparatively larger. Curtailing groundwater diversions may produce a rapid response in streamflow recovery (e.g., hours, days), a gradual response in streamflow recovery after an extended delay (e.g., weeks, months), or the streamflow may not respond at all during the period of interest.

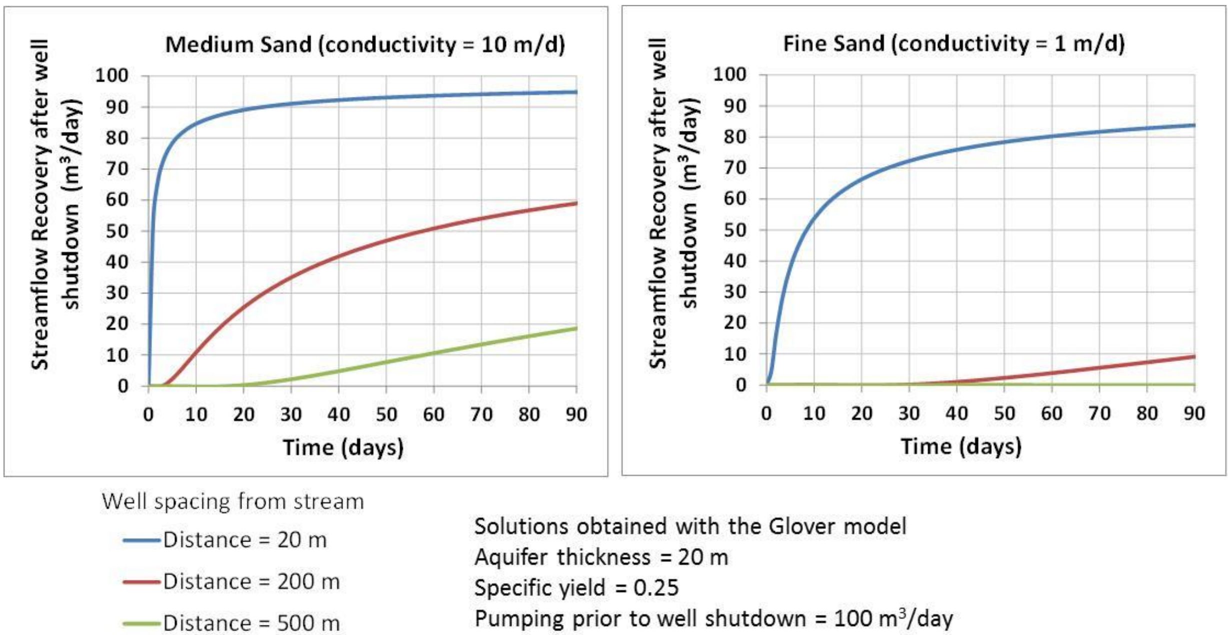


FIGURE 2 Hypothetical streamflow recovery after well shutdown.

1.3 Curtailment Approach

There are two general options for jointly administering short-term restrictions on surface and groundwater use during periods of water scarcity.

1. A decision maker can enforce the precedence of water rights for all surface water users and groundwater users in the connected aquifer based on FITFIR.
2. The Minister can make an order respecting diversion of water from a stream or connected aquifer that deviates from FITFIR to protect the survival of a fish population.

The screening tool broadly identifies areas where curtailment of groundwater pumping is most likely to result in recovery of streamflow within the period of interest to the decision maker. Thus, the tool informs curtailment activities in accordance with FITFIR, but only where curtailment actions are likely to have a benefit to streamflow recovery within the timeframe of interest.

This approach is analogous to current practices applied to surface water. When flow in a reach of a stream is too low and action needs to be taken on surface water users, the engineer will look upstream rather than downstream to address the problem. The challenge for curtailing groundwater diversion is identifying those groundwater wells that will provide for streamflow recovery during temporary periods of curtailment.

The screening tool is intended as a support tool that the decision maker may which to consider during water scarcity. Thus, the tool supports taking action under either of the curtailment options above.

2. SCREENING TOOL DESCRIPTION

2.1 Objective and Description

The objective of the screening tool is to support decision makers in groundwater curtailment and data collection activities. The screening tool identifies a zone of interest that is most likely to have a positive and timely influence on streamflow recovery during a specified short-term curtailment period. The screening tool is not intended to definitively identify those wells subject to curtailment; that needs to be done separately once the zone of interest has been identified using the screening tool.

The screening tool is a spreadsheet application adapted from the work of Bekesi and Hodges (2006). The tool uses a simplified approach to quantify the volume of streamflow recovery following curtailment of groundwater pumping at a well with a known pumping rate and distance from a stream. The result is a variable setback distance from the stream outside of which the curtailment of groundwater diversions is unlikely to have a positive or timely effect on streamflow recovery within an anticipated period of water shortage. This setback distance is referred to as the curtailment envelope.

Figure 3 illustrates the curtailment envelope concept. The blue line is the calculated curtailment envelope that relates the well distance from a stream and a pumping rate that would produce a target amount of streamflow recovery (0.2m^3/day in this example, the quantity for essential household use) within a forecasted curtailment period (30 days in this example). Wells that plot above this line are not likely to have appreciable effect on short-term streamflow recovery within the specified duration (30 days in this case). Wells that plot below the curtailment envelope should receive greater focus by the decision maker during periods of water scarcity and could be candidates for curtailment in accordance with FITFIR, for example. These wells should also receive focus on data collection efforts prior to curtailment activities, such as verification of well location, design, aquifer source, hydraulic connectivity, water use, and pumping rates in order for the model to reflect, as much as possible, actual conditions.

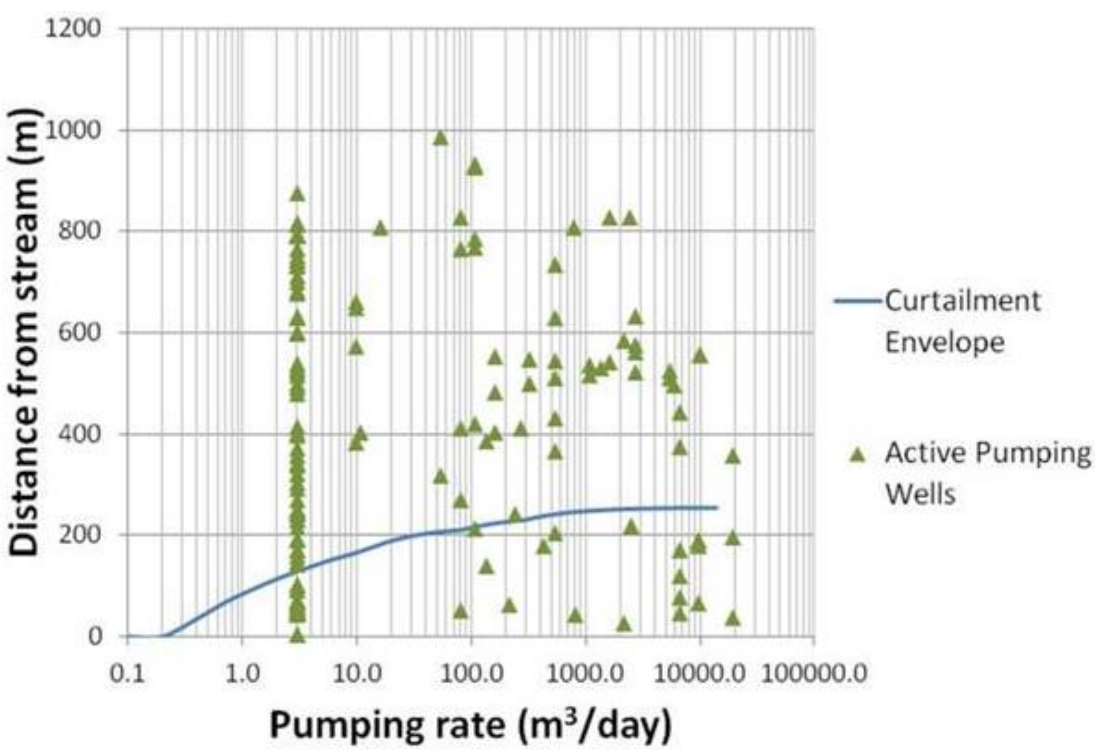


FIGURE 3 Curtailment envelope example.

Note the curtailment envelope concept and the screening tool do not provide estimates of streamflow recovery resulting from curtailment action, on either an individual well basis or a cumulative basis. Although estimates of streamflow recovery could be developed, use of streamflow recovery estimates to guide curtailment activities would be subject to uncertainty from modeling assumptions (described below), and could bias curtailment activities to larger users. The curtailment envelope concept is equitable in that all groundwater users (licensed and excluded) are treated equally within the FITFIR framework, regardless of the magnitude of streamflow recovery resulting from curtailment.

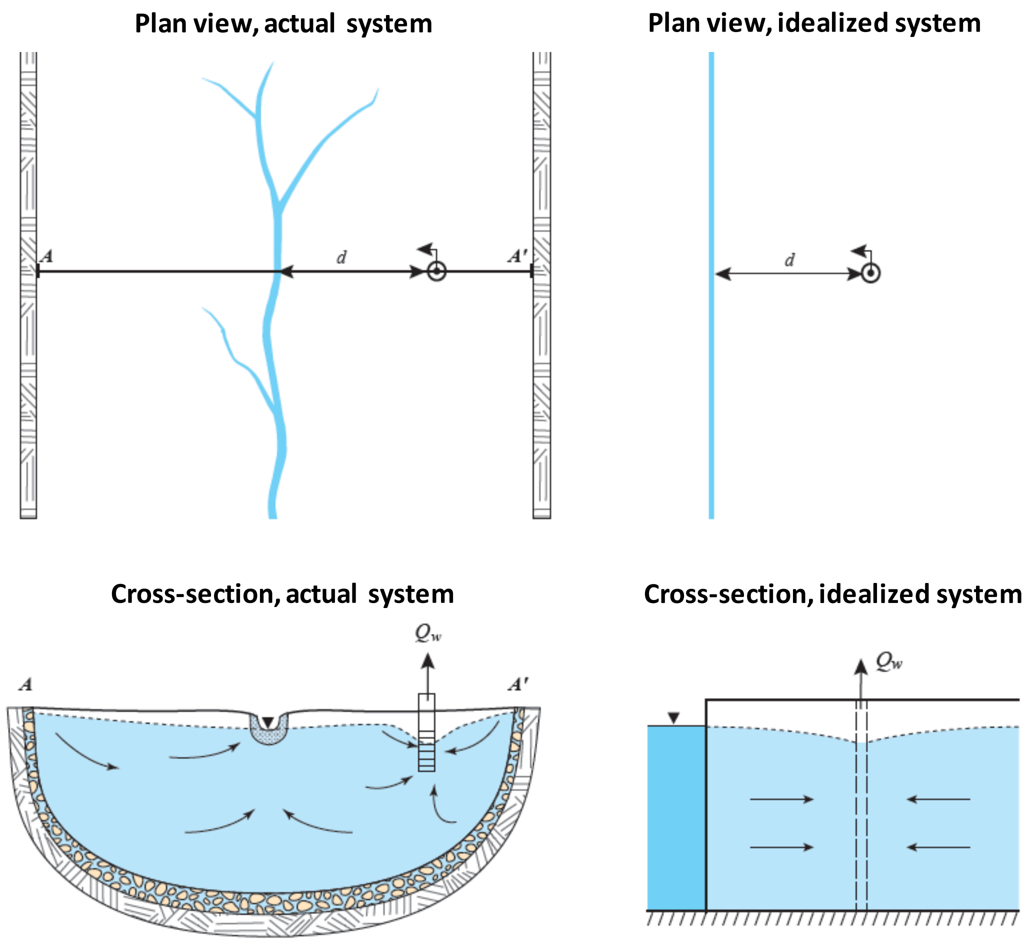
The screening tool is not designed to be used as a decision tool for curtailment action. Rather the tool is intended to assist decision makers in guiding a range of curtailment activities, including pre drought planning efforts, helping to focus and prioritize data collection efforts, and supporting evaluation of curtailment options. To this end, conservative assumptions are used to establish an initial curtailment envelope. Subsequently, the model parameters and the curtailment envelop should be refined as knowledge of groundwater use, aquifer parameters, and aquifer connectivity is gained.

2.2 Methodology and Assumptions

The procedure for determining the curtailment envelope uses the Glover model (Glover and Balmer, 1954) to calculate streamflow recovery following pump shutoff. The Glover model is among the first and most widely used methods to estimate streamflow depletion from groundwater pumping. The model is appropriate for screening tool applications for three reasons: 1) it is simple to solve in spreadsheets, 2) it has few parameters that are reasonably easy to determine or estimate, and 3) it is conservative in that it tends to over-estimate the streamflow depletion and recovery; i.e., estimates for streamflow recovery are more likely to place a well within the curtailment envelope.

The Glover model is founded on an idealized conceptualization of the aquifer/stream system shown in Figure 4, which encompasses the following 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 – water in the stream and the aquifer are perfectly connected;
- 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. If the aquifer is unconfined, the water table drawdown due to pumping is small and negligible;
- The stream is the only source of possible recharge;
- Pumping occurs from a single well screened over the entire thickness of the aquifer; and
- The pumping rate is constant and continuous.



Source: Barlow and Leake (2012)

FIGURE 4 Aquifer-stream conceptualization used in the Glover model.

Using the foregoing assumptions, Glover and Balmer (1954) developed the following expression to estimate the rate of streamflow depletion from groundwater pumping:

Glover Eq.

$$\frac{\Delta Q_s}{Q_w} = \mathrm{erfc}\left(\sqrt{\frac{Sd^2}{4Tt}}\right) \qquad \text{(Eq. 1)}$$

where

ΔQ_s	is change in streamflow caused by groundwater pumping (m^3/day);
Q_w	is the constant pumping rate (m^3/day);
$\Delta Q_s/Q_w$	is streamflow depletion expressed as a fraction of pumping;
erfc	is the complementary error function;
S	is aquifer storativity for confined aquifers or aquifer specific yield for unconfined aquifers (unitless);
d	is the distance between the well and the river (in metres);
T	is aquifer transmissivity (m^2/day); and
t	is time since the start of pumping from the well (in days).

Figure 5 shows example solutions of the Glover model for aquifer parameters that are typical of unconfined sand and gravel aquifers in B.C. The rate of streamflow reduction caused by groundwater pumping depends on the distance between the well and the stream. A well adjacent to the stream bank (5 m) rapidly reduces streamflow, with greater than 90% of the pumping volume derived from streamflow in less than a day. Wells situated further from streams also cause streamflow depletion, but the rate of depletion slows as the spacing distance increases. Given sufficient time, all three wells will approach a steady-state where pumping has little effect on aquifer storage and nearly all water pumped from the well is derived from streamflow (i.e., $\Delta Q_s/Q_w = 1$).

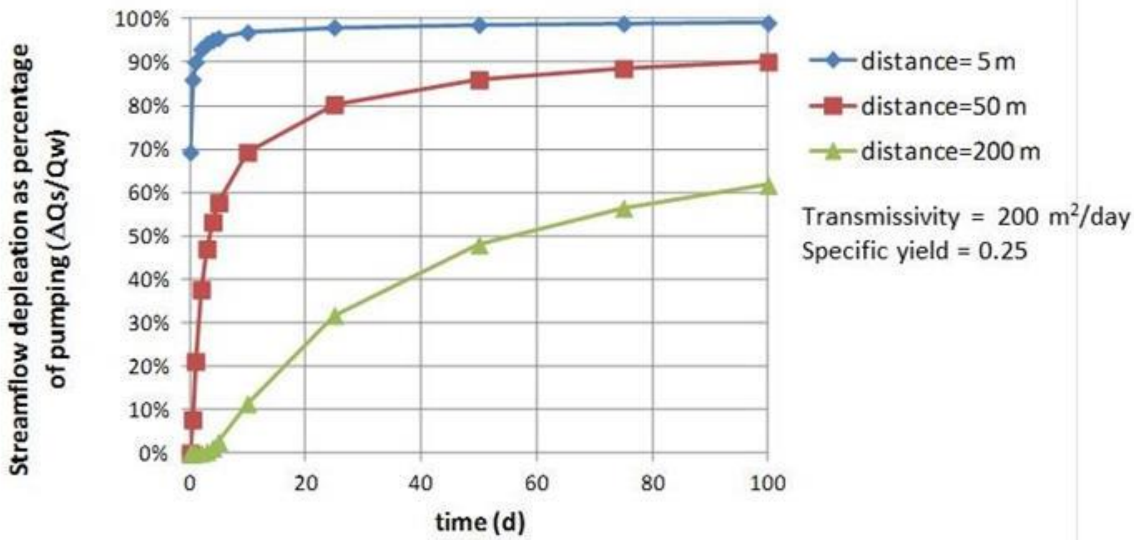


FIGURE 5: Example solutions of the Glover model.

Jenkins (1968) extended the Glover model to estimate the response of streamflow depletion following pump shutoff. Using the method of superposition, Jenkins (1968) estimated streamflow recovery as the difference between the rate of streamflow depletion from the pumping well (pumping continuously) and an imaginary injection well at the same location, where injection is equal to the pumping rate and begins at the time of pump shutoff. This can be expressed as,

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

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

where t_s is the time at pump shutoff. Figure 6 illustrates the Jenkins approach where groundwater diversions stop after 30 days of pumping ($t_s = 30$ days). Similar to depletion, streamflow recovery is fastest from curtailment of wells that are closest to the stream. Wells, further from the stream also contribute to streamflow recovery, but the response time is longer.

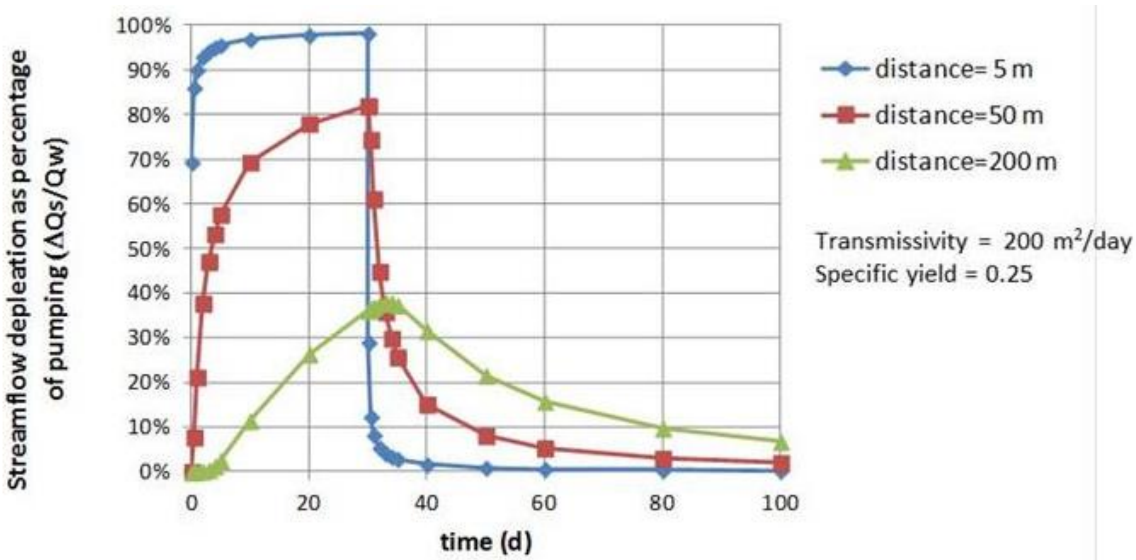


FIGURE 6: Example solutions with the Jenkins method to estimate streamflow response following pump shutoff.

The screening tool uses the Jenkins approach (Eq. 3) to determine streamflow recovery following pumping curtailment. However, the transient conditions of the drawdown cone at the time of pumping curtailment are unknown (i.e., the value of $\Delta Q_s/Q_w$ at t_s is unknown). Therefore, we further assume that groundwater pumping prior to well shutdown is at steady state. In other words, all pumped groundwater just prior to pump shutoff is from streamflow depletion (i.e., $\Delta Q_s/Q_w = 1$). This is a conservative approach, as the model will over-predict streamflow recovery. With this additional assumption, Eq. 3 becomes:

$$\frac{\Delta Q_s}{Q_w} = 1 - \operatorname{erfc}\left(\sqrt{\frac{Sd^2}{4Tt}}\right) \quad \text{after pump shutoff } (t > t_s) \qquad \textit{(Eq. 4)}$$

The second term on the right-hand-side represents the change in streamflow following pump shutdown. From this term, the volume of streamflow recovery resulting from pumping curtailment is expressed by:

$$\Delta Q_s = Q_w \operatorname{erfc}\left(\sqrt{\frac{Sd^2}{4Tt}}\right) \qquad \textit{(Eq. 5)}$$

Eq. 5 is equivalent to the Glover model in Eq. 1. This equation is used to calculate the curtailment envelope as follows.

Curtailment Envelope Calculation Procedure

1. Based on input from water managers, determine the forecasted curtailment period in days (t_c).
2. Specify the target streamflow recovery discharge for curtailment action ($\Delta Q_{s\,min}$). This is the target amount of streamflow recovery that curtailment action at individual wells should achieve within the forecasted curtailment period. If curtailment action at a particular well is estimated to achieve less than the target recovery discharge, then curtailment is considered unlikely to affect streamflow recovery within the forecast period and the well can be excluded from consideration of curtailment. In this work, the target streamflow recovery discharge is initially set to the exemption quantity for essential household uses, but alternative values are also explored.

3. Estimate ranges of aquifer transmissivity (T) and storativity (S) from available measurements or literature information.
4. For a given pumping rate (Q_w), use Eq. 5 to determine the corresponding well spacing (d) that produces the threshold streamflow recovery ($\Delta Q_{s\,min}$) at the end of the curtailment period (t_c). In other words, find the well spacing distance (d) that satisfies:

$$\frac{\Delta Q_{s\,min}}{Q_w} = \text{erfc}\left(\sqrt{\frac{Sd^2}{4Tt_c}}\right) \qquad \textit{(Eq. 6)}$$

   The spreadsheet application solves Eq. 5 with Visual Basic functions developed by Dr. Bruce Hunt (Hunt, 2012). The spreadsheet model uses interpolation procedures to find the distance d associated with a single pumping rate Q_w, and the specified values of t_c, $\Delta Q_{s\,min}$, T, and S.
5. Repeat step 4 over the range of pumping rates present in the aquifer. The result is single curtailment envelope for a specified value of t_c, ΔQ_{min}, T, and S (e.g., Figure 3).

Given that aquifer hydraulic properties are inherently heterogeneous and uncertain, the spreadsheet application includes the capability to determine a curtailment envelope from a range of transmissivity (T) and storativity (S) values that reflects the variability of available information. For example, users could specify measured values for T and S compiled from local pumping test data if available, or in the absence of local measurements, a range of T and S estimates based on regional studies, lithological information, professional judgement, or textbook values may be used.

Following the approach of Bekesi and Hodges (2006), the screening tool assembles a collection of curtailment envelopes based on a range of T and S values provided by the user. For example, Figure 7 shows 50 curtailment envelopes calculated from T values that range between 6 to 6500 m^2/day, and S values between 0.2 and 0.3. Each curve is generated with a fixed value of T and S taken randomly from the values provided by the user.

Once a family of curtailment envelopes is determined, a single envelope for groundwater governance is established as a percentile from the collection of curves (Figure 7). This percentile value is referred to as a confidence factor, and is a user defined input parameter. Bekesi and Hodges (2006) used a conservative 90th percentile curve for groundwater allocation. For temporary groundwater curtailment, a 50th percentile curtailment envelope is recommended because curtailment actions do not have long-term consequences, and because solutions from the Glover model are conservative in that they over-estimate the rate of streamflow recovery.

A limitation of the probabilistic approach is that the calculated curtailment envelope is not unique and will vary from run-to-run. The degree of variability in the final curtailment envelope depends on the specified number of curves in the family of envelopes and the range of specified of T and S values. The variability in the final curtailment envelope can be reduced by increasing the specified number of curves in the family of envelopes and reducing the range in specified of T and S values.

Alternatively, the user may calculate a single (unique) curtailment envelope by specifying a single value for T and S that are assumed to represent homogeneous aquifer conditions.

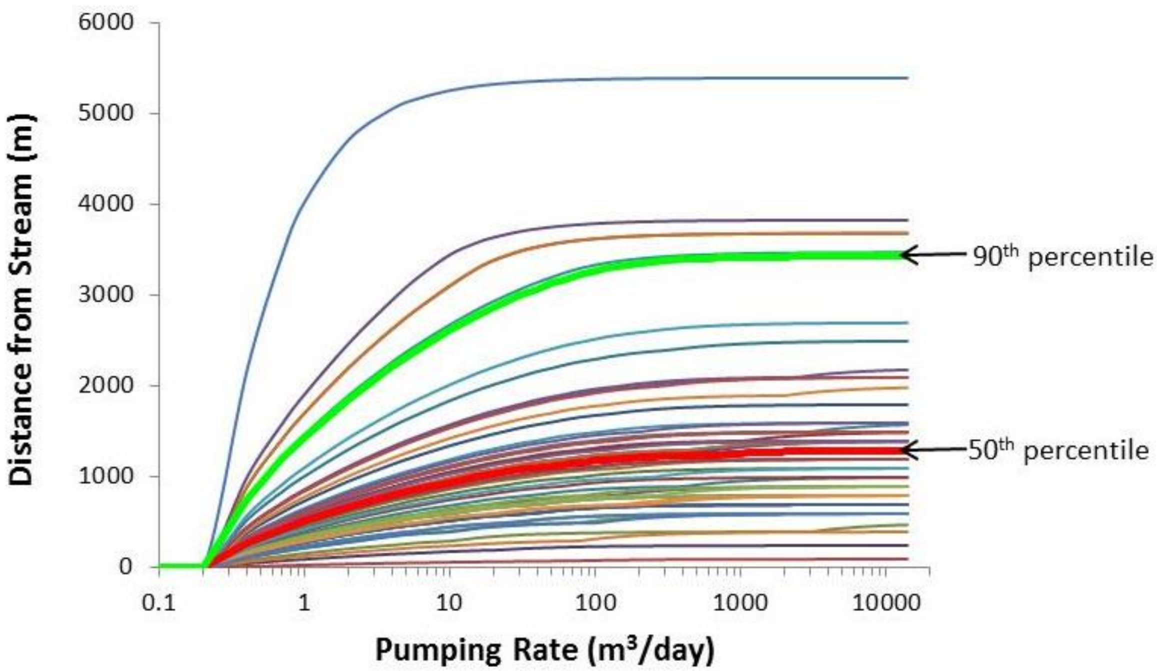


FIGURE 7: Collection of curtailment envelopes generated from a range of T and S values.

3. DATA REQUIREMENTS AND DATA SOURCES

3.1 Groundwater Well Locations

Information on the location of all water wells is essential for jointly regulating surface and groundwater use. Historically, there has been no mandatory requirement to report the location of water wells to the provincial government. The B.C. Ministry of Environment (MoE) maintains a database of voluntarily submitted water well records called WELLS. This database contains information on well location, diameter, depth, construction materials, aquifer lithology, static water level, and well yield at the time of drilling. In some cases, a well record might also contain pumping test data. With implementation of the WSA, water well drillers are required to submit well records to MoE for processing into WELLS.

Information in WELLS is publically assessable through an online search engine (https://a100.gov.bc.ca/pub/wells/public/indexreports.jsp), and through the online mapping program iMapBC (https://arcmaps.gov.bc.ca/ess/sv/imapbc/). The data are also accessible through the provincial GIS data warehouse for provincial staff and qualified users.

Given that information in WELLS is incomplete or includes inaccurate information, local well surveys and ground-truthing of existing information should be considered for high-priority areas where there is a likelihood of curtailment activities. The screening tool can assist in identifying stream setbacks where data collection efforts should be focused. Ideally, well surveys are conducted in advance of water scarcity periods, and survey results are used to update well records in WELLS.

3.2 Hydraulic Connectivity

Determining the hydraulic connectivity between water wells and surface waters is a key task, as this establishes whether groundwater diversions or changes in groundwater pumping rates potentially affect surface water levels or flows. After establishing the location of wells in the vicinity of surface waters, the screening tool requires users to specify the hydraulic connectivity (“yes” or “no”) for each well.

All hydraulically connected wells are treated equally in the screening tool in that response of surface waters to changes in pumping is determined only by the well's distancefrom the stream and the aquifer's hydraulic properties. The screening tool does not account for other factors that can impede connectivity between wells and surface waters, such as aquifer heterogeneities and streambed properties.

Establishing hydraulic connectivity of individual wells requires consideration of the aquifer and local stratigraphy. It is not sufficient to establish connectivity solely on the basis of the well's proximity to surface waters. Wells can be effectively disconnected from surface water, even when located in close proximity to streams; for example if wells are drilled into underlying bedrock aquifers, or into deeper confined aquifers separated from surface waters by thick strata of low hydraulic conductivity. Conversely, shallow, high-capacity water wells in productive water table aquifers can be strongly connected to streams, even when located at considerable distances from streams.

Another consideration is the potential for water wells to intercept groundwater flow to different stream segments and neighboring watersheds when pumping occurs in a stream network. In particular, wells pumping below semi-confining aquitards create a wider distribution of surface water depletion, potentially affecting both local and regional systems (Morgan and Jones, 1999). For simplicity, the spreadsheet tool does not apportion effects from pumping on multiple stream segments. Rather, the spreadsheet tool assigns connectivity from a pumping well to a single stream/watershed defined by the user-supplied distance to stream. This is justified because methods to apportion streamflow depletion would overly complicate the modeling approach, inconsistent with intended use for screening level assessments.

Various desktop and field methods are available to assess stream-aquifer connectivity and to quantify SW-GW fluxes. Desktop methods include hydrograph analysis, hydrograph separation, and Darcy law calculations. Rosenbury and LaBaugh (2008) provide guidance on field techniques to infer or measure GW-SW connectivity and fluxes.

A guidance document on determining hydraulic connectivity developed by MoE (Wei et al, 2016) provides a simple method for inferring the hydraulic connectivity between water wells and surface water based on aquifer types (Wei et al, 2014). As a first approximation, Table 1 can be used to qualitatively evaluate potential for hydraulic connection based on aquifer type. The aquifer type associated with a well can be determined in three ways depending on available information.

- *WELLS database*: Many of the wells registered in the WELLS database have been associated to particular aquifers, which already have the type assigned to them. This information is accessible through attribute tables in the provincial GIS data warehouse.
- *Well construction report*: If a well in WELLS is not associated with a mapped aquifer, determine if the well is within the polygon of one of more mapped aquifers. If yes, then relate the lithologic descriptions from the well construction report to the characteristics of the aquifer type(s).
- *Other information*: If the well is outside of a mapped aquifer or there is no lithologic description, other information can be used to infer aquifer type, including: well depth and location, well lithology information inferred from neighboring wells (if available), regional surficial or bedrock geologic mapping, and topography to infer the aquifer type; staff with knowledge in hydrogeology would be of help.

The screening tool has a comment field to note the basis of hydraulic connectivity determination or to note data limitations.

TABLE 1: Aquifer type and associated hydraulic connectivity.

Aquifer type	**Hydraulic Connectivity Potential**
Type 1: Unconfined or partially confined fluvial and glaciofluvial aquifers along large (type 1a), medium (type 1b) and small (type 1c) streams.	SW-GW connectivity is likely. GW discharges support baseflow. Streamflow depletion from GW diversions is expected.
Type 2: Unconfined deltaic aquifers formed in river deltas.	SW-GW connectivity is likely. GW generally supports baseflow. Streamflow depletion from GW diversions is expected.
Type 3: Unconfined alluvial fan aquifers.	SW-GW connectivity is likely for aquifers at the base of mountains and along valley walls.
Type 4a: Unconfined aquifers of glaciofluvial origin	SW-GW connectivity is likely when surface water is present.
Type 4b: Confined aquifers of glaciofluvial origin.	SW-GW connectivity is variable. SW-GW connectivity is unlikely when confining aquitards are thick, broadly continuous, and have low hydraulic conductivity in comparison to the aquifer. SW-GW interaction potentially occurs where aquitards are discontinuous, thin, have significant permeability, or aquifers outcrop to surface waters.
Type 5a: Fractured sedimentary rock aquifers.	SW-GW is usually limited due to the typically large depth, low transmissivity, and low yield of most bedrock wells. Strong hydraulic connectivity between bedrock wells and surface water is possible but connection is often confirmed empirically from response to pumping. Factors that suggest 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 the presence of shallow water tables in bedrock terrains that sustain baseflow.
Type 5b: Karstic limestone aquifers.	There is a potential for strong hydraulic connectivity to surface waters. However, there are few identified aquifers in BC and they are sparsely developed for groundwater use.
Type 6a - flat-lying or gently-dipping volcanic flow rock aquifers.	Same as 5a.
Type 6b - Crystalline granitic, metamorphic, metasedimentary, metavolcanic and volcanic rock aquifers.	Same as 5a.

3.3 Distance to Stream

The shortest distance between wells and nearby streams is a required input parameter for all wells. The distance calculation can be automated using the ArcGIS analysis tool "proximity-generate near table function." The Generate Near Table function (GNT) determines the nearest distance from each input features (i.e., water wells) to one or more user defined nearby features (i.e., streams and their tributaries). The results from GNT are recorded in an output table that contains the proximity information such as IN_FID (input feature ID, i.e. water well), NEAR_FID (nearest feature ID, i.e. stream name), and NEAR_DIST (nearest distance).

Prior to running the GNT function in ArcMap, the shape file for the input feature (water wells) needs to be customized to include only the wells of interest. For example, the wells associated with a particular aquifer are extracted/clipped from WELLS using the extent of the aquifer polygons. Similarly, the shape file of the near feature (i.e., streams and major tributaries) needs to be customized to extract/clip the streams and tributaries using the extent of the aquifer polygons. The rule of thumb here is to include only streams and tributaries with licensed Points of Diversion (PODs), excluding the smaller tributaries from the near feature shape file where no diversion and use is occurring. The GNT function joins the input feature table (water well) and the near feature table (streams and tributaries) using the join and relate function in ArcMap. The result is an output table of wells and associated shortest distances to the nearest stream or tributary.

3.4 Groundwater Pumping Rates

The groundwater pumping rate is an input requirement for all wells, as the curtailment envelope is a direct function of pumping rate. The screening tool assumes a constant and continuous pumping rate.

Information on groundwater pumping is difficult to obtain as there is generally no requirement to monitor and report usage. Voluntary submission of groundwater pumping information can be gathered through requests to specific users (i.e., large users) or through broader regional surveys. The screening tool can also help identify focus areas for data collection.

In the absence of specific pumping records, pumping rates can be estimated from water use information (domestic, irrigation, commercial) and well construction information including the well size, aquifer properties, and estimated yield measured at the time of drilling. Pumping rates can be updated over time as data is collected, or can be inferred from licensed allocations after groundwater licenses are issued. The screening tool has a comment field to note the basis of pumping rate estimates or to flag wells with data limitations for follow up investigation.

In the absence of any information from which to estimate pumping rate, the input field may be left blank. The well is then included in an output list of wells with incomplete pumping information. Because some of these wells are potentially subject to curtailment, they warrant follow-up investigation to update pumping information.

3.5 Aquifer Transmissivity and Storativity

The aquifer transmissivity (T) is a measure of the aquifer's ability to transmit water to a well. The storativity (S) is a measure of amount of water released from the aquifer under pumping stresses. Long-term aquifer pumping tests generally provide the most representative estimates of T and S. Therefore, values used in the screening tool are ideally from local pumping test data. Potential sources of pumping test data include the WELLS database, specific reports in EcoCat, and reports held by local water purveyors and municipalities. With implementation of the WSA, groundwater pumping test data will also be available from technical assessment reports that are provided as part of the groundwater license application.

If aquifer-specific pumping test data are limited or not available, characteristic values of T and S from similar aquifer types may be used, if appropriate. 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), and the Cowichan Valley Regional District (Carmichael et al., 2014). An objective of these studies was to compile all available pumping test data and to reinterpret these data with a consistent analysis approach. Detailed study information and individual test data are available from these source reports.

3.6 Curtailment and Aquifer Parameters

The curtailment and model parameters are input quantities that define the constraints of the specific curtailment action and how the curtailment envelope is calculated.

- *Curtailment period*: This is the anticipated duration of curtailment action (i.e., t_c in Eq. 2). This is a forecasted duration of water shortage based on local management conditions and criteria, for example expected irrigation periods or duration of fish runs. It is a short-term or temporary period generally no more than 90 days as specified in the WSA. The curtailment period directly affects the size of the curtailment envelope. A longer curtailment period will have a wider curtailment envelope affecting a larger number of groundwater users.
- *Target recovery discharge*: Is the minimum amount streamflow recovery that curtailment action on any individual well should produce within the forecasted curtailment period (i.e., $\Delta Q_{s\,min}$ in Eq. 6). Wells that do not achieve the minimum level of streamflow recovery during the curtailment period are not subject to curtailment. In this work, the target streamflow recovery is set to the exemption volume for essential household needs, approximately 0.2 m^3/day/household (The *WSA* defines essential household needs to be 250 l/d/household). This small value was selected in order to capture all groundwater users in the curtailment process (including excluded domestic users) that can potentially affect some recovery in streamflow, even if the amount is small compared with the magnitude of streamflow. This provides an element of fairness to the curtailment process because all groundwater users are addressed equally. However, alternative streamflow recovery thresholds can be specified in the screening tool. In general, a smaller threshold value will result in a wider curtailment envelope affecting a larger number of groundwater users.
- *Confidence Factor*: A percentile value (0-100%) that is used to define the curtailment envelope from the collection of curves calculated with a range of T and S values (Figure 7). The recommended percentile to provide for reasonable curtailment is 50%. A larger percentile can be used to increase confidence of effective curtailment action. However, this will widen the size of the curtailment envelope and affect a larger number of users.
- *Number of curves in the collection of curtailment envelopes:* A value between 1 and 500 that determines the number of curtailment envelopes calculated using random values of T and S (Figure 7). A larger number (e.g., 500) provides more stable results but requires more computation time. A smaller number (e.g. 10) has short computation time but leads to more variable results. A small number is recommended during input and testing, and a large number is recommended for final calculations.

4. SCREENING TOOL LAYOUT

The screening tool is a Microsoft Excel based application. There are three worksheets associated with each modeled area as follows:

1. A ‘water wells’ data worksheet;
2. An ‘input data’ sheet that defines the aquifer and curtailment parameters; and
3. An ‘output’ worksheet that identifies the wells in the study area, shows the calculated curtailment envelope, and lists the wells within the curtailment envelope. Wells within the curtailment envelope are ranked in accordance with their FITFIR precedence dates.

4.1 Water Wells Worksheet

The ‘water wells’ worksheet contains the regional water well information. These data provide input to the screening tool, which searches the available information to identify those wells that are potentially subject to curtailment in a particular watershed, aquifer, or study area of interest.

Information in the ‘water wells’ worksheet is not limited to a particular study area, and may include wells that are disconnected from the surface waters of interest, or wells outside of the study area. This provides flexibility for making changes to well information or examining alternative study areas. Users may modify the worksheet to include new wells, or to rearrange or sort existing information.

Table 2 describes the information in the ‘water wells’ worksheet, the primary data sources, and how the information is used in the screening tool. Columns A through G are required information used by the screening tool. Subsequent columns display optional supporting information. The optional columns may be deleted or users may add additional columns of information, as preferred.

TABLE 2: Input information in the Water Wells worksheet.

Column ID & variable name	Required / optional	Data source	How information is used in screening tool
A) Well tag number	Required	WELLS database	Used as the primary well identifier.
B) Construction or License date	Required	WELLS database	In the project, construction data is used to infer date of precedence in a licence. If unknown, the well is assigned unknown precedence date and unknown FITFIR rank.
C) Distance to stream (m)	Required	User input	Used directly in Glover equation. Determined from the ArcGIS Generate Near Table function.
D) Stream name	Required	User input	Determined from the ArcGIS Generate Near Table function. Not used directly in calculations, but included in output tables.
E) Pumping rate (m^3/day)	Required	User input	Used to determine if a well is inside or outside of calculated curtailment envelope. If blank, the well is flagged with incomplete pumping info. This could be either the licensed rate or actual measured rate, if known, or an estimated rate if unknown.
F) Local aquifer identification number	Required	User input	The numeric value in this field is used to link the well to a specific study area of interest. The ID number may be equivalent to a mapped aquifer, or may be a unique number representing a combination of aquifers or area of interest that includes mapped and/or unmapped aquifers. Keep in mind that wells within an aquifer or area of interest does not imply a hydraulic connection to surface waters; it can be either connected or disconnected.
G) Assumed hydraulic connection	Required	User input	A ‘yes’ or ‘no’ input indicating if the well is hydraulically connected to surface waters. This field is used in the ‘output’ sheet to identify the wells subject to curtailment.
H) Basis for pumping	Optional	User input	Comment field for pumping quantity estimation.
N) Basis for connectivity	Optional	User input	Comment field for connectivity assessment.

There are two main sources of information in the ‘water wells’ worksheet: the WELLS database and user supplied information. The first step is to populate the Water Wells worksheet with well tag numbers and associated information obtained from the WELLS database. The easiest approach is to compile the appropriate WELLS database attribute tables for a spatial area of interest through ArcGIS. Next, supplemental and supporting information and can be entered, as available. For example, information in WELLS such as well diameter, water use type, and estimated yield might help to infer pumping rates.

4.2 Input Worksheet

The 'Input' worksheet has two functions: 1) to specify the user-supplied model input parameters and 2) to perform the curtailment envelope calculations.

Model input parameters are entered into the yellow highlighted cells as shown in Figure 8. All other cells should not be changed.

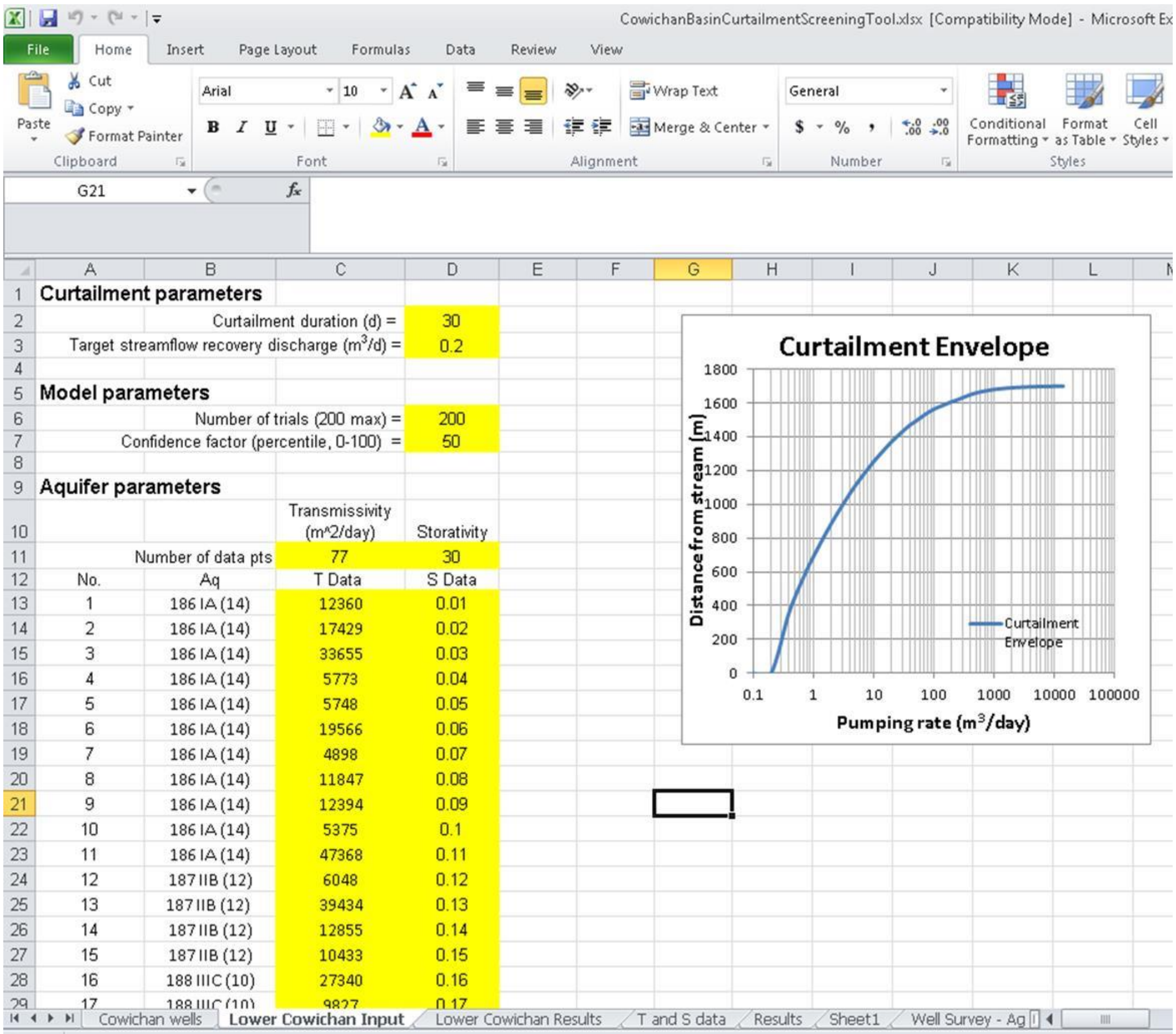


FIGURE 8: Screen capture of the 'Input' worksheet. Highlighted cells are user-defined parameters.

The user must specify the following input data.

<u>*Curtailment parameters*</u>

Cell D2 Curtailment duration (days) is the anticipated duration of short-term curtailment action (i.e., t_c in Eq. 6). This is a forecasted period specified by the decision maker in the public notice of water use restrictions.

Cell D3 Target streamflow recovery discharge (m^3/day): The minimum amount streamflow recovery produced by a curtailment action on an individual well (i.e., $\Delta Q_{s\,min}$ in Eq. 6).

Model parameters

Cell D6 Number of trials (0-500): The number of curtailment envelopes calculated with random values of T and S (i.e., the number of curves in the family of curtailment envelopes shown in Figure 7). A large number of trial (i.e., 500) is recommended to reduce variability in the calculated curtailment envelope.

Cell D7 Confidence factor (0-100%). A percentile value used to define the curtailment envelope from the collection of curtailment curves. A confidence factor of 50% is reasonable.

Aquifer parameters

Cell C11 Number of transmissivity data points.
Column C The corresponding transmissivity data (m^2/day) are entered in column C, beginning in row 13. The number of T values (rows) must equal the number specified in C11.
Cell D11 Number of storativity data points.
Column D The corresponding storativity data are entered in column D, beginning in row 13.

If the user prefers to calculate a single (unique) curtailment envelope assuming homogeneous T and S, then set the number of T values (C11) and S values (D11) equal to 1. Specify the homogeneous T and S values in cells C13 and D13, respectively. Also, set the number of trials (D6) to 1, and set the confidence factor to 100%.

4.3 Output Worksheet

The 'output' worksheet is used to define the aquifer area of interest and shows the corresponding model results. There are five components of information as follows:

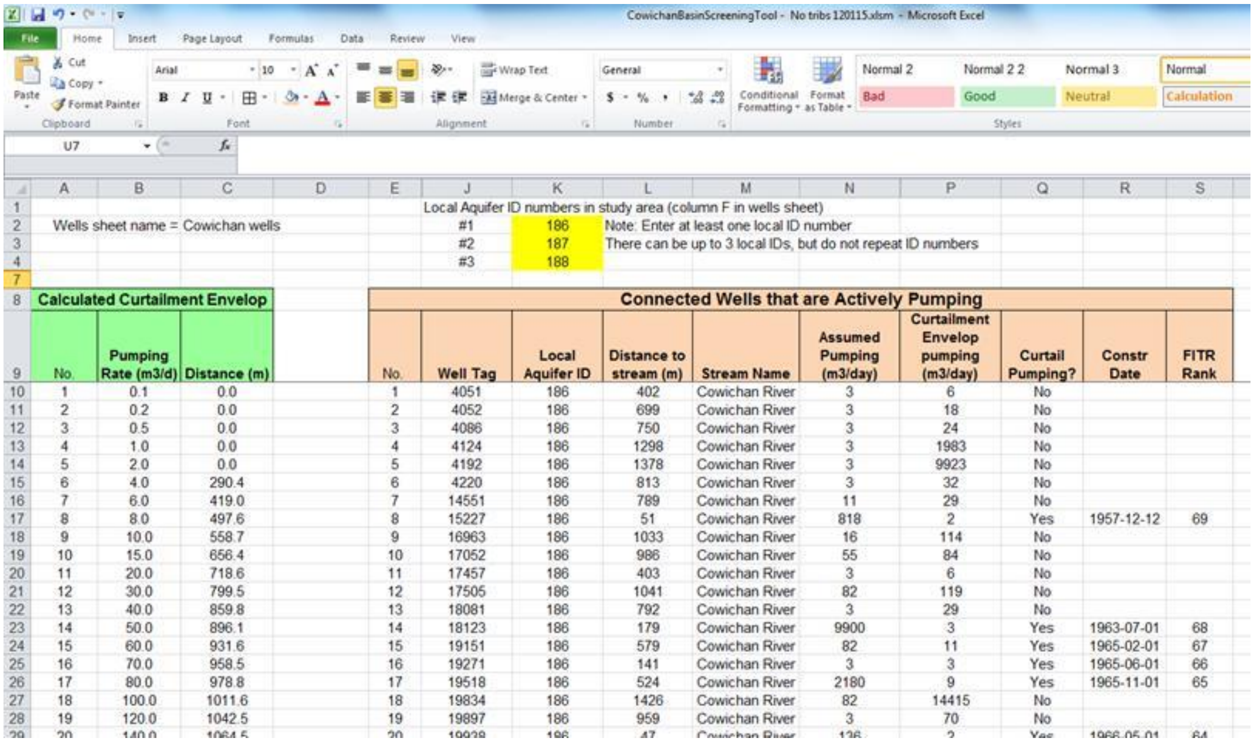
Study area identification

The user must first identify the aquifer study area to which curtailment actions are under consideration. The study area is defined by the specifying aquifer ID numbers in the highlighted cells K2, K3, and K4 of the 'output' worksheet, as shown in Figure 9. These aquifer ID numbers correspond to local ID numbers in column F of the 'water wells' worksheet (see Table 2). Note the aquifer ID numbers can coincide to mapped aquifer numbers or alternatively can be a local user defined ID number.

The user can specify up to three aquifer ID numbers, which is useful if the study area includes multiple aquifers such as stacked or overlapping aquifers. If there are less than three aquifers in the study area, the unused fields should be left blank. However, at least one ID number must be specified. If there are more than three aquifers in the study area, the user can use local IDs to represent combined aquifer systems.

Calculated curtailment envelope

Columns B and C show the tabulated curtailment envelope based on parameters specified in the 'input' worksheet (Figure 9).



Calculated Curtailment Envelop			Connected Wells that are Actively Pumping									
No.	Pumping Rate (m3/d)	Distance (m)	No.	Well Tag	Local Aquifer ID	Distance to stream (m)	Stream Name	Assumed Pumping (m3/day)	Curtailment Envelop pumping (m3/day)	Curtail Pumping?	Constr Date	FITR Rank
1	0.1	0.0	1	4051	186	402	Cowichan River	3	6	No		
2	0.2	0.0	2	4052	186	699	Cowichan River	3	18	No		
3	0.5	0.0	3	4086	186	750	Cowichan River	3	24	No		
4	1.0	0.0	4	4124	186	1298	Cowichan River	3	1983	No		
5	2.0	0.0	5	4192	186	1378	Cowichan River	3	9923	No		
6	4.0	290.4	6	4220	186	813	Cowichan River	3	32	No		
7	6.0	419.0	7	14551	186	789	Cowichan River	11	29	No		
8	8.0	497.6	8	15227	186	51	Cowichan River	818	2	Yes	1957-12-12	69
9	10.0	558.7	9	16963	186	1033	Cowichan River	16	114	No		
10	15.0	656.4	10	17052	186	986	Cowichan River	55	84	No		
11	20.0	718.6	11	17457	186	403	Cowichan River	3	6	No		
12	30.0	799.5	12	17505	186	1041	Cowichan River	82	119	No		
13	40.0	859.8	13	18081	186	792	Cowichan River	3	29	No		
14	50.0	896.1	14	18123	186	179	Cowichan River	9900	3	Yes	1963-07-01	68
15	60.0	931.6	15	19151	186	579	Cowichan River	82	11	Yes	1965-02-01	67
16	70.0	958.5	16	19271	186	141	Cowichan River	3	3	Yes	1965-06-01	66
17	80.0	978.8	17	19518	186	524	Cowichan River	2180	9	Yes	1965-11-01	65
18	100.0	1011.6	18	19834	186	1426	Cowichan River	82	14415	No		
19	120.0	1042.5	19	19897	186	959	Cowichan River	3	70	No		

FIGURE 9: Screen capture of the 'Output' worksheet. Highlighted cells are user defined parameters.

<u>Connected wells that are actively pumping</u>

Columns E through T identifies those wells in the study area aquifers that are specified as hydraulically connected to surface waters and are actively pumping (i.e., the pumping rate is greater than zero). These wells are potentially subject to curtailment depending on the well's distance from surface waters and the pumping rate. For each well, the 'output' worksheet shows the following information:

Columns K-N	Basic well information: Information copied from the 'water wells' worksheet including the well tag number, the associated aquifer ID, distance from surface waters, and assumed pumping rate.
Column P	Curtailment envelope pumping rate: This is the pumping rate on the calculated curtailment envelope corresponding to the distance between the well and the surface waters (Column L). It is calculated by linear interpolation from the tabulated curtailment envelope in columns B and C.
Column Q	Curtail pumping?: This column indicates if the well is inside (Yes) or outside (No) of the curtailment envelope. If the assumed pumping rate of the well (Column N) is less than curtailment pumping rate (Column P), the well is outside of the curtailment envelope. This suggests groundwater curtailment at this location is not likely to affect streamflow recovery within the forecasted curtailment period. Conversely, if the assumed pumping rate of the well (Column N) is greater than curtailment pumping rate(Column P), the well is inside of the calculated curtailment envelope. This suggests groundwater curtailment at this location could potentially have a positive benefit to streamflow recovery within the curtailment period.
Column R	Construction date: The well construction date copied from the 'water wells' worksheet is used as a surrogate date of precedence for the well. An unknown

	('Unk') construction date indicates no information is available and follow up investigation could be warranted for this well.
Column S	FITFIR rank: This column indicates the precedence of curtailment activities for all wells within the curtailment envelope based on the well construction date. A rank of 1 indicates the most junior precedence date, and would be the first well subject to curtailment under the FITFIR policy.

A chart showing the curtailment envelope (columns B and C) and the active pumping wells (columns L and N) is shown in the adjacent columns. The user may need to manually adjust the scales of the chart to match data ranges for the area of interest.

Connected wells with insufficient pumping information

Columns AI and AH identifies well tag numbers of wells in the study area aquifers that are considered hydraulically connected to surface waters but have insufficient pumping information. These wells potentially contribute to streamflow depletion depending on pumping rate and should be flagged for follow up investigation prior to curtailment action.

Connected wells that are not actively pumping

Columns AQ and AR identifies well tag numbers of wells in the study area aquifers that are considered hydraulically connected to surface waters but are not actively pumping (i.e., zero pumping rate). These wells may include monitoring wells, test wells, or wells used infrequently such as wells dedicated to firefighting activities.

5. CASE STUDY - LOWER COWICHAN WATERSHED

To evaluate and demonstrate the screening tool approach, we applied the model to the Lower Cowichan River Basin on the southeast coast of Vancouver Island (Figure 10). This area is part of an overall study of surface water-groundwater interactions in the Cowichan Basin downstream of Lake Cowichan (Lapcevic et al., 2015). Water management in the Cowichan Basin is a priority due to multiple water use objectives including recreational activities, water supply for agricultural, industrial, commercial, municipal use, and protection of high value fisheries. Surface and groundwater use in the watershed reduces dry season flows. During drought conditions, surface and groundwater sources may not meet demand for all competing water use objectives. With implementation of the WSA, the statutory decision maker has authority to curtail surface and groundwater use should streamflow fall below critical levels.

5.1 Study Area Aquifers

Application of the screening tool focused on wells in the Lower Cowichan Aquifers A, B, and C (numbers 186, 187, 188, respectively) and adjacent aquifers 185 and 196. Figure 11 shows the location of the aquifers and Table 3 lists general aquifer characteristics. Lower Cowichan aquifers A, B, and C were selected for pilot application because there is heavy reliance on groundwater for municipal and commercial supply, the aquifers are hydraulically connected to streams, and because ongoing studies provide considerable local knowledge of surface-groundwater interaction, groundwater use, and aquifer parameters. Adjacent aquifers are included in the study area to consider application to different aquifer types and varying hydraulic properties and connectivity.

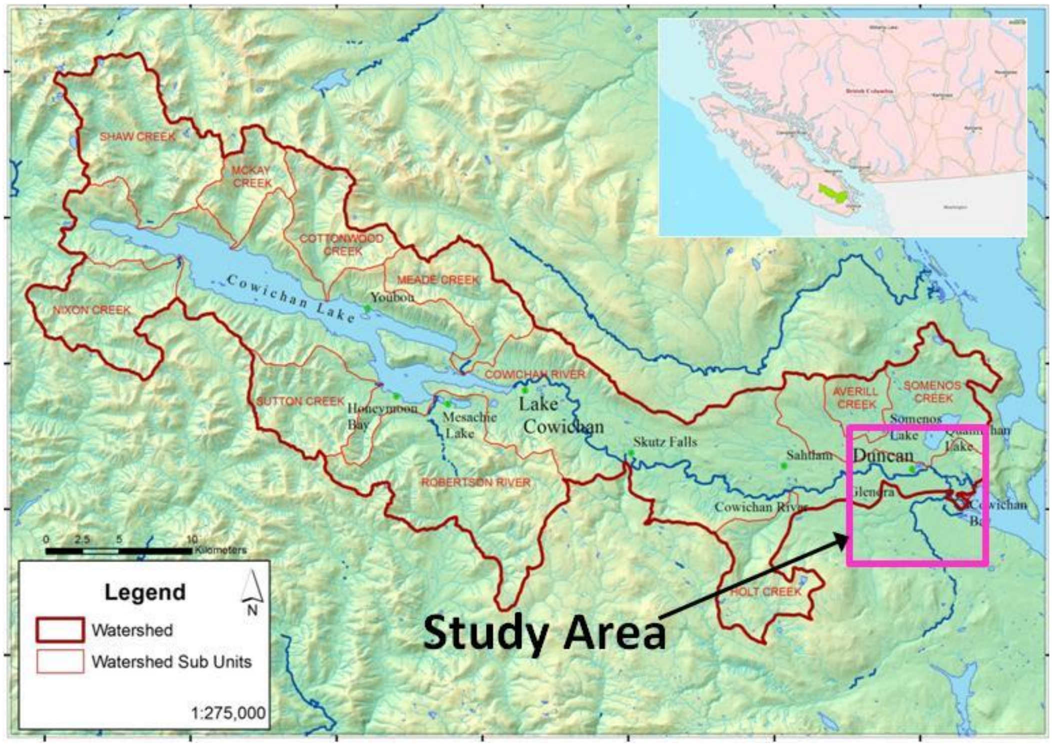


FIGURE 10: Lower Cowichan River Basin study area.

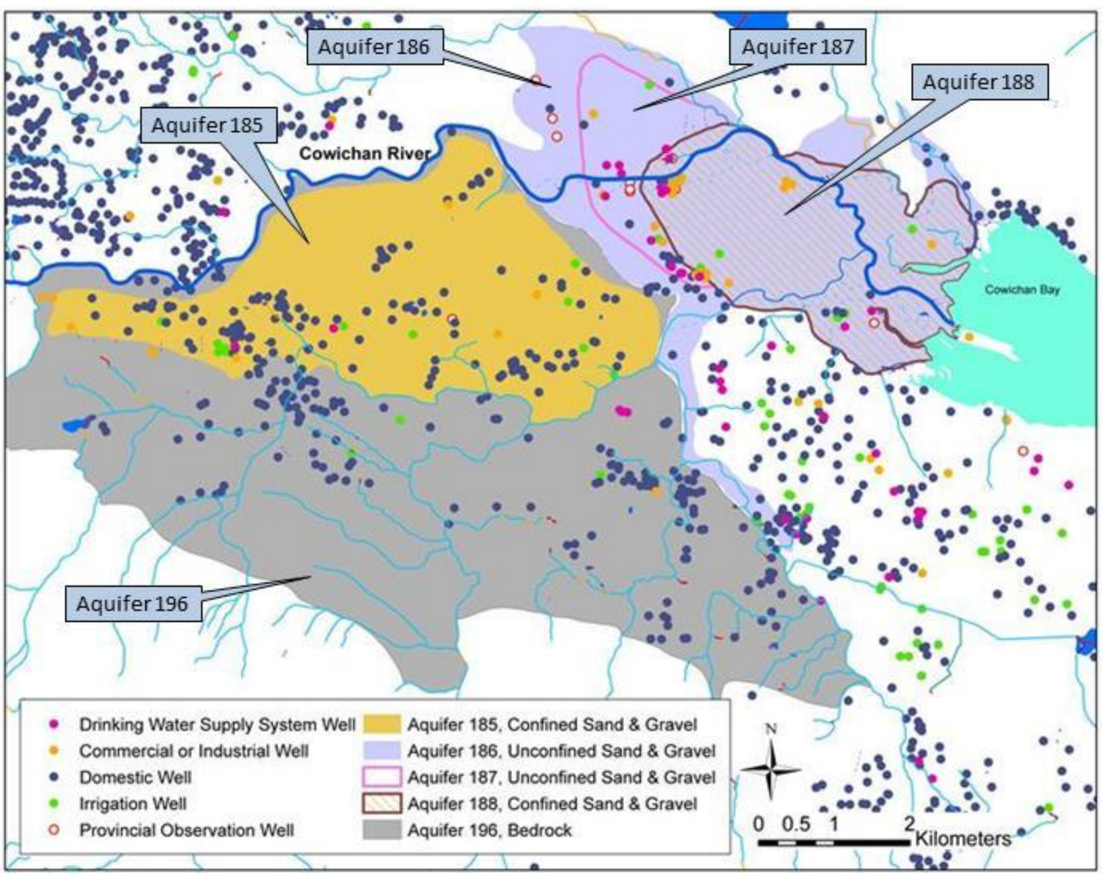


FIGURE 11: Aquifer and water well locations in the Lower Cowichan Basin study area.

TABLE 3: Characteristics of study area aquifers.

Aquifer No.	Aquifer Name	Aquifer Size (km^2)	Aquifer Type	Lithology	Median Well Depth (m)	Median Depth to GW (m)	Productivity, Vulnerability, Demand
186	Lower Cowichan A	17	1b - Fluvial and glaciofluvial aquifers	Unconfined sand & gravel	7.6	2.7	High, High, High
187	Lower Cowichan B	11.4	1b - Fluvial and glaciofluvial aquifers	Partially confined sand & gravel	21.3	3	High, Moderate, Moderate
188	Lower Cowichan C	8.7	4b - Confined aquifers of glaciofluvial origin	Confined sand and gravel	39.9	3	High, Low, Low
185	Glenora	14.9	4b - Confined aquifers of glaciofluvial origin	Partially? confined sand and gravel	24.7	13.7	Moderate, Low, Moderate
196	Deerholme / Duncan	46	5a - Fractured sedimentary bedrock	Bedrock	54.9	5.2	Low, Low, Low

The Lower Cowichan aquifers A, B, and C (aquifer numbers 186, 187, and 188, respectively) are stacked aquifers comprised of permeable sands and gravels (Table 3). Lapcevic et al. (2015) prepared hydrogeologic cross-sections of the aquifer complex. Figure 13 shows the cross-section locations, and Figure 13 through Figure 15 show the cross-sections.

Unconfined aquifer 186 is the largest and shallowest of the three aquifers with an average depth to groundwater of about two metres. It is the most heavily used of the three aquifers, particularly in the west side of the aquifer where the water bearing units are much thicker (cross-sections A-A' and C-C' in Figure 13 and Figure 14) compared to the east side (cross-section F-F' in Figure 15).

Aquifer 187 lies beneath aquifer 186, partially confined by thin (i.e. less than a few metres) layers of silty sands, till, and clay. Connectivity between aquifers 186 and 187 is greater in the west where the confining units become thin and discontinuous (cross-section A-A' and C-C').

Confined aquifer 188 is the smallest and deepest of the three aquifers, separated from 187 by units of clay, silts and tills of varying thickness. This aquifer is thicker and more heavily used toward the east side of the study area (cross-section F-F'). All three aquifers merge into one to the west, as the intervening confining layers pinch out.

The Lower Cowichan aquifers A, B, and C are hydraulically connected to the Cowichan River and its tributaries. Direct evidence supporting connectivity are the measurement of elevated groundwater temperatures in pumping wells close to surface waters (Lapcevic et al., 2015), and pumping tests showing rapid stabilization and recovery in groundwater levels, indicating the presence of a hydraulic boundary at a surface water source (Carmichael, 2014). Water budget calculations show groundwater use in the Lower Cowichan aquifers is about ten times greater than recharge from precipitation estimates without significant change in groundwater levels. This suggests groundwater wells in the Lower Cowichan basin derive approximately 90% of their source water from surface flows in the Cowichan River (Lapcevic et al., 2015).

Foster and Allen (2015) developed a comprehensive hydrogeological model for the Cowichan watershed. The model is developed with MIKE-SHE, a comprehensive numerical modeling package that couples surface hydrological processes and subsurface groundwater flow processes. The model was used to study surface-groundwater interactions throughout the watershed and the effects of pumping on stream/groundwater interaction. Simulation results in Figure 16 show that both gaining and losing conditions occur in the lower reaches of the Cowichan River adjacent to aquifer 186. Losing conditions are associated with major groundwater withdrawals identified in Figure 16.

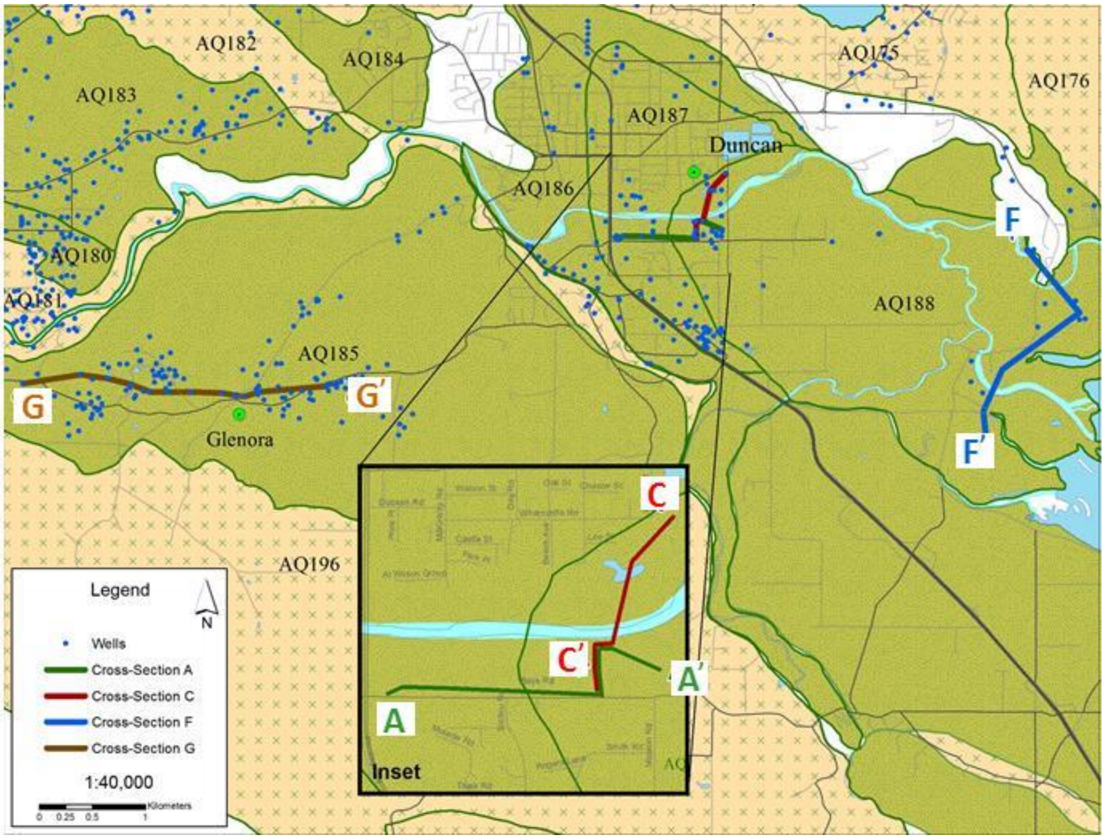


FIGURE 12: Location of cross-sections in study area aquifers (Source: Lapcevic et al.., 2015)

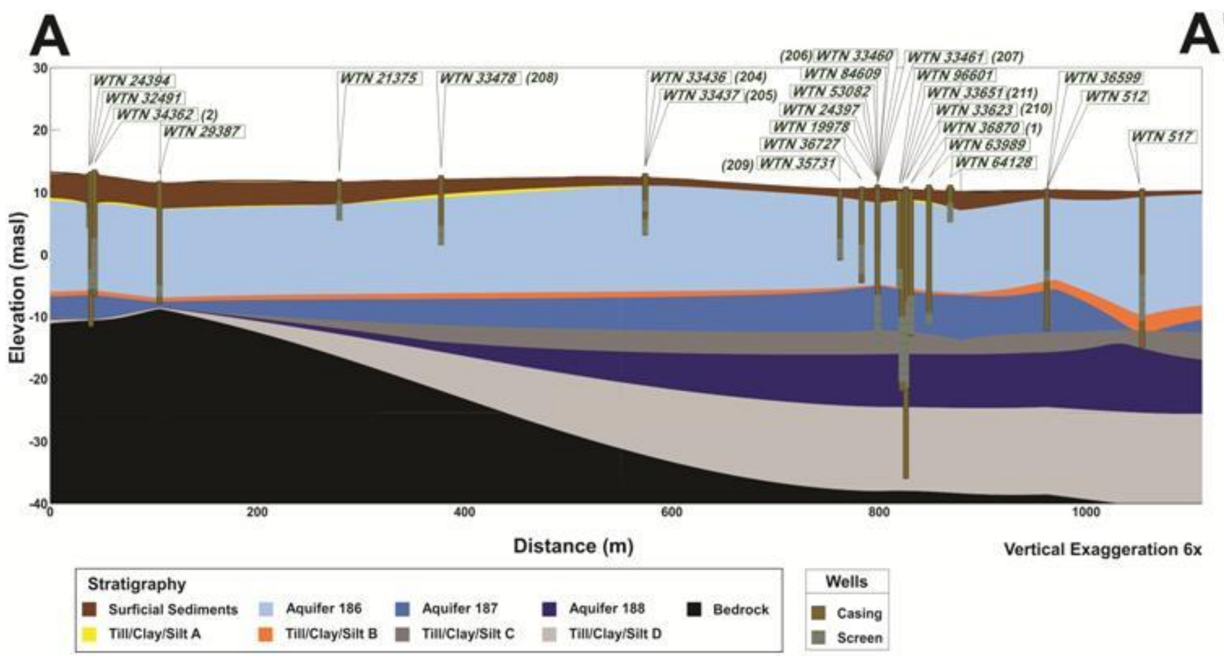


FIGURE 13: Cross-section A-A' transecting aquifers 186, 187, 188 (Source: Lapcevic et al., 2015).

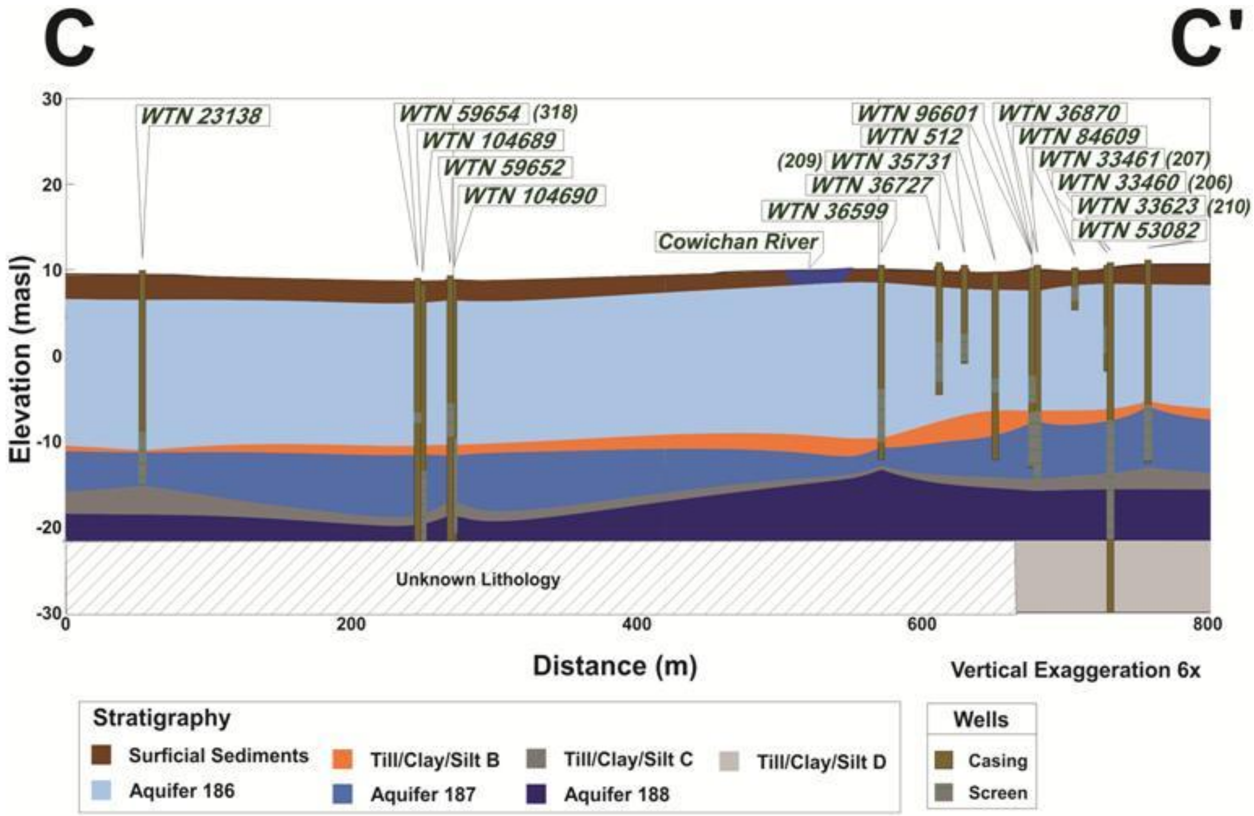


FIGURE 14: Cross-section C-C' transecting aquifers 186, 187, 188 (Source: Lapcevic et al., 2015).

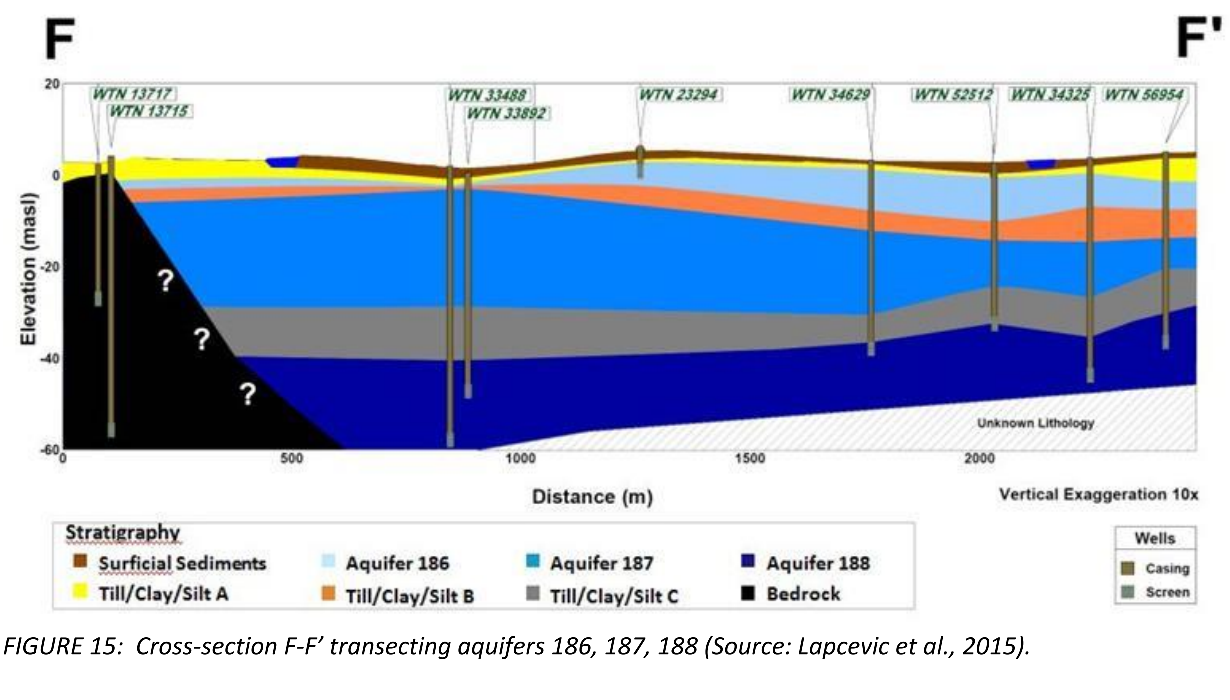


FIGURE 15: Cross-section F-F' transecting aquifers 186, 187, 188 (Source: Lapcevic et al., 2015).

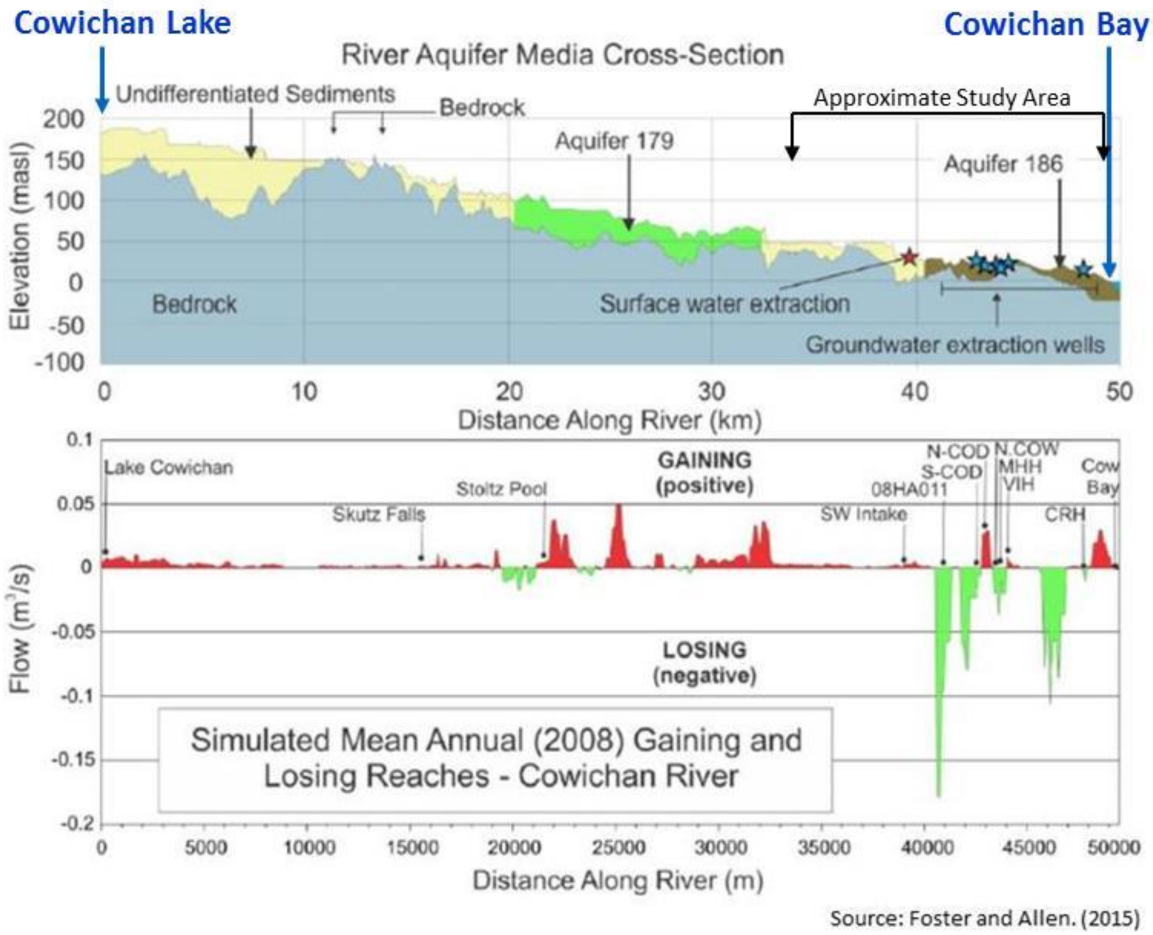


FIGURE 16: Numerical modeling results from Foster and Allen (2015) showing annual exchange between the Cowichan River and aquifers, from Lake Cowichan to Cowichan Bay. Pumping wells: S-COD/N-COD = City of Duncan wells; MHH = Marine Harvest Hatchery wells, N.Cow = North Cowichan well, VIH = Vancouver Island Hatchery wells, CRH = Cowichan River Hatchery wells. Gaining reaches of the river are shown in red and losing reaches are shown in green.

The Glenora aquifer (No. 185) is a confined sand and gravel aquifer that lies to the west of the Lower Cowichan aquifers A, B, and C. It is bordered by the Cowichan River to the north (Figure 11). The aquifer has moderate productivity supporting groundwater use mainly for domestic supply with some use for irrigation, commercial, and small water system supply. A large portion of the aquifer is confined by a clay aquitard, ranging in thickness to over 30 m (cross-section G-G' in Figure 17). However, the thickness of the confining aquitard is variable and a significant number of wells have little confinement (Ronneseth , 1995). In areas where the aquitard is absent, the overburden in the vadose zone is comprised of sand and gravels (cross-section G-G' in Figure 17).

Confined aquifers have variable connectivity to surface waters. Groundwater pumping from a confined aquifer does not necessarily eliminate the possibility of streamflow depletion. To the contrary, Barlow and Leake (2012) note pumping stresses in confined aquifers propagate faster than in unconfined aquifers, allowing drawdown to spread to distant edges of the aquifer or locations where it can more easily propagate upward. Moreover, when confining units are discontinuous, the contact windows between the underlying confined aquifer and the overlying unconfined aquifer can act aa bridges or preferential flow paths that can increase the effects of streamflow depletion from pumping in the confined aquifer. Based on this information, and because confining units in the Glenora aquifer are discontinuous, a conservative approach for initial screening purposes is to assume all water wells in the Glenora aquifer are hydraulically connected to surface waters. Additional assessment on connectivity can be undertaken for those wells where screening results indicate a consideration for curtailment activities.

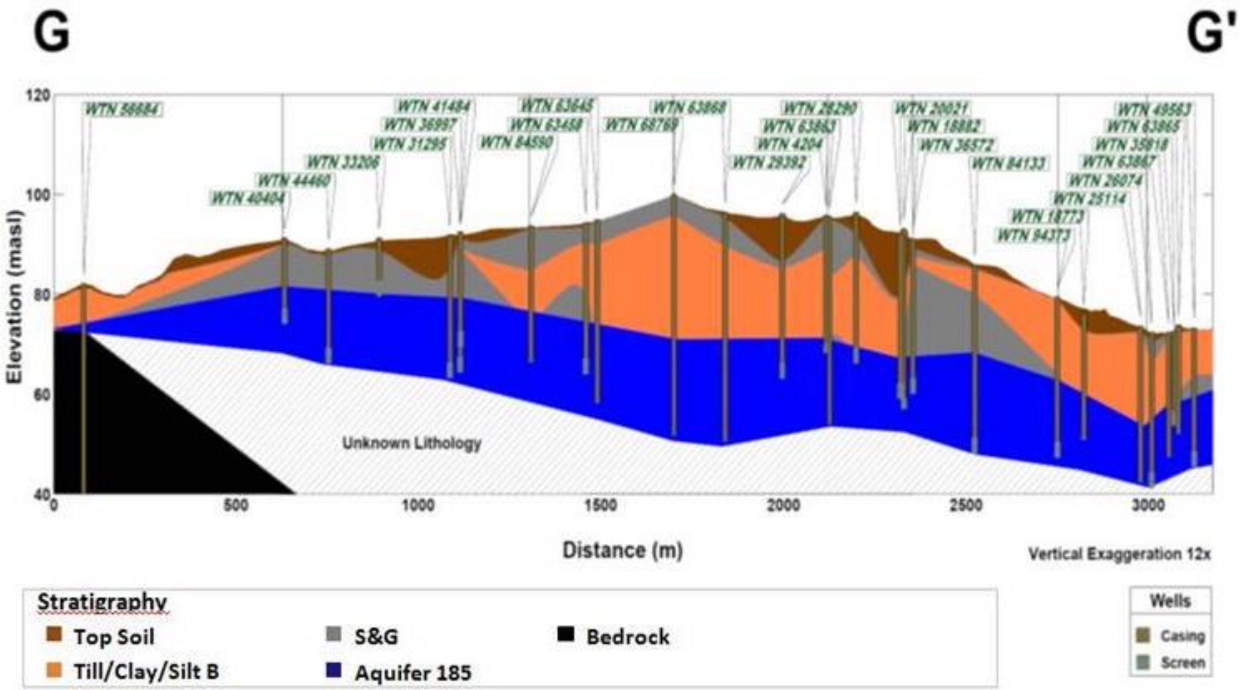


FIGURE 17: Cross-section G-G' transecting aquifer 185 (Source: Lapcevic et al., 2015).

5.2 'Cowichan Wells' worksheet

The initial step for setting up the screening tool is to compile available well information into the 'Cowichan wells' worksheet. Information was compiled as follows.

Gather information from the WELLS database: The WELLS database was accessed as a GIS shapefile available through the provincial spatial databases warehouse. The WELLS database shapefile was clipped to the polygons for aquifers 186 and 196, because these aquifers comprise the largest footprint of the mapped aquifers in the study area. The WELLS database contained 802 wells within the study area. Data from the attribute table were copied into 'Cowichan wells' worksheet, including required information for the well tag ID and well construction date (Table 2).

Determine distance to surface waters: The distance between each well and a licensable stream was determined for the 802 wells using the GIS Near Table function described in Section 3.3. We investigated two alternative methods for determining well spacing:

1) use distance to the Cowichan River or major licensable tributaries, whichever is nearest; and
2) use only distance to the Cowichan River, neglecting major tributaries.

The first method is more conservative as distances will be shorter. However, use of this approach should be supported with further analysis or evidence indicating hydraulic connectivity with tributary streams. Limiting distances to only the Cowichan River is a more straightforward approach, but potentially less conservative. The distances and stream names are entered into columns C and D of the worksheet.

***Estimate pumping rates**:* A well-by-well analysis was conducted to estimate groundwater pumping rates entered in column E of the 'Cowichan wells' worksheet. The rationale of pumping estimates is noted in column H.

Efforts to estimate groundwater pumping relied heavily on the work of Lapcevic et al. (2015) who conducted an extensive analysis of regional groundwater use ('water well survey') through the collection of pumping records, phone surveys, and estimation based on land use. They classified groundwater use into large, medium, and small user categories, and focused data collection efforts on the large and medium users, which are the major users on a volumetric basis. Groundwater pumping rates were estimated as follows:

- **Small users** are private well owners who use less than 10 m^3/day.
  - *Domestic wells:* A large number of wells are listed as domestic use wells in the WELLS database, which are water supply wells for individual family homes. A number of wells were also inferred as domestic use wells based on ownership or well construction information listed in the well record. Domestic use wells were assigned a pumping rate of 3 m^3/day, which is likely high for typical domestic needs in a single family dwelling.
  - *Small users:* The water well survey identified a few small users based on a classification of 'water supply system' or 'other' use in the provincial well records. A conservative pumping rate of 10 m^3/day was assumed for these small users.
- **Medium users** are well owners that use between 10 and 250 m^3/day.
  - *Water well survey:* The water well survey identified a number of medium users, both with and without reported pumping rates. The assigned pumping for small users was set to the reported pumping rate, if provided. If no pumping information was reported, the pumping rate was conservatively estimated in one of two ways:
    - *i.* The assumed pumping rate was set to the drillers yield estimate in the well record, if less than 250 m^3/day. This is the assumed maximum pumping capacity of the well.
    - *ii.* If the drillers yield estimate was greater than 250 m^3/day or was not included in the well record, the well was assigned a pumping rate of 250 m^3/day, the maximum quantity of medium users.
  - *Inferred medium user:* The well survey was not able to obtain information for all wells. For a subset of wells, ownership information or remarks in the well record provided a basis to infer groundwater supply for commercial, industrial, irrigation, or water system uses. Wells supplying groundwater for these purposes were inferred as belonging to medium users. We conservatively assigned pumping rates for these wells as equal to the drillers yield estimate or the maximum use rate for a medium user (250 m^3/day), whichever is smaller.
- **Large users** are major municipal, irrigation, and commercial owners that use more than 250 m^3/day.
  - *Water well survey:* Lapcevic et al. (2015) compiled groundwater pumping records for large users in the study area. For those wells with available pumping records, an average annual pumping rate was calculated and assigned to the individual well. In cases where the pumping records relate to a well field, an average annual pumping rate was calculated for the well field and assigned to each well within a well field. This approach ensures that assessment of curtailment activities is applied to the well field as a whole, and not individual wells in the well field.
  - *Inferred large user:* A few wells lacked water use and pumping information, but could be inferred to be a potential large capacity well based on ownership by municipalities, water supply companies, or fish hatcheries. Without available pumping records, it is not possible to confirm current usage for these wells. Therefore, a conservative approach was used in

assuming these wells are active supply wells with a pumping rate equal to the drillers yield estimate.

- **No active pumping.** A number of wells were assigned a zero pumping rate for the following reasons.
  - Provincial well records indicate the well is abandoned, closed, dry, or a test well.
  - The well is a provincial observation well.
  - Information from the GW user survey indicates the well is no longer actively used.
- **Insufficient information.** A number of wells did not have adequate information to base an estimate of groundwater pumping (i.e., no information was obtained in the water well survey, and the well records lack information on ownership, water use, and well yield). These wells were not assigned a pumping rate, leaving Column E in the 'Cowichan wells' worksheet blank.

Specify Local Aquifer ID. A well-by-well analysis was conducted to assess the aquifer association of the wells. We first reviewed the well lithology in the well record (if available) to establish the depth and lithology of the water bearing formation. Figure 18 shows the location of wells that are completed in sand and gravel deposits and bedrock formations.

The local aquifer ID numbers in column F of the 'Cowichan wells' worksheet were determined on the basis of information in Figure 18 as follows:

- Lower Cowichan Aquifers A, B, C Polygons (aquifers 185, 186, 187): Local IDs coincide with provincial aquifer numbers 185, 186, and 187, based on lithology and associated aquifers specified in WELLS.
- Glenora Aquifer Polygon (aquifer 185): Local IDs coincide with the water bearing formation and provincial aquifer numbers. Wells completed in unconsolidated deposits are assigned local ID number 185, and wells completed in bedrock formations are assigned local ID number 196.
- Deerholme /Duncan aquifer polygon (aquifer 196), exclusive of the Glenora aquifer polygon: Local IDs for all bedrock wells coincide with the provincial aquifer number, 196. Any well completed in unconsolidated deposits are assigned a local ID=-196, indicating the well is within a bedrock aquifer polygon but is completed in unconsolidated deposits.

Specify Hydraulic Connectivity. Figure 18 shows the majority of wells are completed in formations consistent with the aquifer type in which they are located. However, there are deviations, particularly in the bedrock aquifer 196, which shows a number of wells completed in unconsolidated deposits with little or no confining overburden. Whether these deposits are localized or are part of a broader regional system that is hydraulically connected to surface waters is unknown. It is also interesting to note that several wells in close proximity to the Cowichan River are completed in bedrock, which are not likely to be substantially connected to the River. Collectively, this analysis shows that establishing hydraulic connectivity between a well and surface waters cannot be based solely on the proximity of the well to surface waters, or its location within mapped aquifer polygons. The connectivity assessment must include consideration of the hydrogeology, both at the well and on at the regional basis.

The hydraulic connectivity of each well ('yes' or 'no') is entered in column G of the 'Cowichan wells' worksheet. The connectivity of study-area wells was assigned by a simple and conservative approach, consistent with the screening level assessment.

- **Bedrock wells:** All bedrock wells are considered hydraulically disconnected from surface waters during short-term curtailment based on comparatively larger depth, lower transmissivity, and lower yields of typical wells in the area.

- **Wells in unconsolidated formations**: Any well completed in unconsolidated sand and gravels (aquifers 185 to 188) is considered hydraulically connected to surface waters, whether the aquifer is confined or not.

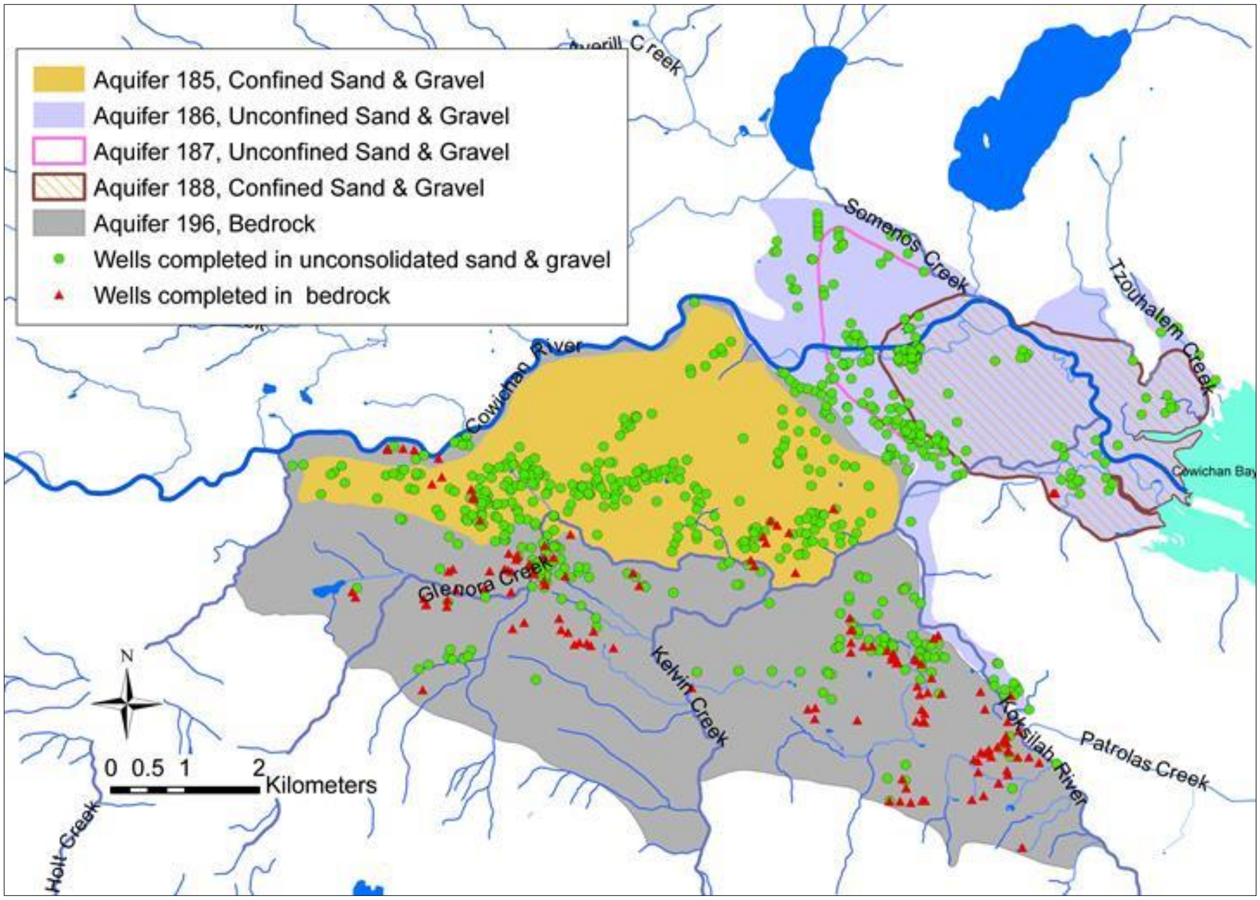


FIGURE 18: Water bearing formations in study area wells.

5.3 'Lower Cowichan input' worksheet

The second step for setting up the screening tool is to enter the required input parameters into the 'Lower Cowichan input' worksheet. The specified input values and information sources are as follows.

Curtailment parameters

Curtailment duration:	Short-term curtailment periods between 1 to 6 weeks were assumed to be reasonable curtailment forecast periods. A range of curtailment periods was tested to evaluate the sensitivity to this input.
Threshold pumping rate:	The allowable pumping rate below which wells are not subject to curtailment was set to 0.2 m^3/day. This is approximately the volume needed for essential household needs in a single-family dwelling. Although 0.2 m^3/day is likely insignificant relative to flow in the Cowichan River, this value was initially selected to ensure domestic uses are captured in the curtailment process. Larger values were also tested to assess model sensitivity to this parameter, which is discussed later in the report.

Model parameters

Number of trials:	Set to 500 to reduce variability in the calculated curtailment envelope.
Confidence factor:	Set to 50% per recommendations.

Aquifer parameters

Aquifer transmissivity estimates are available from Carmichael (2014) who compiled and re-analyzed pumping test data from wells in the Cowichan Valley Regional District (CVRD). Table 4 shows summary statistics of the re-analyzed pumping test data.

The study area aquifers (186, 187, and 188) are highly permeable, with hydraulic conductivity values that are representative of coarse sands and gravels. Median transmissivity in the confined type 4b aquifer (188) is about an order-of-magnitude smaller than the unconfined type 1b aquifers (186, 187), but is still considered very permeable. A total of 77 transmissivity estimates from other type 1b and 4b aquifers within the CVRD were selected for input into the spreadsheet tool. The regional transmissivity information was used over the study area information because the data set is larger and provides a wider range of transmissivity estimates.

TABLE 4: Summary statistics of re-analyzed pumping test data in the CVRD.

Location	Parameter	Aquifer types	Aquifer numbers	Number of data	Min	Max	Average	Median
Study Area	Transmissivity (m^2/day)	1b	186, 187	15	4900	47000	16000	12000
		4b	188	9	150	28000	7900	1000
		1b & 4b	186, 187, 188	24	150	47000	13000	10000
	Storativity (-)	1b	186	2	1.8E-03	5.6E-02	2.9E-02	2.9E-02
		4b	188	3	6.5E-05	5.4E-04	2.6E-04	1.8E-04
		1b & 4b	186, 188	5	6.5E-05	5.6E-02	1.2E-02	5.4E-04
	Hydraulic Conductivity (m/day)	1b	186, 187	13	320	5400	1900	1100
		4b	188	9	32	4300	1200	130
		1b & 4b	186, 187, 188	22	32	5400	1600	920
Cowichan Valley Regional District	Transmissivity (m^2/day)	1b	161, 172, 186, 187	26	240	120000	18000	12000
		4b	178, 180, 188, 197, 205, unmapped	51	1	28000	1700	140
		1b & 4b	161, 172, 178, 180, 186, 187, 188, 197, 205, unmapped	77	1	120000	7100	350
	Storativity (-)	1b	172, 186	4	1.8E-03	5.6E-02	1.7E-02	6.2E-03
		4b	178, 188, 197	13	1.4E-05	3.1E-03	5.7E-04	3.0E-04
		1b & 4b	172, 178, 186, 188, 197	17	1.4E-05	5.6E-02	4.6E-03	3.8E-04
	Hydraulic Conductivity (m/day)	1b	161, 172, 186, 187	23	140	9000	2400	1100
		4b	178, 180, 188, 197, 205, unmapped	56	0.2	4300	210	13
		1b & 4b	161, 172, 178, 180, 186, 187, 188, 197, 205, unmapped	79	0.2	9000	840	30

There are significantly fewer storativity estimates than transmissivity estimates because observation wells are needed to determine this parameter and most pumping tests are performed without an observation well. There are only four storativity estimates for unconfined type 4b aquifers, and the reported values appear low (0.002-0.06) in comparison to typical values for specific yield of sands and gravels (0.1-0.3) (the storativity of unconfined systems is approximately equal to the specific yield). It has also been noted in the literature that analysis of pumping test data can lead to unrealistically low estimates for specific yield due to problems associated with delayed yield (Nwankwor et al., 1984). Because of these data limitations, the measured storativity estimates were not used in the spreadsheet tool. Rather a storativity range from 0.01 to 0.3 was specified based on literature information for specific yield.

5.4 Results for Lower Cowichan Aquifers A, B, C

Figure 19 shows screening model results for the Lower Cowichan aquifers A, B, and C where well spacing distance was calculated to the main-stem Cowichan River. This approach assumes groundwater withdrawals only affect surface flows in the main-stem of the Cowichan River, neglecting potential impacts to flows in tributary streams. These results suggest nearly all major groundwater users and many small and domestic groundwater users should be subject to groundwater curtailment during periods of water scarcity. The main exception is when the projected curtailment period is short (2-3 weeks) and for only wells that are a large distance from the Cowichan River, approximately one km or more.

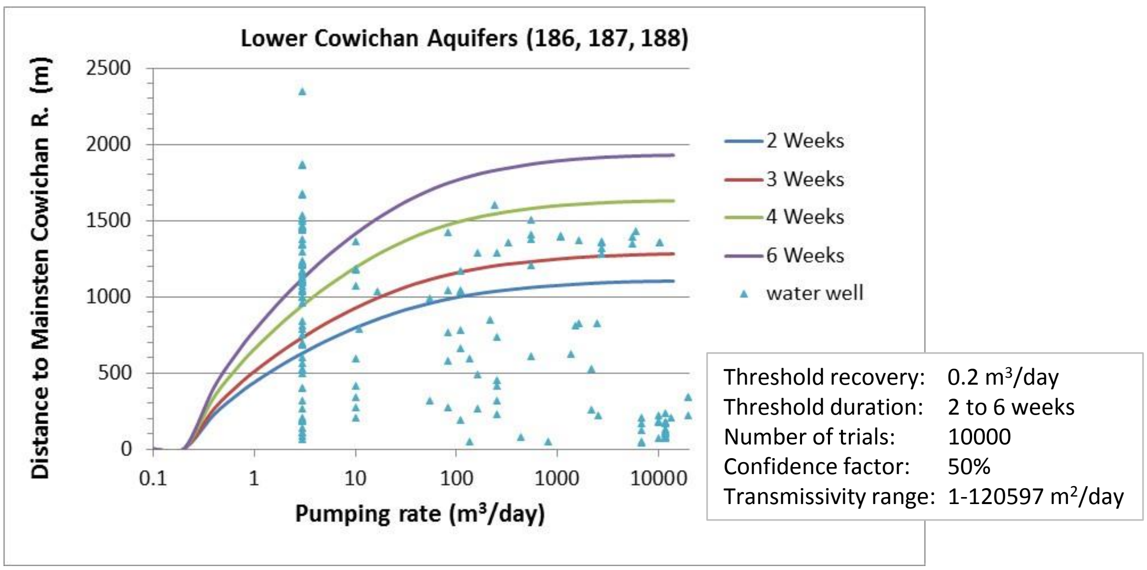


FIGURE 19: Results for Lower Cowichan aquifers A, B, and C with well spacing to the Cowichan River.

Figure 20 shows the same results, except in this case hydraulic connectivity to surface waters was calculated to the main-stem of the Cowichan River or major tributaries, whichever is closest. The tributary streams are shown in Figure 18 and include Tzouhalem Creek, Somenos Creek, and the Koksilah River. This approach assumes groundwater discharges support tributary baseflow and that short-term curtailment of groundwater withdrawals will result in recovery of tributary flows, subsequently increasing flows in the main-stem of the Cowichan River. This is a more conservative approach that should be justified by evidence and understanding of local surface water-groundwater interactions. The outcome of this approach is curtailment envelopes are shifted upwards, capturing many more users within the same curtailment periods.

The large number of groundwater users captured under the curtailment envelops in Figure 19 and Figure 20 is a direct result of the highly permeable characteristic of the aquifer materials, which are comprised coarse sands and cobbles. Transmissivity measurements in aquifers 186, 187, and 188 are extremely large (Table 4) and there is evidence of strong hydraulic interactions between the aquifer and surface waters during pumping tests. The results suggest that drought planning and curtailment planning activities should focus on nearly all major and medium users within the aquifer boundaries including identification and verification of well location and groundwater use.

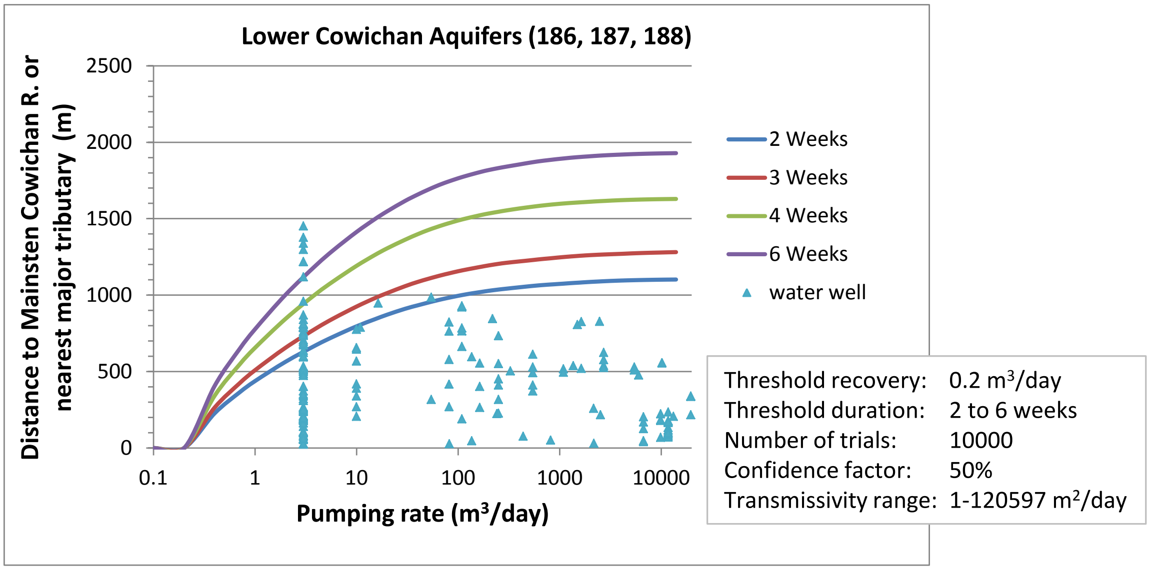


FIGURE 20: Results for Lower Cowichan aquifers A, B, and C with well spacing to the Cowichan River or closest major tributary.

5.5 Observations from the Probabilistic Modeling Approach

As described in Section 2.2, the screening tool is an adaptation of the model by Bekesi and Hodges (2006) which uses a probabilistic approach to determine a single curtailment envelopment based on a range of T and S values provided by the user and a specified confidence factor. This approach calculates a family of curtailment envelops based on the random values of T and S selected from the input range. The resulting curtailment envelopments were found to span a very wide range as shown in Figure 21. Consequently, the 50th percentile envelope varied substantially when the specified number of trials was less than 500. A total 10,000 trials was used to obtain stable curves shown in Figure 19 and Figure 20, However, computing time increase as the number of trials increases. 10,000 trials required about 10-15 minutes or longer to update, depending on the computer speed.

For comparison, Figure 21 shows the results of single run using the median T value (350 m^2/s) and an average value for S (0.15). This single deterministic run produced results that are comparable to the 50th percentile curve. The deterministic approach produces results that are not variable, and the computation time is fast because only a single envelope is calculated. The main disadvantage is that alternative confidence factors cannot be specified; for example, Bekesi and Hodges (2006) used a 90th percentile curve for groundwater allocation. Based on these observations, a deterministic approach is suggested for most applications, and a probabilistic approach should be used when a higher confidence factor is desired.

5.6 Results for Aquifer Areas 185 and 196

Figure 22 shows screening model results for aquifer areas 185 and 196 where well spacing distance was determined to the main-stem Cowichan River only. Although aquifer 196 is mapped as a bedrock aquifer, many of the wells within the aquifer boundary are completed in unconsolidated materials, which have been assumed to be hydraulically connected to surface waters. In contrast, all wells competed in bedrock formations are considered hydraulically disconnected from surface waters for purposes of evaluating streamflow recovery during short-term curtailment. Values for T and S were estimated from regional information for Type 4b aquifers, as no pumping test data is available for aquifer 185.

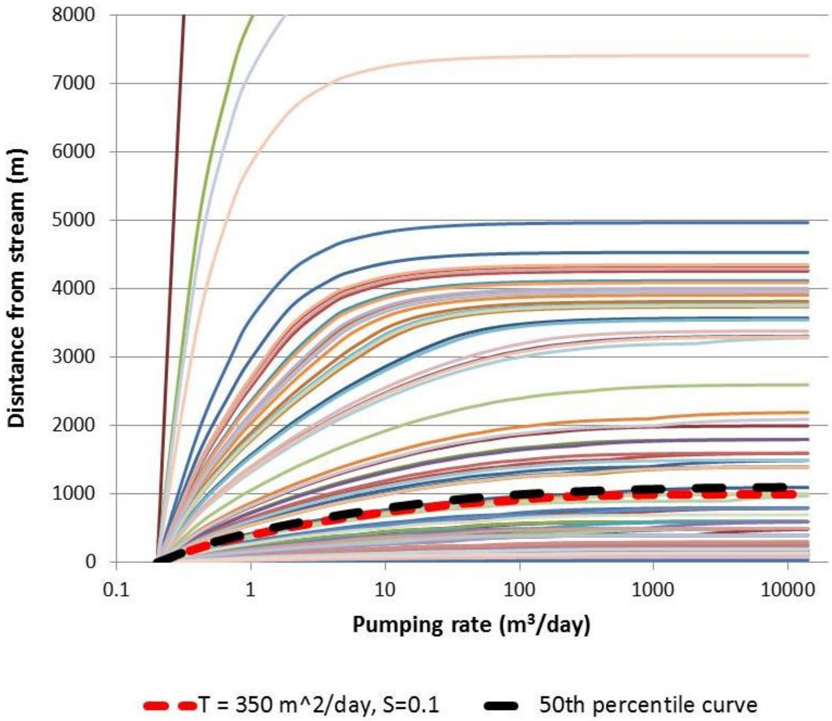


FIGURE 21: Comparison of probabilistic modeling results (50th percentile of 10,000 trials, only 100 curves shown) and a deterministic result with the median transmissivity value.

5.7 Results for Aquifer Areas 185 and 196

Figure 22 shows screening model results for aquifer areas 185 and 196 where well spacing distance was determined to the main-stem Cowichan River only. Although aquifer 196 is mapped as a bedrock aquifer, many of the wells within the aquifer boundary are completed in unconsolidated materials, which have been assumed to be hydraulically connected to surface waters. In contrast, all wells competed in bedrock formations are considered hydraulically disconnected from surface waters for purposes of evaluating streamflow recovery during short-term curtailment. Values for T and S were estimated from regional information for Type 4b aquifers, as no pumping test data is available for aquifer 185.

In comparison to the Lower Cowichan aquifers A, B, and C, there are considerably fewer major groundwater users in aquifer area 185 and 196 and the pumping rates are substantially smaller. The vast majority of wells are used by individual domestic users. Figure 22 indicates groundwater curtailment activities should be focused on wells within about one to two km of the Cowichan River, assuming connectivity to tributary streams is ignored. This setback distance is comparatively larger than previous results for unconfined aquifers 186, 187, and 188, due to the semi-confined nature of aquifer 185. Groundwater pumping from confined and semi-confined aquifers typically causes a larger and faster developing cone-of-depression than in unconfined aquifers.

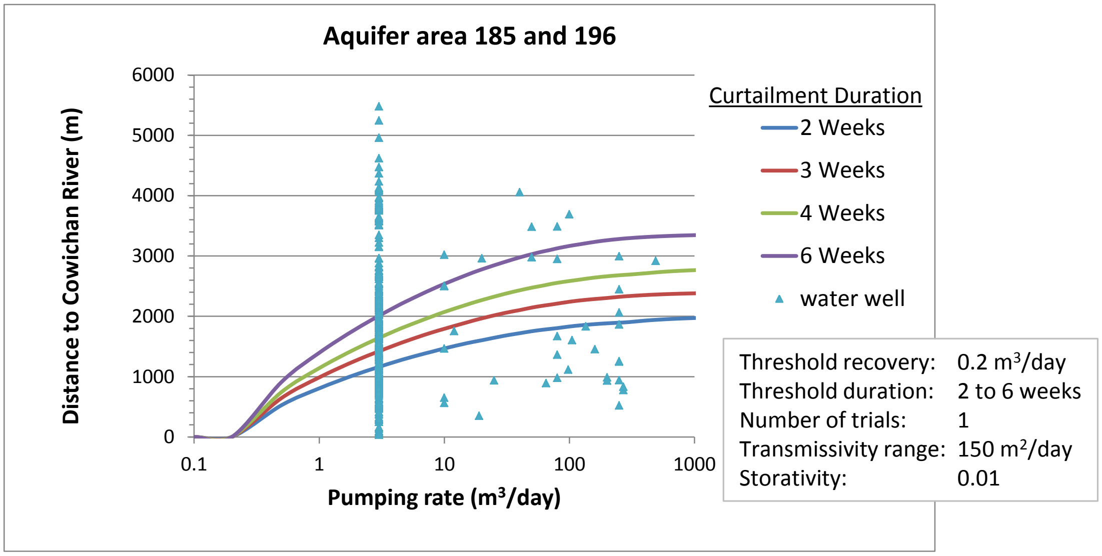


FIGURE 22: Results for aquifer areas 185 and 196 with well spacing determined to the Cowichan River.

Figure 23 shows screening model results for the aquifer areas 185 and 196 where hydraulic connectivity is considered to tributary streams, which include Holt Creek, Glenora Creek, Kelvin Creek, and the Koksilah River (Figure 18). Because these tributary streams bisect much of the aquifer, Figure 23 shows nearly all wells in the aquifer boundary should be subject to curtailment during droughts. However, application of this more conservative result should be supported by evidence of groundwater connectivity to tributary streams.

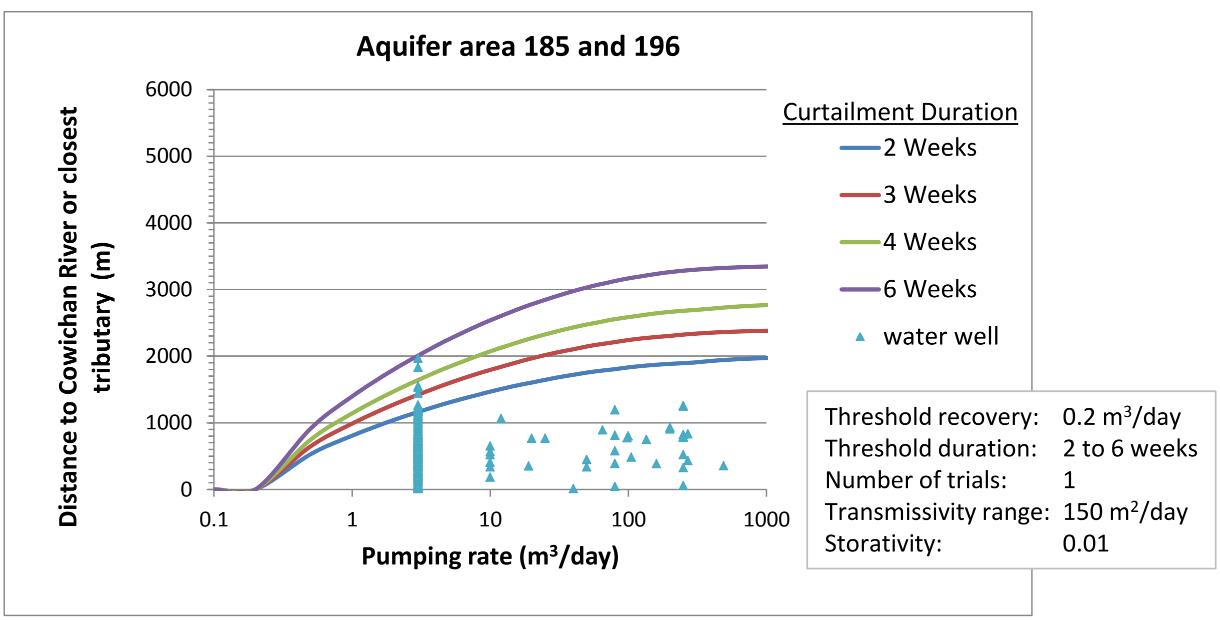


FIGURE 23: Results for aquifer areas 185 and 196 with well spacing determined to the Cowichan River or closest major tributary.

5.8 Parameter Sensitivity

This section presents results of parameter sensitivity analyses to assess effects of uncertainty in key model parameters, specifically the threshold recovery volume and the aquifer hydraulic parameters. The analysis uses a common approach wherein input parameters are varied one-at-a-time and observing the effect on the model output, namely the predicted curtailment envelopment.

As discussed in Section 2.2, the threshold recovery volume is a model input parameter that represents the minimum level of streamflow recovery for curtailment action. For example, if model estimates indicate streamflow recovery from curtailment of an individual well is greater than the threshold recovery volume, then the well is subject to curtailment. Conversely, wells that do not achieve a level of streamflow recovery equal to the threshold recovery volume are not subject to curtailment. In this work, the threshold recovery volume was set to 0.2 m^3/day, approximately equal to the exemption volume for essential household needs. This value provides an element of fairness to the curtailment process because all groundwater users are addressed equally. However, other criteria may be considered. For example, the threshold could be set to intentionally exclude curtailment action on individual domestic users (e.g., 3 m^3/day in the application), or it could be set to a large value perhaps representing a percentage of streamflow.

Figure 24 shows the influence of threshold recovery volume on the curtailment envelops. The effect of increasing the threshold volume is to exclude a larger number of domestic and small users from curtailment action, as well as some large users when the wells are located a large distance from the river. The curves in Figure 24 represent alternative scenarios for curtailment action, and may be useful to decision makers when evaluating options for groundwater curtailment.

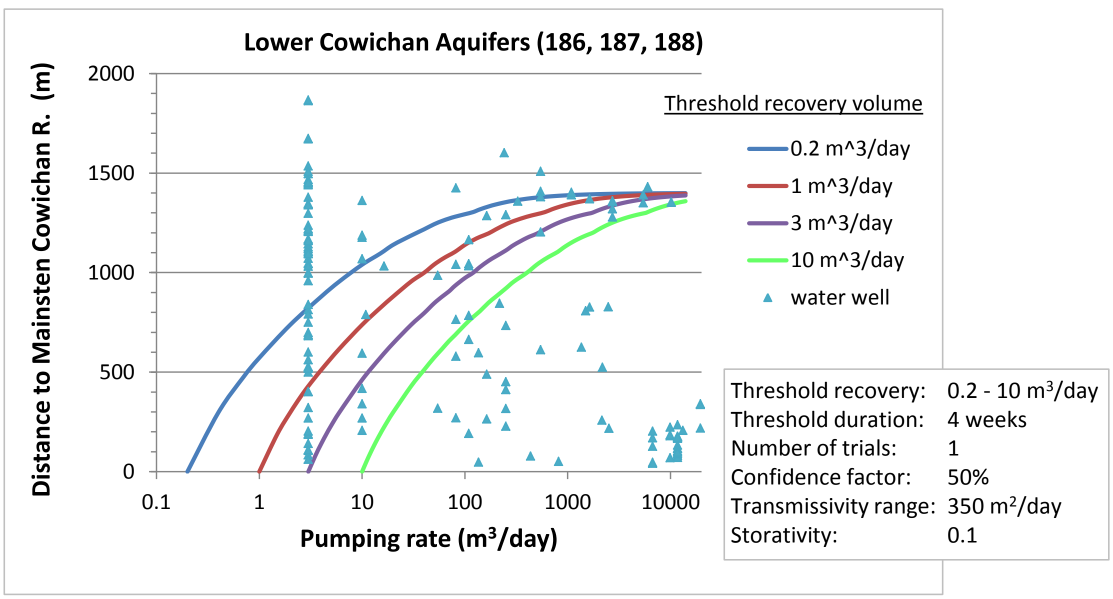


FIGURE 24: Effect of threshold recovery volume on screening tool results for Lower Cowichan aquifers.

The aquifer hydraulic properties (transmissivity and storativity) are spatially heterogeneous and can have wide-ranging values. As an example, the 77 transmissivity measurements in type 1b and 4b aquifers in the Cowichan Valley Regional District range over five orders of magnitude from 1 to 120,000 m2/day. Consequently, there is considerable uncertainty in determining representative values for the aquifer. Moreover, the hydraulic parameters exert a strong influence on the estimated curtailment envelop, as shown in Figure 25 and Figure 26. Small changes in T and S can significantly influence the curtailment envelope. Therefore, a consistent approach for determining transmissivity and storativity is important. A recommended approach is to use the median transmissivity value, either from local data if available, or from provincial hydraulic property information by aquifer type (e.g., Carmichael et al., 2009; Carmichael, 2013, 2014). Storativity can be reasonably estimated as S=0.01 for confined aquifers and S=0.1 for unconfined aquifers.

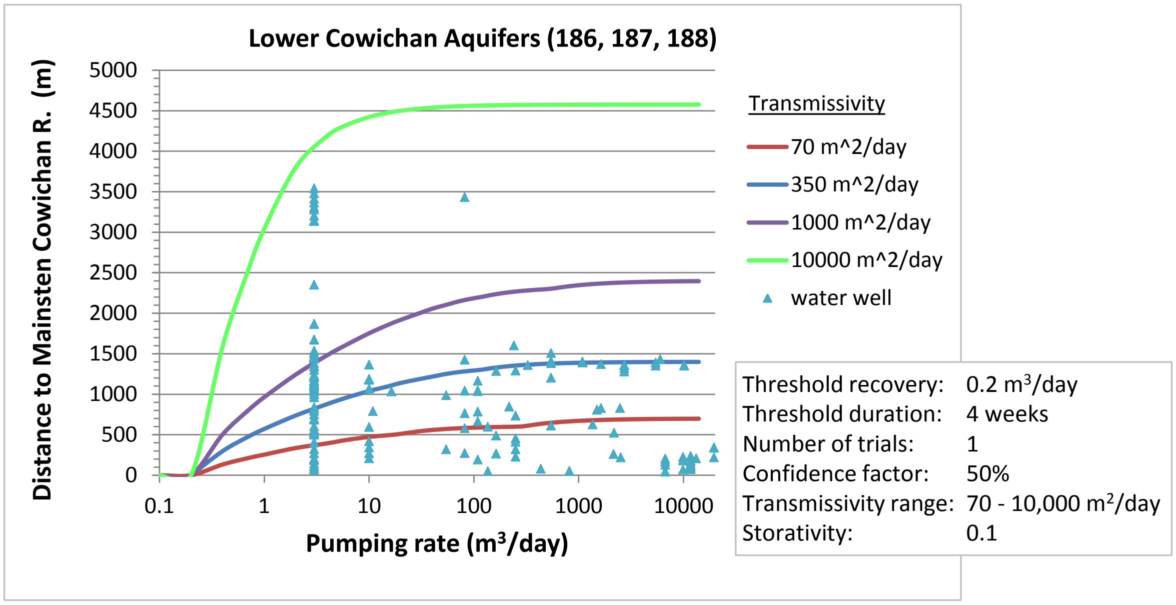


FIGURE 25: Effect of transmissivity on screening tool results for Lower Cowichan aquifers.

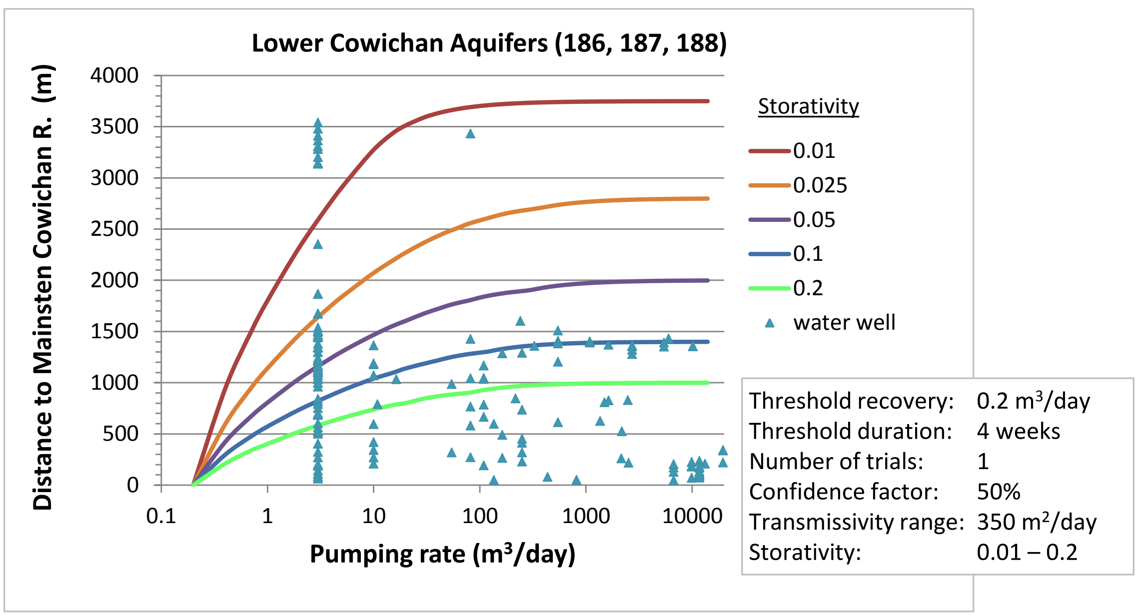


FIGURE 26: Effect of storativity on screening tool results for Lower Cowichan aquifers.

6. SUMMARY AND CONSIDERATIONS

Curtailing groundwater diversions during droughts does not necessarily result in streamflow-recovery. There are three possible streamflow responses to curtailment of groundwater pumping:

1. A rapid response in streamflow recovery (e.g., hours, days),
2. A delayed and gradual response in streamflow recovery (e.g., weeks, months); or
3. No streamflow recovery during the period of interest.

The type of response for individual wells depends on location of the well relative to the stream, the aquifer connectivity to surface waters, and the aquifer hydraulic properties.

To address the variable response of groundwater curtailment, a suggested groundwater curtailment approach is to take action on users in accordance with FITFIR, but to apply FITFIR only where it is likely to result in a benefit to the stream within the period of interest.

A spreadsheet based screening tool has been developed to support decision makers for guiding groundwater curtailment and data collection activities. The screening tool identifies a curtailment envelope where groundwater curtailment is most likely to have a positive influence on streamflow recovery during a specified short-term curtailment period. Applicability of the screening tool is limited a simplifying assumptions inherent in the model. Thus, the screening tool is not intended to definitively identify those wells subject to curtailment; rather it is intended to identify an initial area of interest where follow-up assessments and data collection for individual wells can be focused.

The screening tool was applied to aquifers in the Lower Cowichan River watershed. Results of this pilot application indicate:

- Decisions on short-term GW curtailment should not be based solely on well proximity to streams or on well locations relative to mapped aquifer polygons. Effective and equitable groundwater curtailment requires assessment of aquifer lithology, the hydraulic connectivity to surface waters, and pumping rates on an individual well basis.
- The assessment highlights the need during drought planning and curtailment planning activities to focus on nearly all major and medium users within the aquifer boundaries, including identification and verification of well location and groundwater use.
- Application of the screening tool is data intensive and cannot be easily developed during drought emergencies. Pre-planning of potential groundwater curtailment locations should be systematically conducted for high priority areas. The screening tool can broadly focus pre-planning and data collections activities. During this initial assessment, conservative assumptions should be used regarding pumping rates, aquifer hydraulic parameters, and hydraulic connectivity to surface waters in order to ensure that groundwater users are not incorrectly excluded from the curtailment envelope. Subsequently, the model should be refined to incorporate verification of groundwater use and other data collection efforts.
- Groundwater pumping from confined and semi-confined aquifers typically causes a larger and faster developing cone-of-depression than in unconfined aquifers such that in many cases these groundwater withdrawals cause depletion of streamflows. Decision makers should not exclude wells that are completed in confined and semi-confined aquifers from consideration of curtailment activities. Rather, the hydraulic connectivity of confined and semi-confined for consideration of curtailment activities should be evaluated on a case-by-case basis.

- The screening model is most easily used in a deterministic mode using median values for aquifer transmissivity and storativity. A deterministic approach is suggested for most applications, and a probabilistic approach should be used when a higher confidence factor is desired.
- A consistent approach for determining transmissivity and storativity is important. A recommended approach is to use the median transmissivity value, either from local data if available, or from provincial hydraulic property information by aquifer type.

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