Application of the Derivative and van der Kamp Methods: Enhancing the Interpretation of Pumping Tests for Fractured Bedrock Aquifers on Vancouver Island, BC

by

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A Thesis Submitted in Partial Fulfillment of the Requirements of the

HONOURS PROGRAM

in the School of Earth and Ocean Sciences

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We acknowledge and respect the Lək̓ʷəŋən (Songhees and Xʷsepsəm/Esquimalt) Peoples on whose territory the university stands, and the Lək̓ʷəŋən and W̱SÁNEĆ Peoples whose historical relationships with the land continue to this day.

Acknowledgements

I would like to thank my supervisor, Mike Wei, for fostering my enthusiasm for hydrogeology. Your willingness to learn alongside me and be a valuable mentor at every step of the research process has been invaluable to my growth. I want to also say thank you to my other supervisor Lucinda Leonard for guiding me through my first major research project and helping me learn to research and write with scientific rigor.

To Alan Kohut, Chad Petersmeyer, and others at Western Water Associates, I sincerely appreciate your openness in sharing your pumping test data. Without your cooperation, this research would not have been possible.

Thank you, Garth van der Kamp, for taking the time to offer me constructive feedback throughout the research process, reviewing my drafts. Your insight from decades of work in physical hydrogeology have been instrumental in growing my understanding.

Abstract

Interpreting pumping test responses for fractured bedrock aquifers is challenging, particularly when estimating the transmissivity of an aquifer and the long-term sustainable yield of a well. This study applies the derivative method (e.g., Renard et al., 2009) on the pumping and recovery phase of six pumping tests from bedrock wells on Vancouver Island and the Gulf Islands, sourced from local consultants, to characterize flow regimes to determine how transmissivity calculations can be improved. The van der Kamp method (van der Kamp, 1989) was also tested for its effectiveness in the extrapolation of pumping responses and its potential for improving the ability to estimate a sustainable pumping rate for a 100-day dry season (Q_{100}) that is often prescribed when licencing a well.

Two pumping tests studied were for fractured sedimentary bedrock aquifers while four were for fractured crystalline bedrock aquifers. The tests lasted 12-72 hours and were followed by recovery monitoring of a similar duration. The results showed that for the fractured sedimentary bedrock aquifers, linear flow may precede infinite-acting radial flow for several hundred minutes. For the tests that exhibited infinite-acting radial flow as the final derivative response, the duration was approximately 0.3 log cycles of time, cut off when pumping ended. Infinite-acting radial flow identified using the recovery phase derivative often matched the pumping phase derivative in symmetry, though was sometimes different in magnitude. Identifying periods of radial flow from the pumping and recovery phases facilitated the calculation of transmissivity using various analytical solutions.

Transmissivity values calculated using the Theis curve-matching (Theis, 1935) and Cooper-Jacob (Cooper & Jacob, 1946) methods, from the same radial drawdown data, were similar (within 0.5 log transmissivity values). For three pumping tests, transmissivity values calculated from the symmetrical recovery phase using the Theis recovery method (Theis, 1935) were noticeably different (over 0.19 orders of magnitude smaller or larger) than those calculated from the pumping phase.

The van der Kamp method did not work for all pumping tests analyzed. The extended drawdown calculated using the van der Kamp method for the same three tests exhibited various non-ideal responses. Two tests exhibited a rising static water level, where the water level in the well at the

start of the pumping test was erroneously assumed to be not changing. An unaccounted-for rising static water level induces a drift in the drawdown and subsequent recovery data, causing a discrepancy in the transmissivity calculated from the pumping and recovery phase, evident by a difference in the magnitude of the pumping and recovery derivative plots. The third test may have been subject to dewatering or a falling static water level late in the recovery phase which caused a steepening of the extended drawdown. When the "static" water level is not static, the extended drawdown does not improve the extrapolation of the drawdown to 100 days, which is required when estimating Q_{100}. When the static water level was stable, as for the three other pumping tests, it lent confidence to the extrapolation of drawdown to 100 days to calculate Q_{100}, reducing the reliance on an empirical straight-line extrapolation of drawdown to 100 days.

A rising static water level, if not identified before pumping, negatively affects Q_{100} estimates; especially for high-yield wells where the drawdown rate is slower and may be more sensitive to static water level shifts. The drawdown rate drifts do not as negatively alter transmissivity calculations because transmissivity values are log-normally distributed. Minor drifts in drawdown rate have less impact on the relative accuracy. To enhance test reliability and facilitate the application of the van der Kamp method, future tests should confirm a "static" water level before proceeding with testing. Additionally, to extract maximal utilization of the van der Kamp method and recovery derivative, the recovery phase should last at least as long as the pumping phase, rather than ending at 90% recovery as is currently recommended by the B.C. Ministry of Environment (MoE, n.d.).

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1. Introduction

1.1 Overview

For much of Vancouver Island and the neighboring Gulf Islands, sourcing groundwater from fractured bedrock aquifers for developments is necessary where suitable Quaternary sediments are minimal or absent. Calculating parameters such as transmissivity, storativity, and long-term sustainable yield from these pumping tests is much more challenging than in unconsolidated aquifers (Beauheim et al., 2004), but is often necessary to facilitate water allocation decisions under the recently enacted *Water Sustainability Act* (British Columbia, 2016). Unlike unconsolidated aquifers, fractured bedrock aquifers are often anisotropic, heterogeneous with respect to permeability or transmissivity, and comprise much larger representative elementary volumes (Parashar, 2017). Characterizing drawdown trends in response to pumping with time can be especially challenging in fractured bedrock aquifers. A consistent approach to pumping tests in fractured bedrocks, with as much technical rigor as possible is important for improving the analysis of pumping test data and will yield the most informative results.

Commonly, the primary objective of a constant rate pumping test is to develop an understanding of how an aquifer responds to pumping, to characterize aquifer parameters (i.e., transmissivity and storativity), and to determine the sustainable pumping rate over a long-term period so as not to overly deplete the aquifer. A thorough interpretation of the aquifer is essential to assess long-term pumping response. Aquifer transmissivity is commonly calculated using traditional analytical solutions like Cooper-Jacob (Cooper & Jacob, 1946), Theis (Theis, 1935), and Theis recovery methods (Theis, 1935). These solutions require drawdown to be measured during pumping and recovery from pumping, and assume some ideal conditions, which are rarely fully met in fractured bedrock aquifers. Similar analytical solutions intended for fractured bedrock have been developed, such as by Gringarten et al. (1975). However, additional knowledge of the length of a conductive fracture is required (Allen, 1999), which is not feasible to determine with any certainty. Even with the availability of these solutions, calculation of aquifer storativity is only possible if drawdown data are available from one or more observation wells, which are rarely available in BC.

In BC, the standard technique to assess the long-term sustainable yield (Q_{100}) of an aquifer is the 100-day method (van Everdingen, 2024). Determining Q_{100} can be challenging, as extrapolating the drawdown data from the late period of the test is subject to uncertainties (van der Kamp et al., 2021). Some of these may include: the limited duration of pumping tests (1-3 days) meaning drawdown trends may not be clear, making the pumping response difficult to empirically extrapolate in the long term with certainty. This uncertainty in the interpretation of the pumping test can be amplified when estimating the long-term well yield.

Given these uncertainties, additional methods have been developed to analyze pumping test data to enhance the reliability of interpretations. The derivative method, prompted by the need to emphasize conceptual model identification, was developed by Bourdet et al. (1984). The derivative of the drawdown plot reveals periods of distinct flow regimes during pumping (e.g., linear, infinite-acting radial flow, etc.). This sensitivity helps distinguish the various flow regimes, particularly the infinite-acting flow regime assumed to be present to enable calculation of the Cooper-Jacob (1946), Theis (1935), and Theis recovery (1935) methods of calculating transmissivity (Allen, 1999). The derivative method has been prominent in petroleum engineering for many decades, recently becoming more widely used in hydrogeology practice.

van der Kamp (1989) relied on the assumption of the principle of superposition to extend the effective pumping duration and resultant drawdown for as long as recovery data were recorded. The van der Kamp method (also known as the extended drawdown method) provides greater insight and certainty to the theoretical drawdown for days longer than the pumping duration. This approach improves confidence in assessments of long-term drawdown responses and evaluates the applicability of assumptions important to pumping test analysis (van der Kamp et al., 2021). The van der Kamp method is not yet customary practice in BC (van der Kamp et al., 2021).

1.2 Research Motivation

There have been very few published studies on the use of the derivative method and extended drawdown method in BC. Allen (1999) applied the derivative method to fractured rock aquifers in BC. van der Kamp et al. (2021) applied the extended drawdown method to a limited range of hydrogeologic settings in BC. Demonstrating the use of the derivative method and van der Kamp method in bedrock pumping tests expands on the work done by van der Kamp et al. (2021) and Allen (1999), progressing the discipline by illustrating when derivative and van der Kamp methods improve hydraulic interpretation of especially challenging pumping tests in fractured bedrock aquifers in BC.

1.3 Study Objectives

To assess the application of the derivative and van der Kamp methods, the main objectives of this study include:

1) Characterize common aquifer flow regimes (e.g., wellbore storage, linear flow, infinite-acting radial flow) in fractured bedrock aquifers in BC.
2) Evaluate whether implementing the derivative method and the van der Kamp method improves reliable assessment of aquifer transmissivity and viable source supply (Q_{100}).
3) Provide recommendations on how tests in fractured bedrock in BC can improve or determine whether the current methodology is sufficient to obtain accurate estimates of transmissivity and Q_{100}.

1.4 Study Scope

This study aims to analyze data from select pumping tests conducted in fractured bedrock aquifers around southern Vancouver Island and the Gulf Islands region. Criteria for selecting pumping tests that are ideal for a meaningful application of both the derivative and van der Kamp methods were discussed by Allen (1999) and van der Kamp et al. (2021) and have been refined and summarized below:

1) Fractured bedrock aquifer.
2) Pumping test is a constant discharge rate. Variations of less than 5% and drawdown measurements every 15 minutes for the first hour and every hour until the end of the test.
3) Static water level is fully recovered from any prior tests or water level monitored before and after pumping.
4) Pumping is not interrupted during the pumping phase.
5) Tests of 24 - 72 hours with sufficient duration residual drawdown data. Residual drawdown data are recorded until 90% recovery has been achieved, or the same length of time as the pumping test lasted. In the pumped well, the 90% recovery should not include recovery from well loss (B.C. Ministry of Environment, n.d.).

6) Residual drawdown measurements are taken at the same interval as pumping measurements.

Not all tests selected for this study will meet all these criteria, as the pumping tests were not conducted with this research's specific requirements in mind. While the variability in test conditions will impact comparability, it allows the application of the derivative and van der Kamp method to be evaluated under these various conditions.

2. Theoretical Background

2.1 Q_{100} Long-term Sustainable Yield

The evaluation of a sustainable pumping rate is often a primary objective of a pumping test. In BC, many aquifers are recharged by seasonal precipitation following a 100–180-day dry summer. As such, a 100-day pumping period can be used as a projection of the maximally expected aquifer depletion, based on the assumption that recharge occurs annually after one hundred days (van Everdingen, 2024). The 100-day method was originally developed in the 1970s for bedrock well assessments in coastal BC, but by 1999, had evolved to become the standard approach for assessing wells completed in unconsolidated deposits also (van Everdingen, 2024).

2.1.1 Theory

To estimate the sustainable pumping rate (Q_{100}) that can be maintained over these 100 days, it is assumed that maximum aquifer depletion occurs after one hundred consecutive days of pumping. Q_{100} is then determined using Equation 1:

$$Q_{100} = SADD \times SC = [s_{available} \times S_f] \times Q_t / s_{100\text{-day}} \qquad \text{(Eq. 1)}$$

Q_{100} (m^3/day) is the product of the safe available drawdown (SADD) (m) and the specific capacity (SC) (m^2/day) at one hundred days of pumping. SADD is a maximal depth to which water in the well can be lowered. For fractured bedrock wells, the available drawdown is bounded by the depth of the upper-most major water-bearing fracture ($s_{available}$) (Wei & Kohut, 1986). A deeper fracture, with more available drawdown means a higher Q_{100}. To account for uncertainties and protect the aquifer from excessive depletion, a scaling factor (S_f) is applied, reducing the permissible drawdown. The $s_{available}$ is multiplied by 0.7 to ensure 30% of the available drawdown always remains.

Specific capacity is the drawdown (m) estimated by the 100-day straight-line extrapolation ($s_{100\text{-}day}$) (Figure 1) of the drawdown rate observed in the pumping test, normalized by the discharge rate of the pumping test (Q_t) (m^3/day).

The extrapolation of the drawdown relies on the empirically observed drawdown behavior at late pumping times, which may follow a straight line (on a semi-log plot of drawdown vs logarithm of time), or a curve fit. Therefore, the 100-day method approach can be independent of the Theis assumptions for an ideal aquifer.

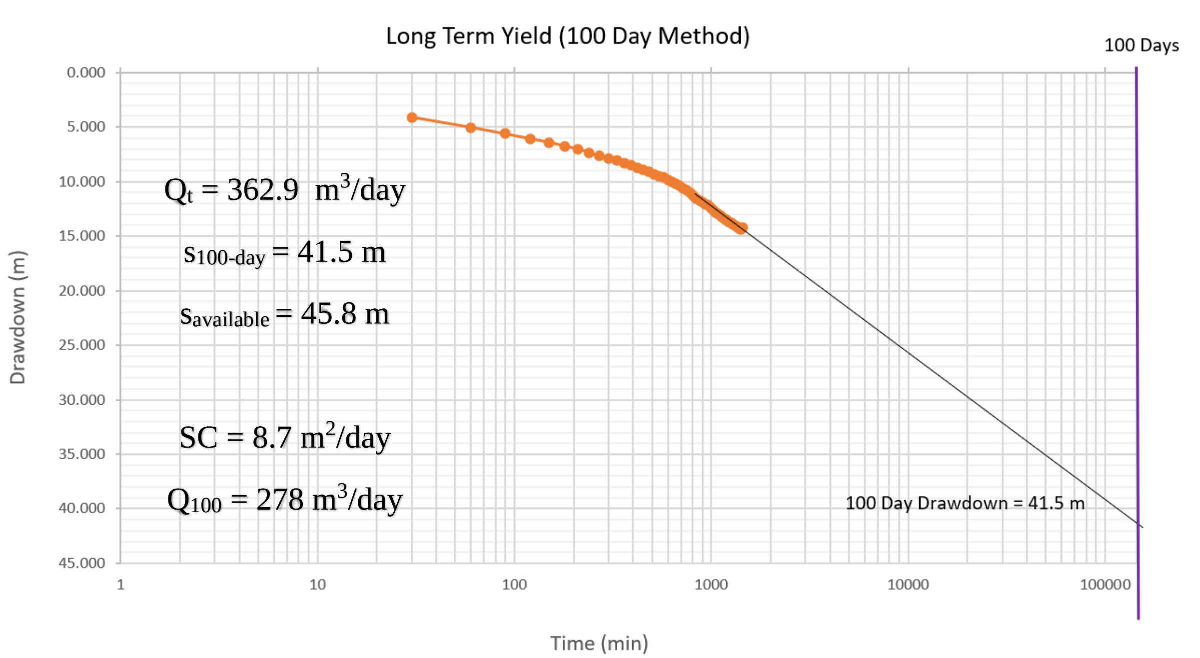


Figure 1: Time drawdown, semi-log graph, showing projected 100-day drawdown using pumping well data and an example calculation of Q_{100}.

2.2 The Derivative Method

Common models like Theis (1935) and Cooper-Jacob (Cooper & Jacob, 1946) apply to infinite acting radial flow. Aquifers can present different pumping responses if they have heterogeneities, positive or negative flow boundaries, unconfined conditions, or anisotropic fracture geometries.

A more effective approach is to define pumping regimes with a stable hydraulic response and constrain analytical models to only use the drawdown data that align with their inherent assumptions (Renard et al., 2009). This is best achieved through the application of the derivative method.

2.2.1 Theory

The derivative method involves plotting the numerical logarithmic time derivative of pumping-induced drawdown or residual drawdown. Using a fixed endpoint algorithm (Spane & Wurstner, 1993), the derivative of drawdown is calculated with respect to the natural logarithm of time at each drawdown datapoint. This is done by evaluating the slope at a point immediately before and after the point of interest, and then averaging the two values, as shown in Equation 2.

$$\left(\frac{dP}{dX}\right)_i = [(\Delta P_1/\Delta X_1)\Delta X_2 + (\Delta P_2/\Delta X_2)\Delta X_1]/(\Delta X_1 + \Delta X_2) \qquad \text{(Eq. 2)}$$

subscript 1 = point(s) before the point of interest, *i*

subscript 2 = point(s) after the point of interest, *i*

P = drawdown or residual drawdown, s

X = natural logarithm of the time, t. *Note:* for recovery data, t is defined as the natural logarithm of the total test time divided by the time since the pump was shut off, (t/t')

The slope of the derivative plot reflects the flow regime occurring during a specific period of the test. The term "flow regime" refers to a distinct drawdown response of the aquifer to pumping, characterized by a specific slope of the derivative. When the slope of the derivative is not changing, it is an indication of hydrodynamic stability during the test, highlighting a spatial-temporal window where flow is infinite-acting and radial (Ferroud et al., 2019).

It is important to minimize the straight-line fitting ambiguity which can be problematic when calculating transmissivity from a drawdown curve using the Cooper-Jacob method and/or Theis recovery method (Allen, 1999). The slope of the Cooper-Jacob asymptote is the same as the logarithm derivative (Equation 3) (Renard et al., 2009). Rather than fitting a straight line to a log-linear segment of a drawdown curve, the slope of the Cooper-Jacob asymptote can be read as the magnitude of the stable regime of the derivative.

$$\frac{ds}{d(ln(t))} = t\frac{ds}{dt} = t\ \frac{Q}{4\pi T}\frac{1}{t} = \frac{Q}{4\pi T} \qquad \text{(Eq. 3)}$$

ds/d(ln(t)) = drawdown per natural log-cycle of time

t = time since pumping started

ds/dt = drawdown rate at time step t

Q = pumping rate

T = transmissivity

2.2.2 The recovery derivative

Applying the derivative method to the recovery data has not yet been thoroughly examined in other published studies. In an aquifer of infinite extent, the recovery phase is ideally an inverse of the pumping phase (Theis, 1935). Thus, the interval interpreted to be infinite-acting radial flow in the pumping phase, $[t_{1,\ radial}, t_{2,\ radial}]$, is mappable to a symmetrical recovery phase of equal duration, $[t'_{1,\ radial}, t'_{2,\ radial}]$ (Equation 4). Allen (1999) also hypothesized this symmetrical behavior. The derivative of the recovery data was plotted alongside the derivative of pumping data in this study to assess that hypothesis.

$$[t_{1,radial}, t_{2,radial}] = [t'_{1,radial}, t'_{2,radial}] \qquad \text{(Eq. 4)}$$

The Theis recovery method calculation of transmissivity should be performed using the data exclusively in this infinite-acting radial flow phase. If transmissivity in the recovery and pumping phases differ, then it may be worth investigating if the aquifer is performing ideally as expected by the Theis (1935) assumptions.

2.2.3 Noise in the derivative

The derivative is sensitive to slight changes in the shape of the drawdown curve (Renard et al., 2009) and can often appear quite noisy. As time passes, drawdown measurement errors are multiplied by the increasing duration time interval between successive measurements. These errors accumulate, causing the derivative to appear most variable later in the test. Reasons for measurement errors may include operational imprecision, pumping rate fluctuations, wind effects, earth tides, barometric fluctuations, or seasonal precipitation (Ferroud et al., 2019). When using the derivative method, the correct interpretation is to neglect these oscillations and focus on the larger trend (Allen, 1999).

Additional smoothing is possible by increasing the length between successive data points for which the derivative is averaged. The number of drawdown measurements skipped between each numerical differentiation is the L-spacing (Figure 2). When the derivative is averaged for each successive drawdown measurement the L-spacing is 0. Increasing the L-spacing can smooth the derivative, making it easier to identify flow regimes. However, care must be taken to avoid using an excessively large L-spacing, as it can over-smooth the derivative and lead to a loss of resolution. This is particularly of concern for long-duration pumping tests (Spane and Wurstner, 1993). Additionally, if the number of drawdown measurements is already limited, increasing the L-spacing may not be beneficial. Figure 3a is an example of a derivative before smoothing. Figure 3b shows how increasing the L-spacing smooths the derivative, making it easier to identify when infinite-acting radial flow is present.

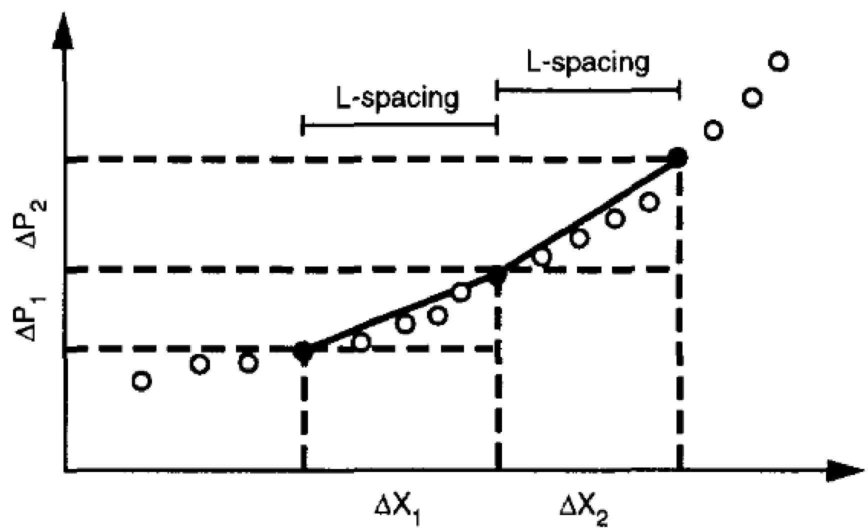


Figure 2: Fixed end point method for calculating mean slope (ΔP/ΔX) (Spane and Wurstner, 1993).

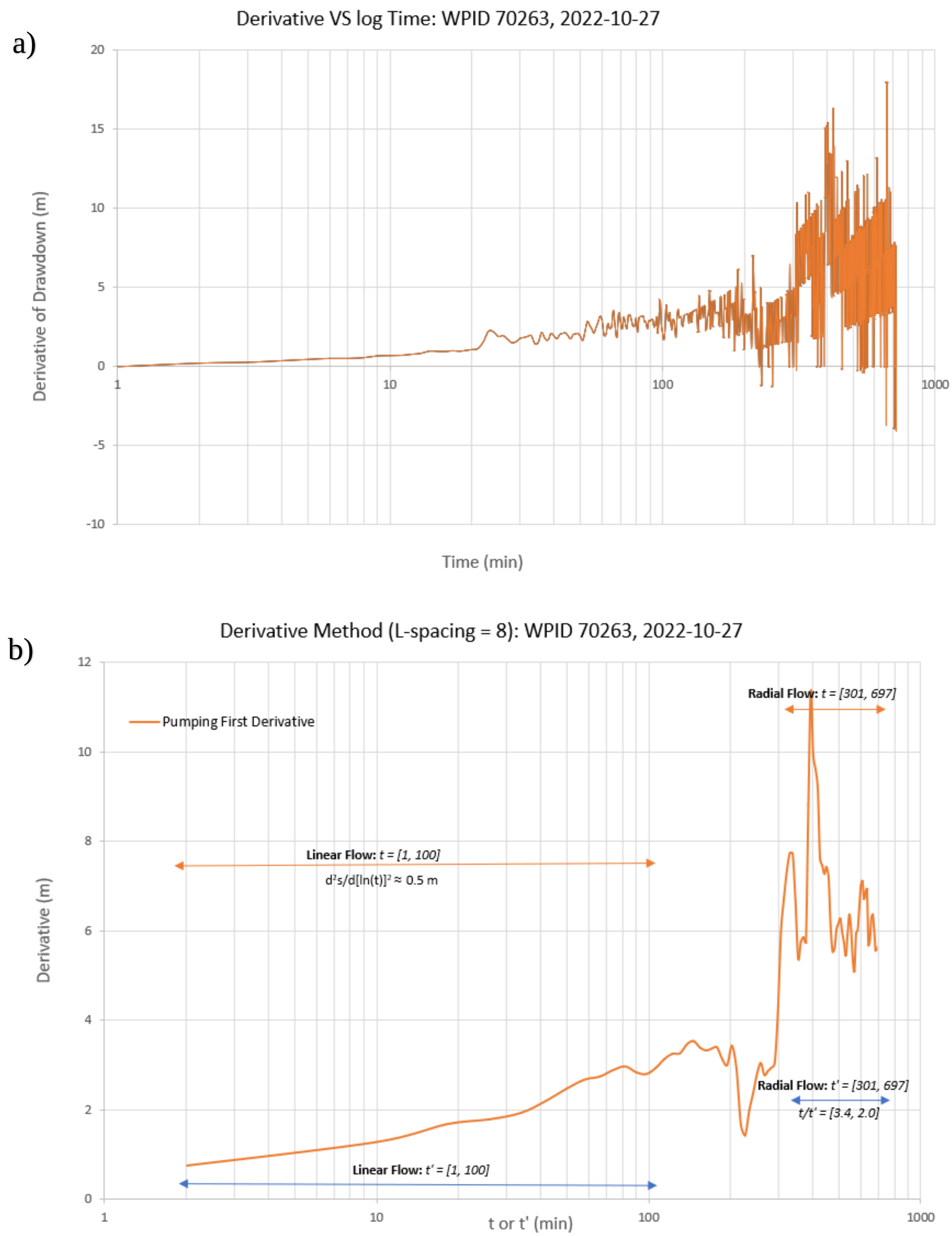


Figure 3: WPID 70263; ***a*** *Example of derivative curve that is highly noisy, requiring smoothing;* ***b*** *Example of the derivative curve post smoothing with an L-spacing of 8.*

2.2.4 Example Results

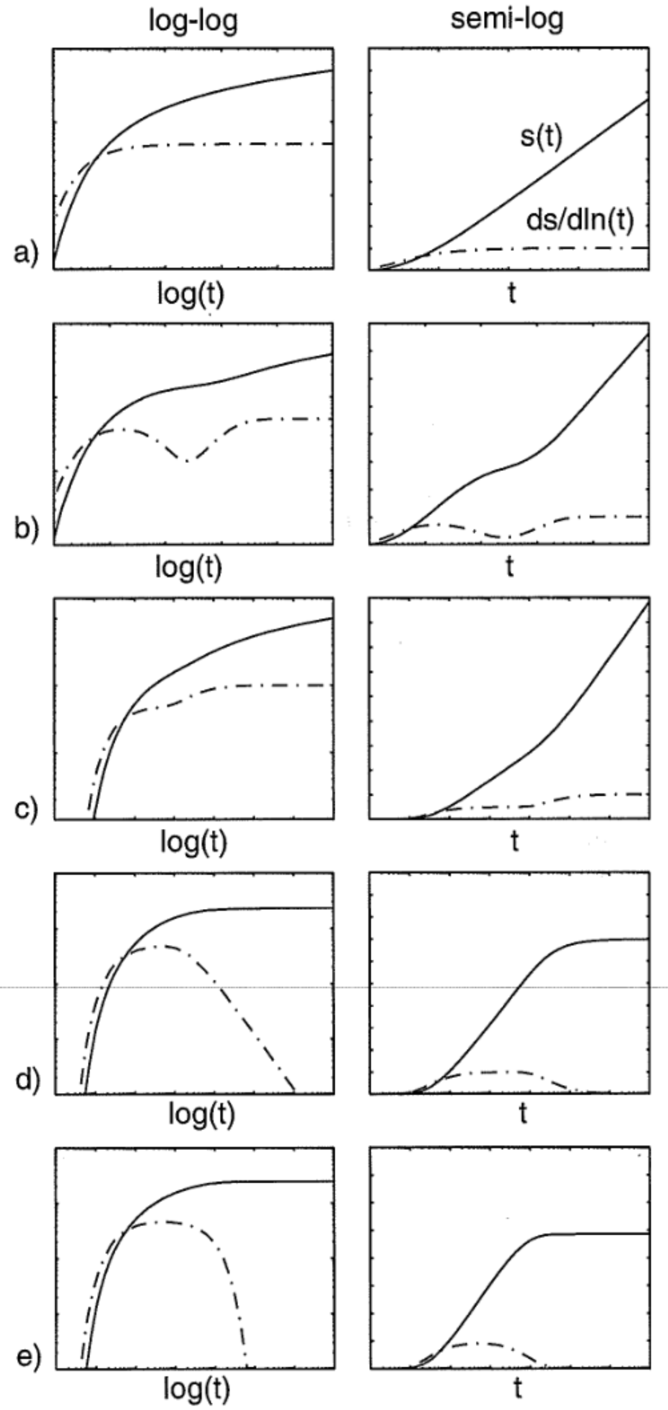
When the derivative is not constant, the dimensionality of the flow regime can be determined by its slope on a log-log plot. The slope (*m)* of the derivative predicts the flow dimension (*n)* using the relationship provided by Chakrabarty (1994):

$$m = 1 - \frac{n}{2} \qquad \text{(Eq. 5)}$$

Computing the flow dimension scales the derivative to represent the number of dimensions from which water is drawn during a given period of the pumping test. For instance, as outlined by Beauheim et al. (2004):

- Linear flow (n = 1) is 1-dimensional flow and has a derivative slope of ½.
- Infinite-acting radial flow (n = 2) is 2-dimensional flow and has a derivative slope of 0.
- Spherical flow (n = 3) is 3-dimensional flow and has a derivative slope of -½.

In practice, flow through an aquifer is often more complex and may not correspond to an integer dimension. In such cases, the flow dimension is approximated to quickly assess the approximate aquifer conditions present during the pumping test. Figure 4 (from Renard et al., 2009) contains idealized example derivative plots overlain with the drawdown data. For demonstration purposes, these plots reflect an ideal circumstance not subject to measurement noise.


log-log
semi-log
s(t)
ds/dln(t)
a)
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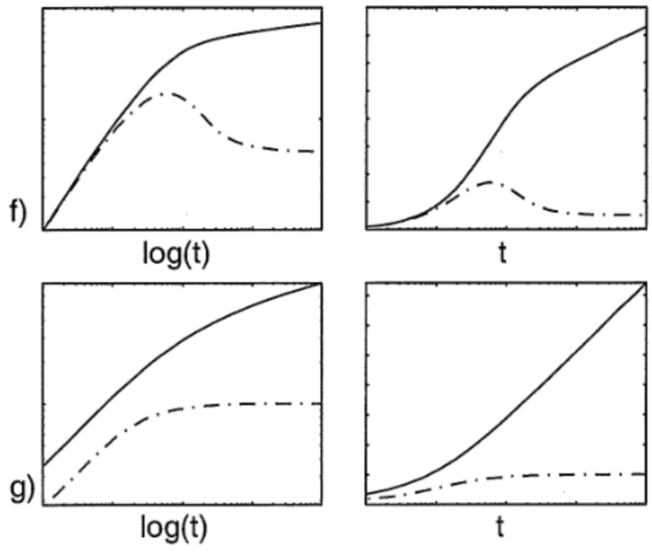

*Figure 4: Example derivative plots encountered in fractured bedrock pumping tests (Left = log-log, Right = semi-log), solid line is drawdown, dotted line is derivative: **a** Theis Model: Infinite two-dimensional confined aquifer; **b** double porosity or unconfined aquifer; **c** infinite linear no-flow boundary; **d** infinite linear constant head boundary; **e** leaky aquifer; **f** well bore storage and skin effect; **g** infinite conductivity vertical fracture (Renard et al., 2009). See terms in Glossary.*

2.2.5 Considerations for the derivative method

It is expected that the longer the pumping test, the larger the volume of the aquifer that will be probed (van der Kamp et al., 2021). Therefore, it is more likely that a larger number of flow regimes will be encountered in longer tests. It should be kept in mind that the derivative signature at the end of the test will not necessarily persist throughout a longer duration of pumping and may evolve further (Ferroud et al., 2019). It is also possible that for highly heterogeneous aquifers, the derivative signal never has stable regimes of constant slope, expressing only transitional non-integer flow regimes (Ferroud et al., 2019). Any pumping test analytical solution requires hydraulic properties to be stable on some scale before those properties can be uniquely quantified. It has been recommended that a stable derivative should persist for at least one log-cycle of time to have confidence in it (Beauheim et al., 2004).

2.3 The van der Kamp Method

Recovery drawdown data are routinely collected during pumping tests but are often underutilized. Typically, recovery data only serve as a secondary check of transmissivity using the Theis recovery method. While treating recovery as an independent phase acknowledges a distinction from the pumping phase, recovery data are intrinsically linked to the preceding pumping phase. When pumping ceases, the drawdown cone flattens but continues to grow. Water flows toward the well from areas beyond the extent of the initial drawdown cone (Figure 5) (van der Kamp et al., 2021), potentially offering insights into the aquifer's long-term response to pumping (van der Kamp et al., 2021). Characterizing the recovery response in relation to the pumping response may be especially valuable for fractured bedrock aquifers for which drawdown responses are more variable.

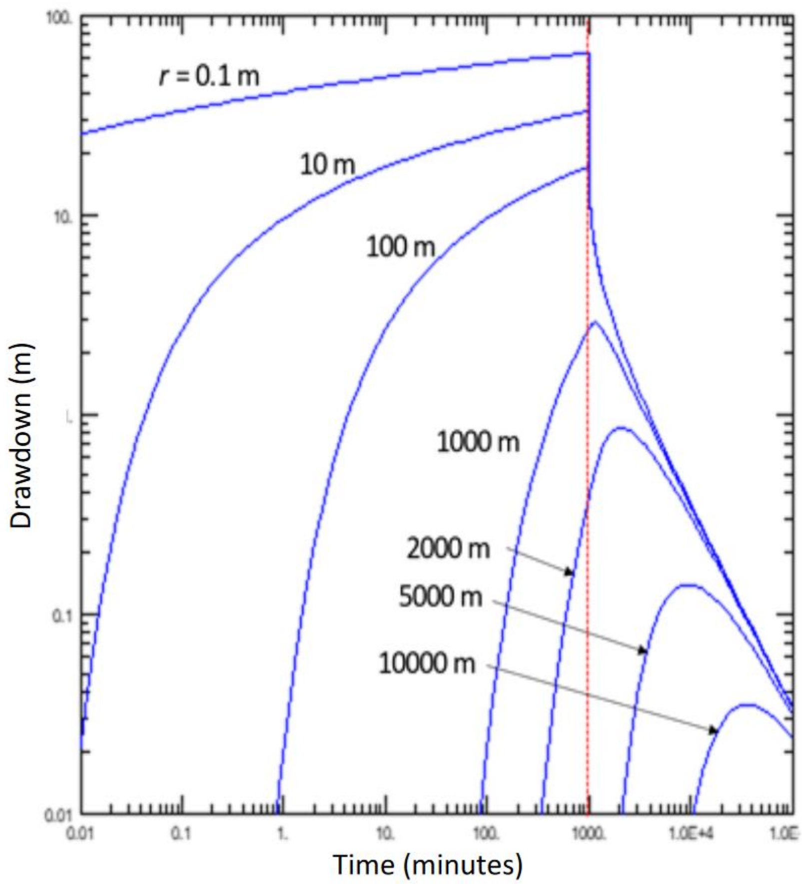

Figure 5: Log-log plot of time evolution of drawdown different distances from the pumped well during the pumping and recovery phases of a 1000-minute pumping test of a confined aquifer (van der Kamp et al., 2021). Red line it time of pump shutoff.

The van der Kamp method (or extended drawdown method), developed by van der Kamp (1989), provides a way to theoretically extend the pumping-induced drawdown curve over the length of the recovery period using the principle of superposition. Extending the effective length of pumping without having to budget for a longer pumping phase can improve estimates of the long-term sustainable yield, minimizing the reliance on the empirical projections of the 100-day method. Drawdown trends late in a pumping test, whether empirical or non-empirical, are most pertinent to long-term projections.

2.3.1 Theory

In the Theis recovery solution (Theis, 1935), the residual drawdown is equivalent to the theoretical continuation of pumping superimposed by an injection at the same rate, so that net withdrawal is zero (Figure 6).

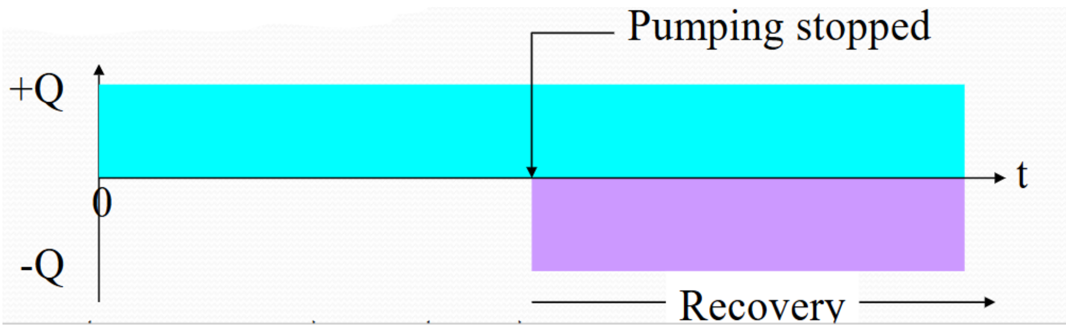

Figure 6: Schematic representation of the principle of superposition.

Superposition is valid for spatial variations, boundaries, anisotropy, fractures, flow dimensions, etc., so long as the assumption in the original governing linear differential equation is not significantly violated. The mathematical derivation of the extended drawdown is depicted in Figure 7.

The parameter $s(t)$ is the drawdown observed during and after pumping; $s_2(t)$ is the negative injection of water starting at t_{off}, delayed by the duration of pumping. Hence, $s_1(t)$ is the constant rate extended drawdown and is the difference between $s(t)$ and $s_{2,}(t)$. Equations 6, 7, and 8 represent these relationships.

$s(t) = s_1(t) + s_2(t)$ $[t > t_{off}]$ (Eq. 6)

$s(t) = s_1(t)$ $[0 \leq t \leq t_{off}]$ (Eq. 7)

$s_2(t) = -s_{1,}(t - t_{off})$ $[t > t_{off}]$ (Eq. 8)

The curve of $s_1(t)$ for the interval beyond t_{off} represents the drawdown that would have occurred had pumping continued. Solving for $s_1(t)$ using Equations 6, 7, and 8 gives Equation 9b for the interval $t > t_{off}$, which is the extended drawdown.

$s_1(t) = s(t)$ $[t < t_{off}]$ (Eq. 9a)

$s_1(t) = s(t) + s_1(t - t_{off})$ $[t > t_{off}]$ (Eq. 9b)

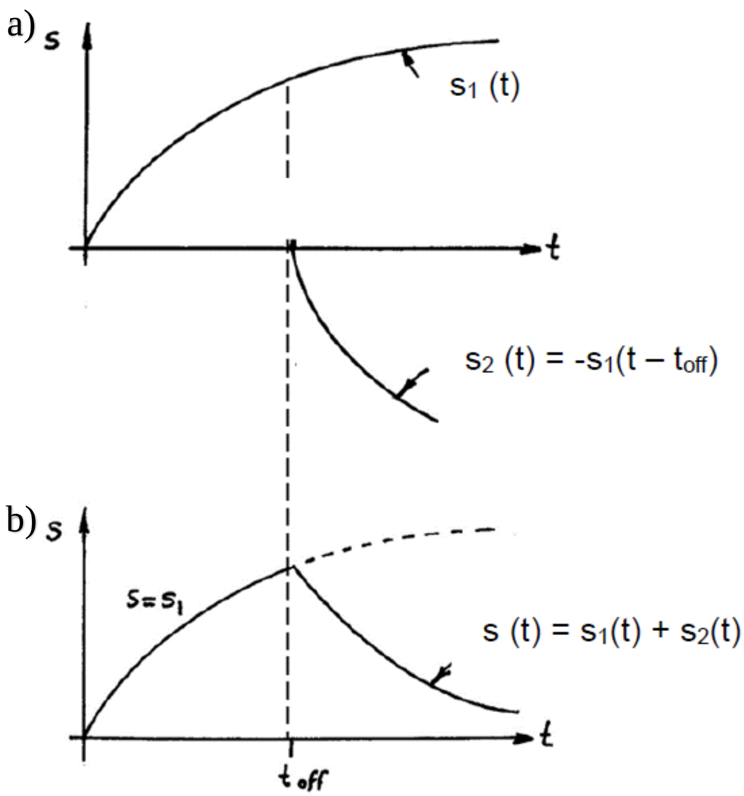

Figure 7: a The principle of superposition applied to the recovery phase. b Drawdown vs time plotted linearly (van der Kamp et al., 2021).

Equation 9b is conditionally applicable if the test was conducted at a constant discharge rate and the principle of superposition is applicable. Determining if the principle of superposition is applicable is practically challenging but can be summarized by a few physical conditions (van der Kamp et al., 2021):

1) Applicability of Darcy's Law. Instantaneous release from storage in linear proportion to a hydraulic head change.
2) Aquifer properties do not change with time.
3) No dewatering. Aquifer saturated thickness is constant.

2.3.2 Plotting "as expected" vs "not as expected"

Assessing the superposition conditions can be done using the result of the extended drawdown plot. If the extended drawdown plots *as expected* (Figure 8a) and the extended drawdown continues to increase in the recovery phase, superposition is applicable and the conditions above apply to the aquifer.

When the extended drawdown plot immediately changes slope after the end of the pumping phase, then the plot is considered to deviate *not as expected*. The extended drawdown plotting not as expected does not detract from its usefulness. An abrupt deviation from the pumping drawdown rate means one or more of the conditions of superposition may not apply or that the “static” water level was not static throughout the test (Figure 8b). Further investigation can be undertaken to determine if one of these conditions was unreasonably assumed to be true. For confined aquifers, the “static” water level may be rising or falling throughout pumping and/or recovery (Neville & van der Kamp, 2012). As a result, there will be an upwards or downwards drift in the pumping and recovery response. A similar response could be attributed to the dewatering of fractures above the pumping water that brings additional water into the well chamber. In such cases, the van der Kamp method has not been able to be usefully applied (van der Kamp et al., 2021).

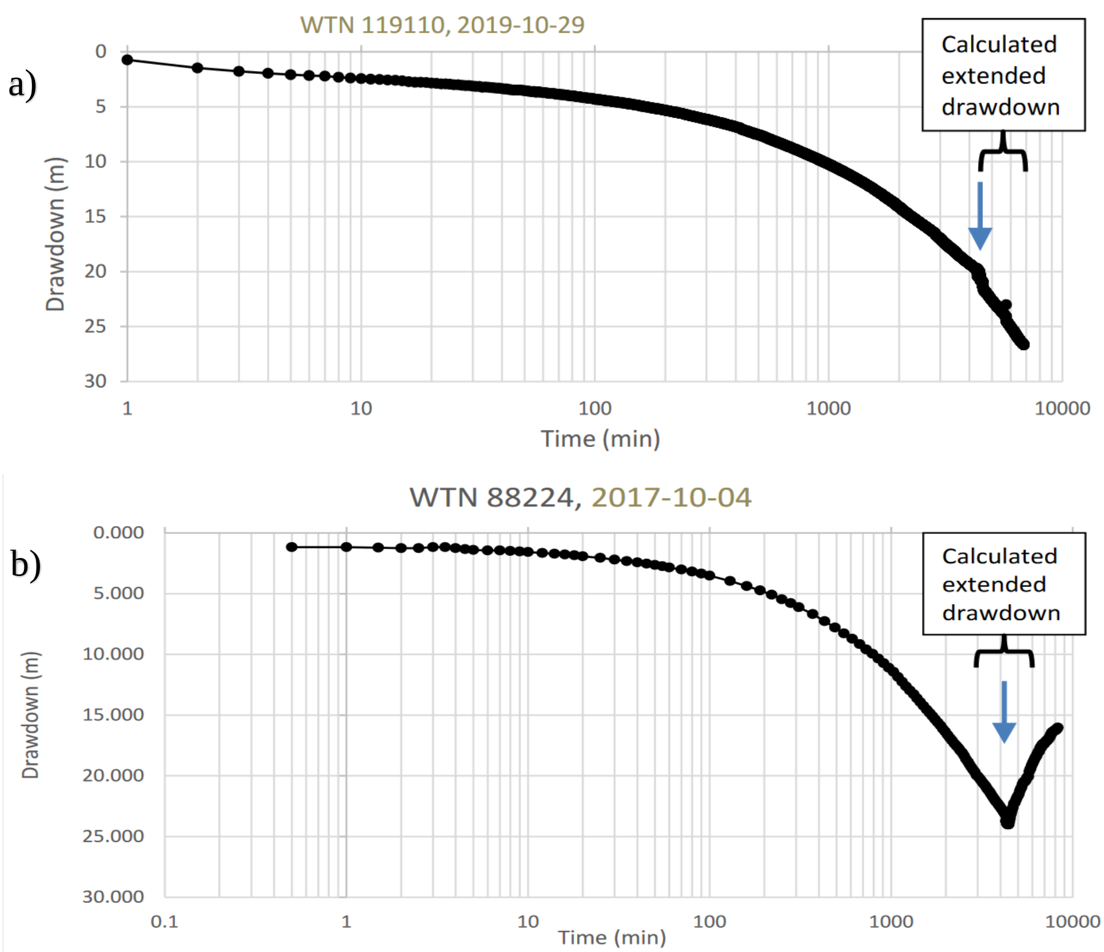

Figure 8: Typical extended drawdown plots: a Plot of drawdown and extended drawdown confirming applicability of superposition; b Plot of drawdown and extended drawdown showing effect of a rising static water level (van der Kamp et al., 2021).

2.3.3 Considerations for the van der Kamp method

The extended drawdown is not intended to permit the reduction of pumping test duration, but to enhance the interpretation of the latter part of pumping and recovery. Optimal application of the van der Kamp method considers the implications of how the extended drawdown curve is interpreted, as well as the risks and benefits of the intended water use.

3. Methods

3.1 Acquisition of Pumping Tests

Seven pumping tests shared by local consultants were deemed to meet enough of the criteria sought. All seven tests are in fractured bedrock, albeit in several bedrock lithologies. One test was not included as it was a few meters adjacent to Mill Bay B and did not have very much recovery data; thus, a total of six tests were analyzed. To make it easier for later discussion, these pumping tests were given names that refer to their approximate location. Searching the well tag number (WTN) using the BC government's GWELLS database or clicking on the numbered hyperlink will provide a precise location. The Errington well was a test well and was not given a WTN or registered in the GWELLS database. It is listed under its well plate identification number (WPID). Table 1 summarizes relevant information from each test.

Table 1: Summary of pumping tests used in this study

General Location	WTN	Aquifer No.	Aquifer Type	Well Depth (m)	Water Level at	Total available
Errington	70263 (WPID)	220	Sedimentary Bedrock	63.1	7.776	52.3
Galiano	91453	320	Sedimentary Bedrock	75.3	33.480	31.1
Saanich South Well	54024	614	Crystalline Bedrock	27,6	0.721	23.7
Saanich North Well	53884	614	Crystalline Bedrock	38.1	5.34	25.8
Mill Bay A	88224	203	Sedimentary Bedrock	135.5	80.88	50.1
Mill Bay B	117952	208	Sedimentary Bedrock	91.4	30.91	45.9

*Values with a * are calculated in the Results section.*

Date of Start of Test	Pumping Duration (min)	Pumping Rate (m^3/day)	Recovery Duration, t/t’	Percent Recovery	Theis Transmissi	Cooper-Jacob
2022-10-27	720	4.32	1.11	107	0.053	0.053
2020-10-16	4320	17.71	13.0	88	0.31	0.35
2022-08-23	4319	38.02	2.57	95	1.5	1.8
2022-08-23	4311	70.84	1.97	92	2.2	2.7
2017-10-10	4320	518.40	2.09	128	4.1	4.5
2019-08-14	1440	362.90	1.87	72	4.7	4.9

Theis Recovery	Q_{100}* (m^3/day)
0.083	3
0.40	23
1.6	30
2.7	45
1.9	335
8.8	280

3.2 Spreadsheet Analysis

The reliability of transmissivity and Q_{100} values needs to be evaluated in conjunction with the results from the van der Kamp and derivative methods.

Pumping test analysis will be formatted similarly to the extended drawdown template spreadsheet created by van der Kamp et al. (2021), only modified to be more specific to the goals of this study. The spreadsheets are downloadable as embedded files in the appendix. To conserve space and not over-clutter this report, only the derivative method figure and van der Kamp method figure will be shown in the results.

The first tab of the spreadsheet contains background information about the well, mapped aquifer, and pumping test. Any available well construction/alteration report(s) are included. The second tab contains all the data recorded from the pumping test: time since pumping started (*t*), time since pumping stopped (*t'*), time since pumping started over time since pumping stopped ratio (*t/t'*), pumping rate (*Q*), water level, and drawdown *(s)* or residual drawdown *(s')*.

For each pumping test, the extended drawdown was calculated using Equation 9b, plotted on a semi-log scale. Next, the derivative of the pumping and recovery phases was calculated for each test using Equation 2. Once plotted on a semi-log plot, the curves were smoothed by increasing the L-spacing incrementally until the best visualization of flow regimes was determined. Derivatives for both the pumping data and recovery data are on the same figure to facilitate comparison, but the independent variable is different for each: *t* for the pumping curve derivative and *t/t'* for the recovery curve derivative. Any period of pumping that exhibited a constant derivative was deemed to show a radial flow regime and was isolated. An equivalent symmetrical radial interval was mapped to the residual drawdown curve as expressed by Equation 4. Transmissivity was calculated three times from this isolated regime using Theis curve-matching (1935), Cooper-Jacob straight-line (1946), and Theis recovery (1935) methods, respectively. Storativity was not calculated in this study because, as common for the majority of pumping tests, drawdown and residual drawdown data from an observation well were not obtained. Lastly, the drawdown trend from the end of the test was extrapolated with a straight line to one hundred days using the 100-day method, and Q_{100} was estimated. When the extended drawdown was applicable, it was used to confirm the extrapolation.

Using the available knowledge about the test conditions, an interpretation of the specific characteristics of the extended drawdown and derivative plots was made. Takeaways of note were summarized for each test.

4. Results

4.1 Errington (WPID 70263)

Aquifer Geology: The well draws from aquifer 220 (https://apps.nrs.gov.bc.ca/gwells/aquifers/220) a fractured Nanaimo Group sedimentary shale. The aquifer is confined by 32 m of glaciomarine/glaciofluvial sediments. The static water level at the start of pumping was reported as 7.776 m below the top of the casing, above the upper extent of the fractured bedrock.

Pumping Well Summary: The well (WTN not given, WPID 70263) was developed by air lifting to a depth of 63.1 m. The uppermost water-bearing fracture could not be determined as the well was pressurized during air lifting. The well yield was estimated to be 1.5 USgpm (8 m^3/day) by the driller.

Pumping Test Summary: On October 27, 2022, a submersible pump was installed in the well at an intake depth of 49.3 m. The well was pumped for 12 hours at a constant discharge rate of 4.32 m^3/day. This was followed by monitoring the recovery for 4.5 days (t/t' = 1.11); more than 100% recovery was observed.

Results: Using the derivative method, a linear flow regime is observed, with an abrupt transition to radial flow (Figure 9). During pumping the radial phase is t = [301, 697], and symmetrically, during recovery, it is t/t' = [3.4, 2.0]. The extended drawdown (Figure 10) exhibits an upward shift initially, breaking continuity between the pumping and recovery phases. This shift repeats as a sawtooth pattern over the 4.5 days of recovery. Transmissivity values calculated using the Theis curve-matching, Cooper-Jacob straight-line, and Theis recovery methods, utilizing only drawdown data that correspond to the radial regime are 0.053 m^2/day, 0.053 m^2/day, and 0.083 m^2/day respectively. Q_{100} long-term sustainable yield was calculated to be 3 m^3/day using a 30% safety factor.

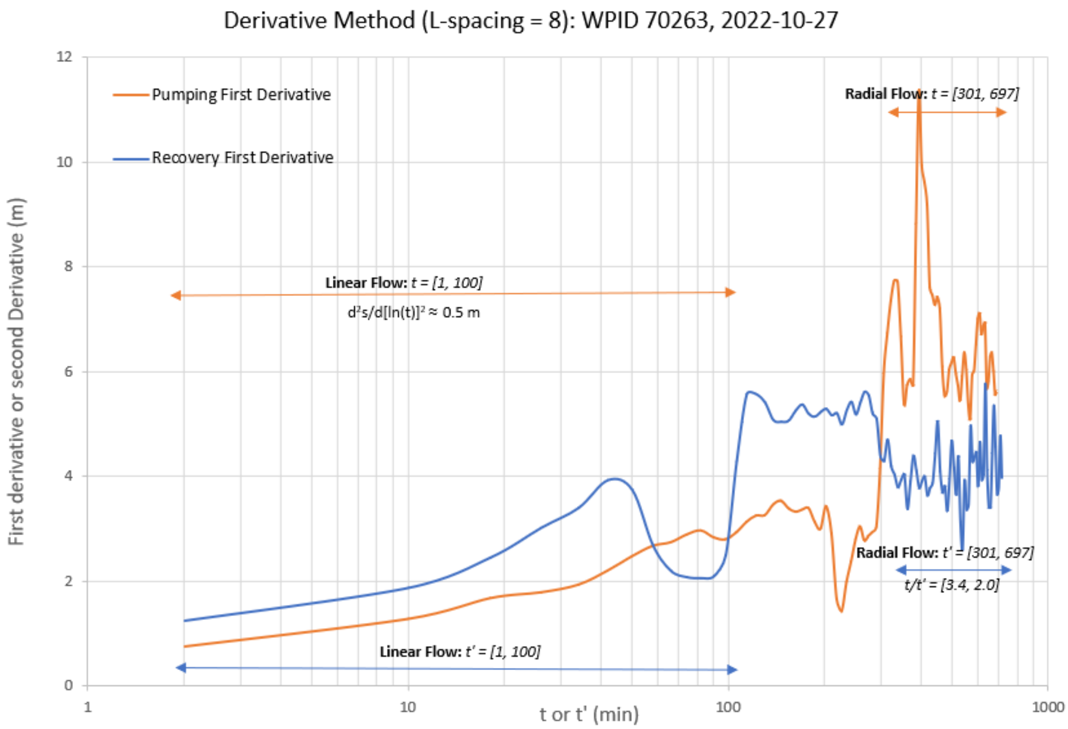

Figure 9: The derivative method (L-spacing = 8) applied to Errington WPID 70263, 2022-10-27.

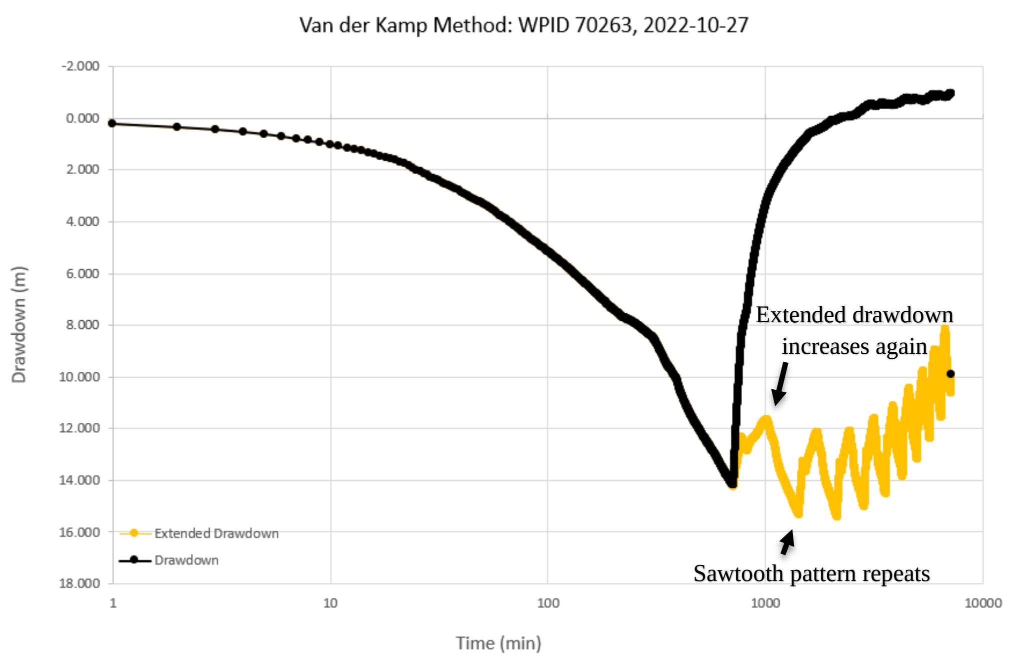

Figure 10: The van der Kamp method applied to Errington WPID 70263, 2022-10-27.

<u>Interpretations:</u> There is evidence that the upward shift sawtooth pattern in the extended drawdown is due to a non-steady static water level (violating the assumption of a "static" pre-pumping water level). The static water level was not monitored before testing, and thus, the static water level reported at t = 0 min should not be assumed to be the true static water level. Despite no recent seasonal precipitation that could have contributed to recharge, the driller reported a static water level of 12.4 m below the top of the casing post-development of the well by airlift on October 25, much deeper than the 7.776 m measured at the start of pumping on October 27. The rising static water level may be due to the recent well development. The suspected rise in the static water level is corroborated by the residual drawdown greater than 100% after 4.5 days of recovery (see Table 1). A constant static water level for the duration of the test is critical for understanding the long-term recovery trends (unless the trend in the rising static water level was adequately characterized and used to correct the true drawdown and residual drawdown). At around t = 1000 min of the extended drawdown, the effects of rising static water level seem to disappear, and the extended drawdown increases again (Figure 10). This may be indicative of a fully recovered static water level that was previously lowered due to airlifting. Regardless, the extended drawdown cannot be used to infer long-term drawdown trends.

Takeaway Comment: This test exhibited a rising static water level throughout pumping that is interpreted to be due to well development. A rising static water level can significantly change the drawdown rate, potentially impacting calculations of transmissivity and Q_{100}.

4.2 Galiano (WTN 91453)

Aquifer Geology: The well draws from aquifer 320 (https://apps.nrs.gov.bc.ca/gwells/aquifers/320), a fractured Nanaimo Group sedimentary shale. The fractured zone of the aquifer is confined by sandstone and minimal glaciomarine sediment. The static water level at the start of pumping was recorded to be 33.48 m below the top of the casing. Aquifer 320 is adjacent to the ocean and has been reported to be at risk of lateral seawater intrusion (British Columbia, 2023).

Pumping Well Summary: The well (WTN 91453, https://apps.nrs.gov.bc.ca/gwells/well/91453) was drilled to a depth of 75.3 m, at a location 725 m from the ocean. A major water-bearing fracture was reported to be at 64.62 m below the top of the well casing. The fracture's yield was reported to be 10 USgpm (55 m^3/day) by the driller.

Pumping Test Summary: On October 16, 2020, a 72-hour pumping test was conducted at a constant discharge rate of 17.71 m^3/day. This was followed by monitoring of the residual drawdown for an additional 6 hours (t/t' = 13), until 88% recovery was observed.

Results: The derivative plot (Figure 11) has a steep, straight-line section at early times that transitions to a flatter near zero slope. For t = [1, 12] the semi-log plot is a straight-line with a slope of 0.5, characteristic of linear flow. Radial flow is observed briefly for t = [12, 60], before the drawdown rate levels off to near zero for the remainder of the test. The recovery derivative appears symmetrical, with a constant drawdown rate at t/t' = [361, 73]. At around t = 1000 min it becomes evident that there is an oscillatory fluctuation in the drawdown. The recovery was only monitored for 6 hours, the extended drawdown plot (Figure 12) is too short to confidently assess if superposition applies. Transmissivity values calculated using Theis curve-matching, Cooper-Jacob straight-line, and Theis recovery methods, utilizing only drawdown data that correspond to the radial regime are 0.31 m^2/day, 0.35 m^2/day, and 0.40 m^2/day respectively. Q_{100} long-term sustainable yield was calculated to be 23 m^3/day using a 30% safety factor.

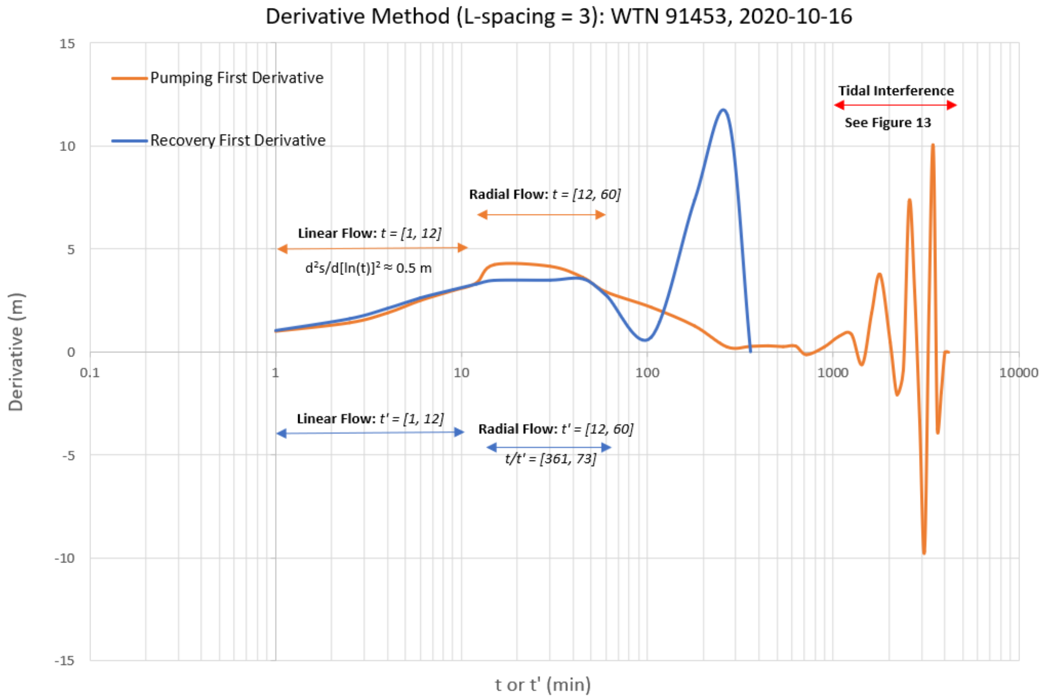

Figure 11: The derivative method (L-spacing = 3) applied to Galiano WTN 91453, 2020-10-16.

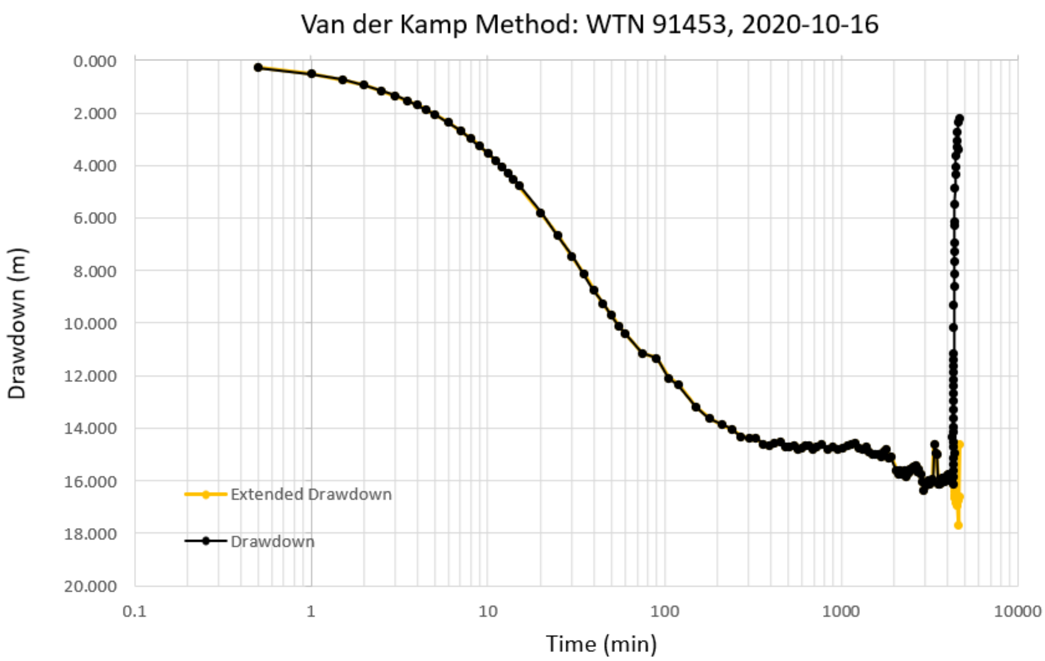

Figure 12: The van der Kamp method applied to Galiano WTN 91453, 2020-10-16.

Interpretations: The late time drawdown fluctuation response is likely tidal interference. Drawdown fluctuations near the end of the test are similar to tidal sea level records from Patricia Bay RCAF station (Figure 13). The changing lateral pressure of the neighboring seawater can cause the land surface and subsurface materials to compress and expand, a process known as tidal loading. This will induce oscillatory shifts in the hydraulic head for confined aquifers (Goyetche, 2022). Tidal loading propagates through the aquifer as pressure waves due to the elastic compression of the aquifer material and the water within it. There is a phase offset between the sea level phase and drawdown fluctuations phase, likely proportional to the aquifer diffusivity. The length of the phase offset is approximately the duration between corresponding wave crests/troughs. It should be noted that tidal interference does not raise or lower the static water level permanently (Goyetche, 2022). This tidal noise is also present in the recovery phase, however, due to the shorter duration of recovery monitoring, it is harder to identify.

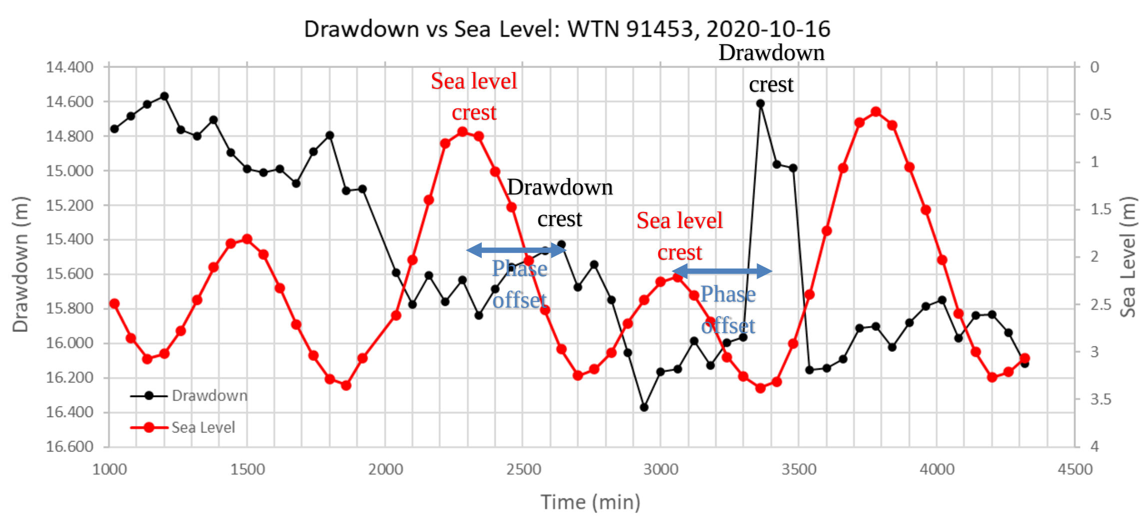

Figure 13: Drawdown fluctuations near the end of the test compared to tidal sea level records from Patricia Bay RCAF station. Galiano WTN 91453, 2020-10-16.

Despite higher than usual seasonal precipitation occurring between September 21 and 24, inducing a temporary rising static water level, the non-pumping water level at the start of the pumping test was 33.48 m, close to the range of water levels (32.5 - 33.0 m) observed at the well on October 5, 2020. This means that the recharge that occurred in September had likely stabilized before the pumping test and did not induce a rising static water level on October 16 or beyond (during the pumping test).

The short duration of recovery measurements limits the extent of the extended drawdown plot. The oscillatory nature of tidal interference does not add or subtract water from the system, it only redistributes pressure temporarily (Erskine, 1991). Q_{100} is consistent with the initial assessments by Alan Kohut in 2018 and 2020 (who shared these pumping tests), and it can be reasonably assumed that the oscillatory effect on the drawdown is not significantly detrimental to the estimation of Q_{100}. The extended drawdown, which is sensitive to changing static water levels, may not work very well for this test.

Takeaway Comment: Tidal interference is not analogous to a continuous rising/falling static water level. Transmissivity and Q_{100} will not be impacted as drawdown rate there are minimal oscillations of the drawdown rate. Oscillations are small in comparison to the overall drawdown trend.

4.3 Saanich South Well (WTN 54024)

Aquifer Geology: The well draws from aquifer 614 (https://apps.nrs.gov.bc.ca/gwells/aquifers/614), a fractured crystalline granite bedrock of the Karmutsen Formation. Fraser Glaciation Quaternary till and clay partially confine the aquifer. Static water level at the start of pumping was recorded to be 0.721 m below top of the casing.

Pumping Well Summary: The well (WTN 54024, https://apps.nrs.gov.bc.ca/gwells/well/54024) was drilled to a depth of 27.6 m, and stopped when a large fracture was encountered at 24.4 m. The yield was reported to be 8 USgpm (44 m^3/day) by the driller.

Pumping Test Summary: On August 23, 2022, the well was pumped at a constant rate of 38.03 m^3/day and drawdown was monitored for nearly 72 hours. Upon pump shutoff, the residual drawdown was monitored for an additional 46 hours (t/t' = 2.57), recovering 95%.

Results: The test exhibits strong continuous radial flow with no preceding linear flow phase (Figure 14). Radial flow dominates for the entire duration of pumping. t = [4, 4319], and symmetrically, for the entire recovery, t' = [4, 2744], until monitoring ends at t/t' = 2.57. The extended drawdown (Figure 15) exhibits an immediate uptick following pump shut off before drawdown continues to decrease steadily as expected by superposition. The anomalous spike at t = 4624 min in the extended drawdown is due to a lapse in data logger measurements and should be ignored relative to the prevailing trend. Transmissivity values calculated using Theis curve-matching, Cooper-Jacob straight-line, and Theis recovery methods, utilizing only drawdown data that correspond to the radial regime are 1.5 m^2/day, 1.8 m^2/day, and 1.6 m^2/day respectively. The Q_{100} long-term sustainable yield was calculated to be 30 m^3/day using a 30% safety factor.

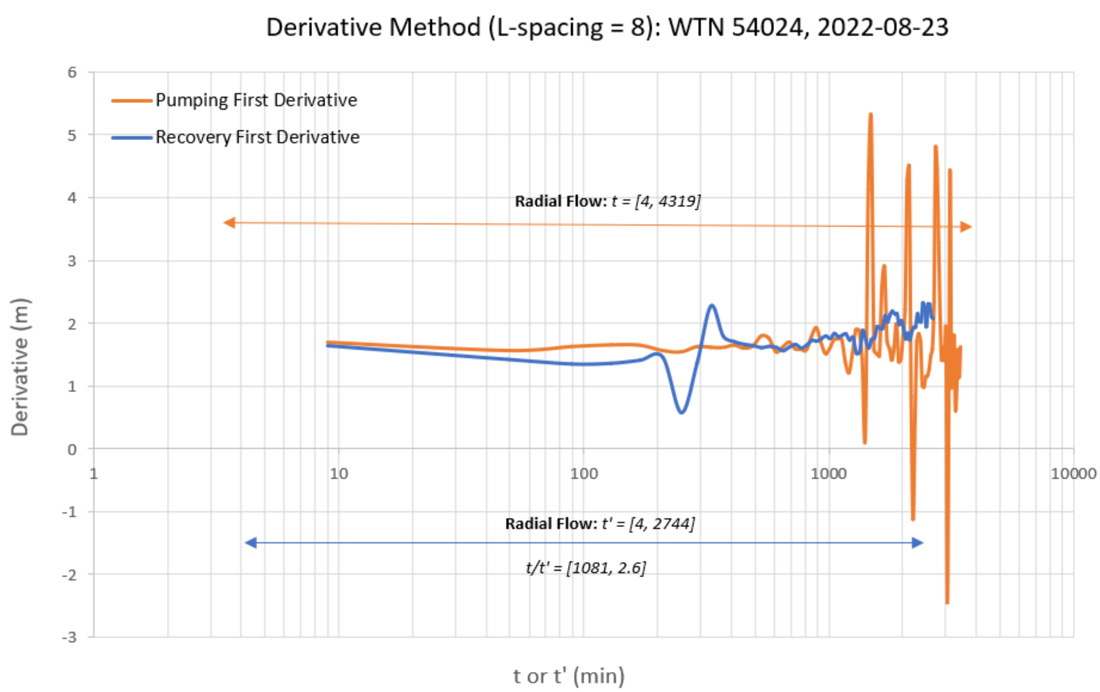

Figure 14: The derivative method (L-spacing = 8) applied to Saanich South Well WTN 54024, 2022-08-23.

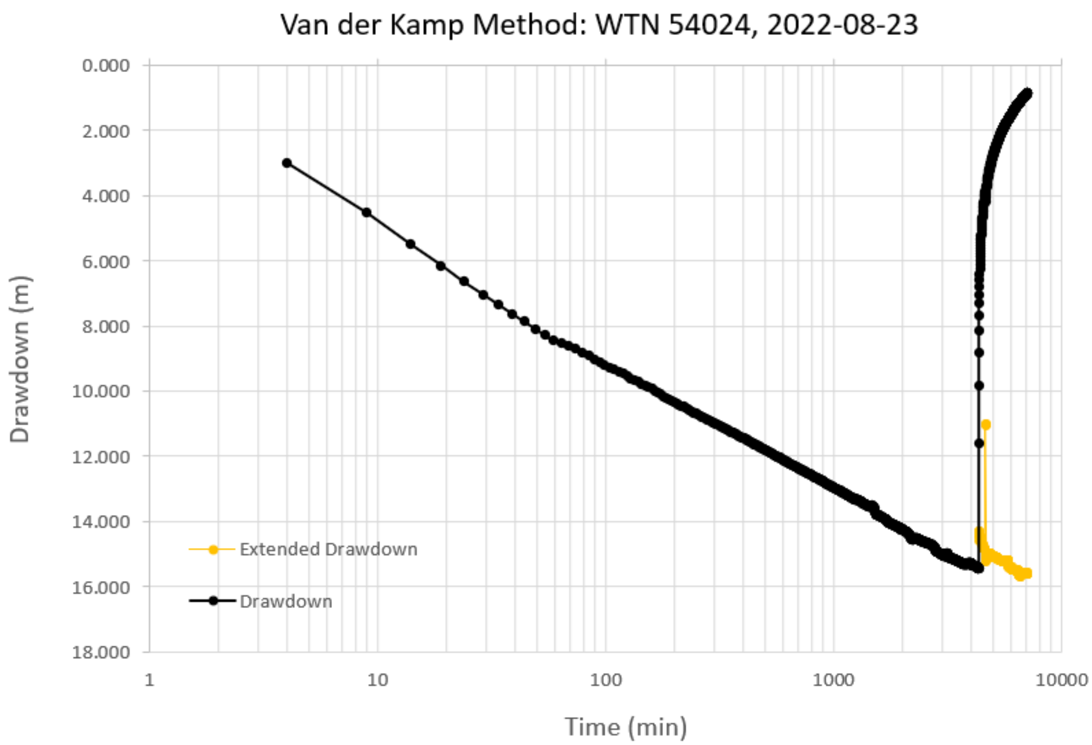

Figure 15: The van der Kamp method applied to Saanich South Well WTN 54024, 2022-08-23.

Interpretations: Consistent radial flow for the entire duration of pumping and recovery indicates there is likely a strong interconnectedness of fractures (Uhl & Sharma, 1978). The major fracture reported at 24.4 m is likely not the only large water-bearing fracture given that the drawdown rate immediately reflects a radial flow regime. This known fracture should still be assumed to be the upper limit of the available drawdown to not risk over-pumping of the well. Dewatering the fracture at the well could disconnect the well from other connected fractures beyond the well, thereby affecting its yield.

The extended drawdown uptick does not invalidate linearity and superposition. In the absence of this uptick, the extended drawdown does continue to increase as expected by superposition. The presence of an uptick in the initial recovery is not impactful to the long-term theoretical drawdown as the extended drawdown trend immediately decreases at the same rate as the pumping phase. The uptick was also observed in the pumped wells analyzed by van der Kamp et al. (2021). The cause of the uptick is not currently known. Q_{100} calculated after extrapolating drawdown to 100 days aligns with the extended drawdown projection, which is an indication that the Q_{100} projection is likely reliable.

Takeaway Comment: It is possible for fractured bedrock wells to not exhibit any linear flow precursory to radial flow. Despite an initial spike in the extended drawdown, superposition applies and can help verify the 100-day straight-line extrapolation.

4.4 Saanich North Well (WTN 53884)

Aquifer Geology: The well draws from aquifer 614 (https://apps.nrs.gov.bc.ca/gwells/aquifers/614), a fractured crystalline granitic bedrock of the Karmutsen Formation. Fraser Glaciation Quaternary till and clay partially confine the aquifer. The static water level prior to pumping was recorded to be 5.34 m below the top of the casing.

Pumping Well Summary: The well (WTN 53884, https://apps.nrs.gov.bc.ca/gwells/well/53884) was drilled to a depth of 38.1 m, stopping when a large fracture was encountered at 31.1 m. The fracture’s yield was reported to be 12 USgpm 65 m^3/day) by the driller.

Pumping Test Summary: On August 23, 2022, the well was pumped at a constant rate of 70.84 m^3/day and drawdown was monitored for nearly 72 hours. Upon pump shutoff, the residual drawdown was monitored for an additional 74 hours (t/t’ = 1.97), recovering 92%. A power surge was briefly used during the test to clear debris (t = 2300 min).

Results: The power surge during the pumping test makes the derivative exceptionally noisy. Despite this, the test exhibits strong continuous radial flow in both phases of testing with no preceding linear phase (Figure 16). Radial flow dominates for the entire duration of pumping, t = [1, 4311], and the entire recovery, t’ = [1, 2744], until monitoring ends at t/t’ = 1.97. The extended drawdown (Figure 17) initially spikes steeply before continuing as expected at the same drawdown rate during pumping. Transmissivity values calculated using Theis curve-matching, Cooper-Jacob straight-line, and Theis recovery methods, utilizing only drawdown data that correspond to the radial regime are 2.2 m^2/day, 2.7 m^2/day, and 2.7 m^2/day respectively. The Q_{100} long-term sustainable yield was calculated to be 45 m^3/day using a 30% safety factor.

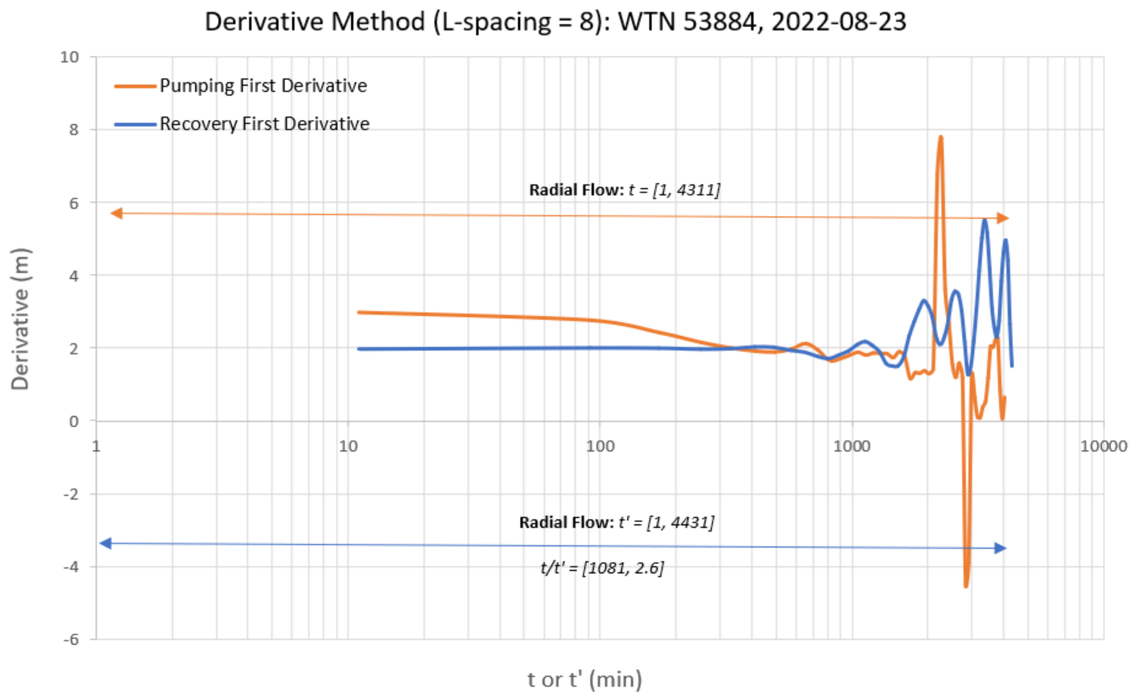

Figure 16: The derivative method (L-spacing = 8) applied to Saanich South Well WTN 53884, 2022-08-23.

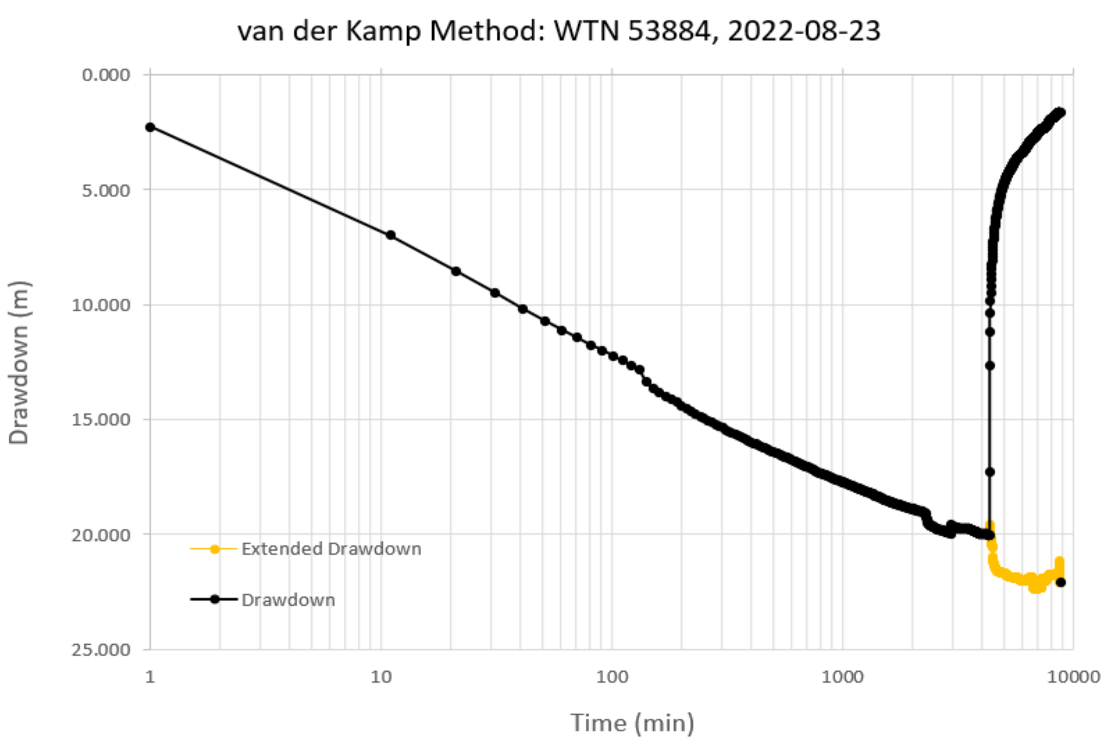

Figure 17: The van der Kamp method applied to Saanich South Well WTN 53884, 2022-08-23.

Interpretations: This well is located approximately 100 m from the Saanich South Well, and both wells were pumped on the same day. The evidence against a rising or falling ambient static water level during the Saanich South Well test should apply to the Saanich North Well. The initial downward spike in water level is likely due to pump rate variations at the start of pumping; therefore, the focus should be on the larger trend, which behaves close to as expected by superposition.

There were a few pump-rate surges over the course of this test which were not necessary for the Saanich South Well test. This results in a much less smooth extended drawdown. Regardless, for both tests, the extended drawdown rate quickly aligns with the drawdown rate from the pumping phase and maintains theoretical continuity.

Due to the pump rate surge, the interpretability of the derivative and van der Kamp methods for the Saanich North Well is not optimal. Despite this, there is a symmetry between the pumping and recovery phases, supporting the applicability of superposition and a stable static water level. The theoretical 100-day straight-line extrapolation of drawdown using the 100-day method aligns with the theoretical plot of the extended drawdown.

Takeaway Comment: Like the nearby Saanich South Well, the Saanich North Well pumping also exhibited entirely radial flow with the recovery derivative aligning with the pumping derivative. The extended drawdown plotted as expected despite an initial temporary shift upon the end of pumping.

4.5 Mill Bay A (WTN 88224)

Aquifer Geology: The well draws from aquifer 203 (https://apps.nrs.gov.bc.ca/gwells/aquifers/203), which comprises fractured granitic bedrock of the West Coast Crystalline Complex, basaltic rocks of the Bonanza Group, sedimentary rocks of the Sicker Group, and igneous rocks of the Island Plutonic Suite. Veneers of gravel, sand, and clay partially confine the aquifer. The static water level at the start of pumping was recorded to be 80.88 m below the top of the casing.

Pumping Well Summary: The well (WTN 88224, https://apps.nrs.gov.bc.ca/gwells/well/88224) was drilled to a depth of 183.5 m in 2007, however, it was backfilled to 135.5 m in 2008 to minimize the chance of bacteria growth in stagnant water below the fracture at 131 m. The fracture's yield was reported to be 100 USgpm (545 m^3/day) by the driller following this alteration.

Pumping Test Summary: On October 10, 2017, the well was pumped at a constant rate of 518.4 m^3/day and drawdown was monitored for 72 hours. Upon pump shutoff, the residual drawdown was monitored for an additional 66 hours (t/t' = 2.1), recovering well over 100% (see Table 1).

Results: The pumping test exhibits a transition from linear flow to radial flow at around t = 2050 min (Figure 18). The transition is smooth and continuous. Radial flow is present until the end of the test at t = 4320 min. The extended drawdown plot (Figure 19) exhibits an immediate upward trend that reflects a rising and not constant pre-pumping water level; the recovery rate is also faster than the pumping rate. Transmissivity values calculated using the Theis curve-matching, Cooper-Jacob straight-line, and Theis recovery methods, utilizing only drawdown data that correspond to the radial regime are 4.1 m^2/day, 4.5 m^2/day, and 1.9 m^2/day respectively. Q_{100} long-term sustainable yield was calculated to be 335 m^3/day using a 30% safety factor.

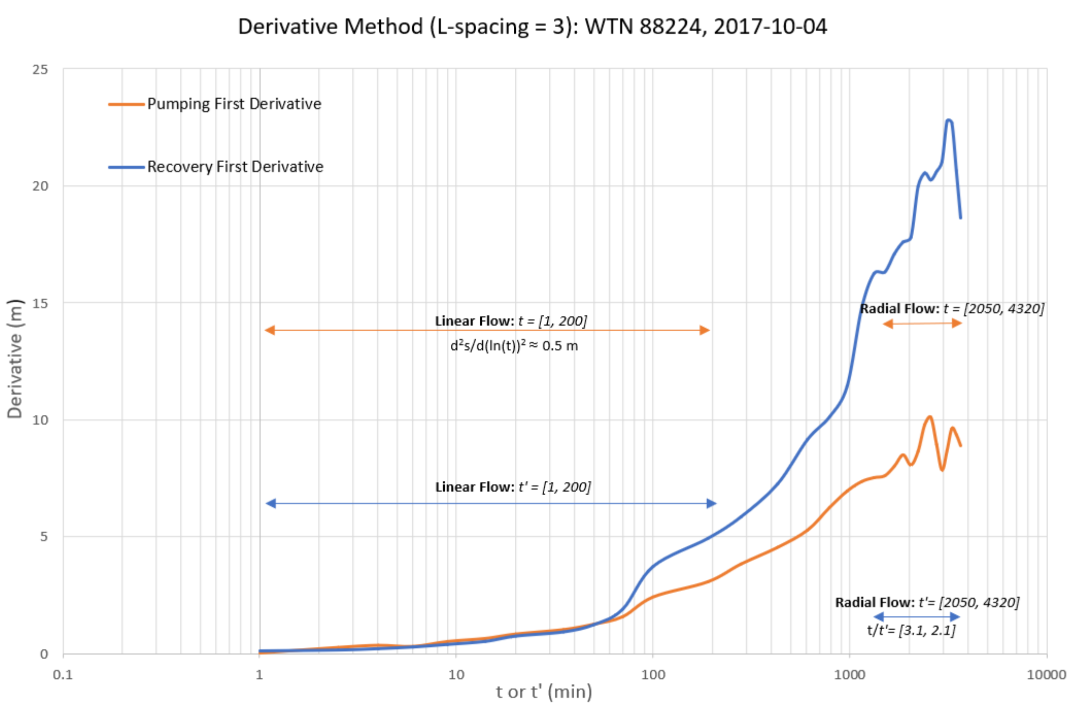

Figure 18: The derivative method (L-spacing = 3) applied to Mill Bay A WTN 88224, 2017-10-04.

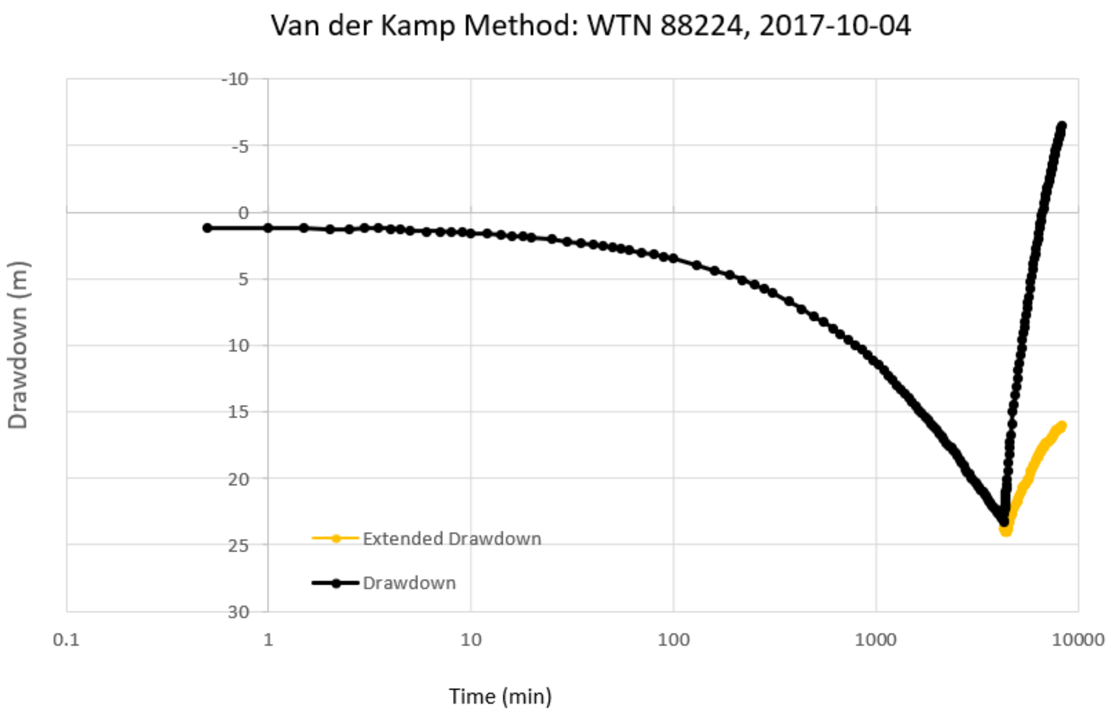

Figure 19: The van der Kamp method applied to Mill Bay A WTN 88224, 2017-10-04.

<u>Interpretations:</u> The gradual transition from linear flow to radial flow implies a progressive change in flow behavior, whereby flow becomes radial as the drawdown zone of influence expands (Beauheim, 2004). The duration of radial flow is brief and is not easily identifiable in the recovery derivative. This may be because it occurred so late in the pumping test.

The extended drawdown plot behaves similarly to the Errington test, where drawdown decreases following pump shutoff. As there is a rising static water level, a similar sawtooth pattern would be present if recovery was monitored for t/t' < 2; if the recovery phase was longer than the pumping phase. The residual drawdown being greater than 100% upon the end of recovery is a good indication that the decreasing extended drawdown is due to a rising static water level. The rising static water level is not likely due to aquifer recharge as historical weather data from Francis Park, Victoria reports no significant precipitation prior to the test (Environment and Climate Change Canada, n.d.). Within one pumping duration (t/t' < 2) into the recovery the upward-trending extended drawdown is still smooth, suggesting that the extended drawdown may only be offset by the drift in the static water level. No other external influences detract from the ability to extend the drawdown.

Takeaway Comment: There is likely a rising static water level; interpreted from a decreasing extended drawdown. The derivative during recovery is also quite different than the derivative during pumping. Transmissivity value calculations could be an underestimate and a Q_{100} calculation could be an overestimate.

4.6 Mill Bay B (WTN 117952)

Aquifer Geology: The well draws from aquifer 208 (https://apps.nrs.gov.bc.ca/gwells/aquifers/208), which comprises fractured granitic bedrock of the West Coast Crystalline Complex, basaltic rocks of the Bonanza Group, sedimentary rocks of the Sicker Group, and igneous rocks of the Island Plutonic Suite. The bedrock is near the surface, with less than 1 m of blanket till and clay confining the aquifer. The static water level at the start of pumping was recorded to be 30.91 m below the top of the casing.

Pumping Well Summary: The well (WTN 117952, https://apps.nrs.gov.bc.ca/gwells/well/117952) was drilled to a depth of 91.4 m in August 2019. No well construction report was made. A neighboring well was subsequently developed, and a large fracture was observed at 76.8 m. The fracture's yield was reported to be 50 USgpm (273 m^3/day) by the driller following this alteration.

Pumping Test Summary: On August 14, 2019, the well was pumped at a constant rate of 362.9 m^3/day and drawdown was monitored for 24 hours. Upon pump shutoff, the residual drawdown was monitored for an additional 27.5 hours (t/t' = 1.87), recovering 72%.

Results: There is a significant change in the derivative as it transitions from linear flow to radial flow, which begins at t = 690 min (Figure 2). Radial flow is not easily identifiable in the recovery regime, yet recovery was still assumed to be symmetric with the radial regime during pumping, present for t' = [690, 1440]. The extended drawdown initially (Figure 21) plots continuously, as expected, upon the end of pumping, but at t = 2160 min, the extended drawdown becomes slightly steeper. Transmissivity values calculated using the Theis curve-matching, Cooper-Jacob straight-line, and Theis recovery methods, utilizing only drawdown data that correspond to the radial regime are 4.7 m^2/day, 4.9 m^2/day, and 8.8 m^2/day respectively. Q_{100} long-term sustainable yield was calculated to be 280 m^3/day using a 30% safety factor.

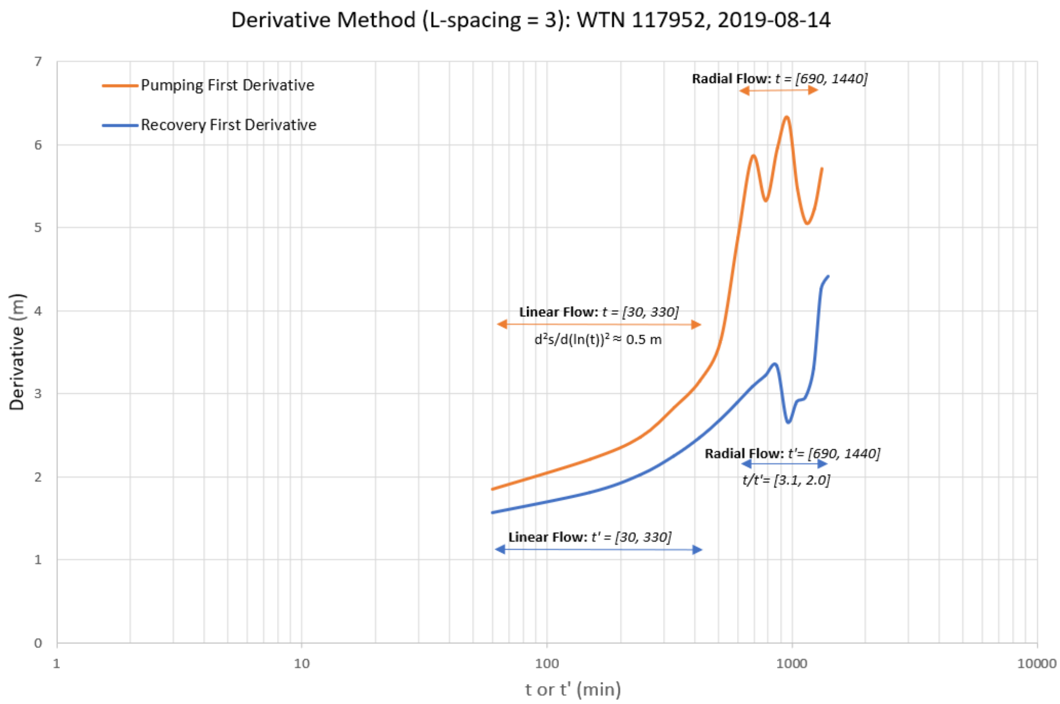

Figure 20: The derivative method (L-spacing = 3) applied to Mill Bay B WTN 117952, 2019-08-14.

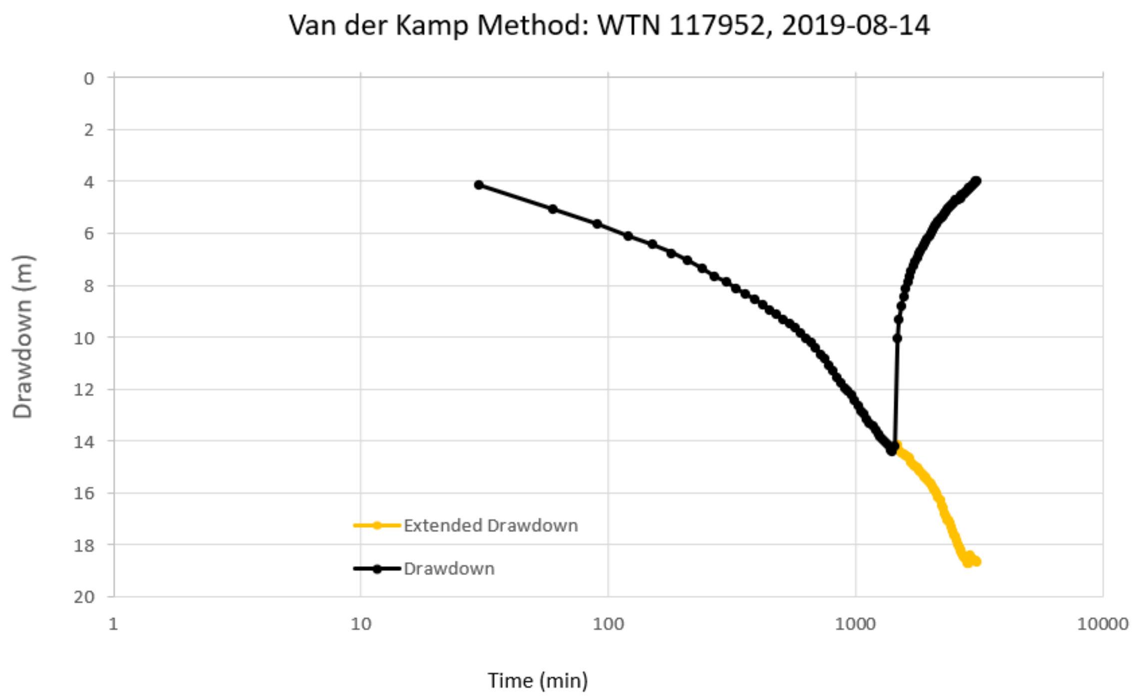

Figure 21: The van der Kamp method applied to Mill Bay B WTN 117952, 2019-08-14.

<u>Interpretations:</u> Dewatering or a falling static water level would explain the steepening of the extended drawdown at t = 2160 min. It is unclear if there were additional wells in use or being developed nearby that are to blame. The impact on drawdown rate is minimal, yet this steepening would explain why transmissivity calculated from the recovery phase is different than that calculated from the pumping phase.

This potential dewatering or falling static water level response is the opposite of the rising water levels observed at Errington and Mill Bay A. The lowering of the ambient static water level removes water from the system during recovery, masking the aquifer's true transmissivity. The dewatering was only present for the latter phase of recovery, so the extended drawdown can still be used to infer longer-term trends. If this dewatering is an environmental response, the extended drawdown may even be less than that extrapolated by the straight-line estimation of the 100-day drawdown, resulting in a higher transmissivity and Q_{100}.

Takeaway Comment: Superposition applies despite dewatering/falling static water level during recovery. Regardless, the extended drawdown plots as expected, pumping and recovery derivatives align, and transmissivity and Q_{100} can be estimated.

5. Discussion

In this study, the general responses of fractured bedrock pumping tests were analyzed using the derivative method to identify key flow regimes. Characterizing a common pumping response in fractured bedrock adds to the understanding of regional hydrodynamics. The reliability of using these flow regimes to estimate transmissivity depends, in part, on the duration of each regime. Comparing the transmissivity values obtained from these tests with those expected from past regional data can further validate the results, particularly when the aquifer behaves in a mostly ideal manner. The van der Kamp method only works when superposition applies and there is a stable static water level for the duration of the pumping test. The impact of suspected rising static water level on the quantification of transmissivity and Q_{100} will also be discussed.

5.1 Flow Regime Insights from the Derivative Method

The general response for the fractured bedrock pumping tests can be characterized by the derivative method. A radial regime was present for all six tests, but four tests exhibited a precursory linear flow regime. The presence of early linear flow may indicate the wellbore's high proximity to a major fracture and could simply be a consequence of the well's location. Linear flow will transition to radial flow once the drawdown cone has grown enough for radial flow to establish. Derivative analysis showed no early-time borehole storage effects (i.e., lack of early-time drawdown plateaus). Due to the high diffusivity of the fractured bedrock aquifers, wellbore storage effects, if present, would be short-lived and may not be detectable in the available drawdown data. Wellbore storage is more noticeable when the well volume is large compared to aquifer flow capacity (e.g., low-permeability formations). Hence, for the pumping tests reviewed here, the fractured bedrock aquifers on Vancouver Island and the Gulf Islands appear to have well-connected fractures with high permeabilities.

The intervals of linear flow and subsequent radial flow observed in these six pumping tests are summarized in Table 2. The radial flow eventually presents, however, depending on the aquifer (i.e., fracture network geometry), the linear flow may not precede radial flow (e.g., Saanich North Well, Saanich South Well). Figure 22 is a schematic depicting the typical flow regimes encountered for fractured bedrock pumping tests on Vancouver Island and the geologically similar Gulf Islands. The time at which linear flow transitions to radial flow is inconsistent but is at least a couple hundred minutes. The variability in transition timing is unpredictable and is influenced by fracture network geometry, pumping rate, and the depth of well penetration relative to dominant fracture zones.

Table 2: Summary of flow regimes during pumping phase.

Well Name	Period of linear flow, [t_1, t_2] (min)	Period of radial flow, [t_1, t_2] (min)	Radial flow number of log-cycles of time, log(t_1/t_2)
Errington	[1,100]	[301, 697]	0.36
Galiano	[1, 12]	[12, 60]	0.70
Saanich South Well	Not observed	[1, 4319]	3.64
Saanich North Well	Not observed	[1, 4311]	3.63
Mill Bay A	[1, 200]	[2050, 4320]	0.32
Mill Bay B	[30, 330]	[690, 1440]	0.32

Beauheim et al. (2004) recommended at least 1 log-cycle of time for a stable derivative to yield accurate estimates of transmissivity. If the derivative is constant for less than one log-cycle of time, Beauheim et al. (2004) hypothesized that transmissivity estimates may be more sensitive to noise in the derivative and could result in an over- or underestimation of the true aquifer properties. Ensuring the derivative is stable for one log-cycle of time is not often feasible in practice. If there is a long precursory linear phase before radial flow, it is unlikely that Beauheim et al.'s condition can be met within the duration of the pumping test. In this study, it was common for radial flow to be observed at the end of the pumping phase, thus a longer pumping test may reach 1 log-cycle of time of radial flow. If these time-constrained tests still provide a reasonable first-order approximation, reaching 1 log-cycle of time of radial flow may not be critical.

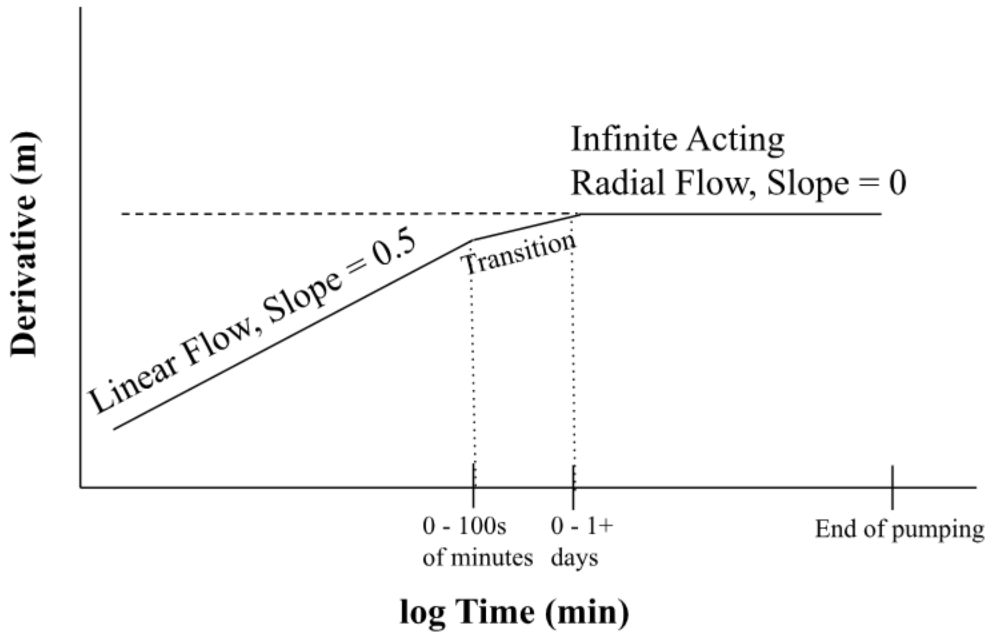

Figure 22: Schematic of typical pumping test response from fractured bedrock aquifers in this study.

5.2 Comparison of Transmissivity Estimates with Regional Aquifer Data

It is good practice to compare transmissivity values estimated in this study with those determined from past regional aquifer data. Carmichael (2014) used the derivative method to identify infinite-acting radial flow and conducted a statistical analysis to assemble median transmissivity values for the various aquifers in the Cowichan Bay region. Her work found that fractured sedimentary bedrock aquifers (Nanaimo Group) had a median transmissivity of 0.2 m^2/day based on five pumping tests. Meanwhile, crystalline bedrock aquifers in the region had a median transmissivity of 3 m^2/day based on eighteen pumping tests. These values are compared with the results from this study in Table 3. This comparison is not a rigorous confirmation of the accuracy of each calculation of transmissivity, but it provides insight into how the transmissivity values obtained here align with expectations based on past studies.

Table 3: Comparison of calculated transmissivity values to those by Carmichael, (2014).

Test Name	Aquifer No.	Aquifer Type	Median Transmissivity, Carmichael (2014) (m^2/day)	Theis Curve-Matching Transmissivity (m^2/day)	Cooper-Jacob Transmissivity (m^2/day)	Theis Recovery Transmissivity (m^2/day)
Errington	220	Sedimentary Bedrock	0.2	0.053	0.053	0.083
Galiano	320	Sedimentary Bedrock	0.2	0.31	0.35	0.40
Saanich South Well	614	Crystalline Bedrock	3	1.5	1.8	1.6
Saanich North Well	614	Crystalline Bedrock	3	2.2	2.7	2.7
Mill Bay A	203	Crystalline Bedrock	3	4.1	4.5	1.9
Mill Bay B	208	Crystalline Bedrock	3	4.7	4.9	8.8

The transmissivity values calculated in this study are similar to those reported by Carmichael (2014), within an order of magnitude of the medians for the two types of aquifers. Transmissivity tends to be approximately an order of magnitude higher in the crystalline bedrock (Aquifers 614, 203, 208) versus the sedimentary bedrock of the Nanaimo Group (Aquifers 320, 220). If more pumping tests were studied, a linear regression could statistically characterize the agreement of the transmissivities. Reaching 1 log-cycle of time with radial flow does not appear to be necessary for reliable first-order estimates of transmissivity. For these aquifers, anything greater than 0.3 log cycles of time is enough to reliably quantify transmissivity as that is the shortest duration of radial flow observed.

5.3 Evaluating the Pumping Phase and Recovery Phase Calculations of Transmissivity

The consistency of transmissivity values obtained in this study with past regional data is not a confirmation of their accuracy for the specific aquifer and pumping test conditions. The deviation of transmissivity under static water level conditions needs to be evaluated. Transmissivity values are log-normally distributed and precise calculations may not be critical for first order approximations. Transmissivity magnitudes are considered comparatively dissimilar (of different water-bearing classes) if separated by more than one order of magnitude (Krasny, 1993). To be conservative, for this study, two transmissivity values were only considered alike if separated by less than a half-order of magnitude.

If a changing static water level significantly impacts drawdown and recovery, the transmissivity values calculated from the pumping and recovery phases will be affected (Figure 23a, 23b). The utility of the recovery derivative is to compare phases that are expected to be symmetrical and then determine if they diverge. However, this may be challenging if there is significant noise in the derivative that cannot be sufficiently smoothed.

Across all tests, transmissivity varies slightly between the pumping and recovery phases. If transmissivity is strongly influenced by a changing static water level, the discrepancy between transmissivity values from the pumping and recovery phases should be more pronounced as the magnitudes of the pumping and recovery derivatives diverge. Conversely, for those tests that performed most ideally and were not subjected to rising/falling static water levels, the derivatives of the pumping and recovery phases strongly aligned (e.g., Saanich North Well, Saanich South Well). Table 4 summarizes the magnitude of the difference between transmissivity estimates from the Cooper-Jacob method and Theis recovery method.

Table 4: Comparison of transmissivity calculated from the pumping phase (Cooper-Jacob) and recovery phase (Theis Recovery).

Test Name	Cooper-Jacob Transmissivity, T_{C-J} (m^2/day)	Theis Recovery Transmissivity, T_{rec} (m^2/day)	Transmissivity Orders of Magnitude Difference, $\log(T_{rec}/T_{C-J})$
Errington	*0.053*	*0.083*	*0.19*
Galiano	0.35	0.40	0.058
Saanich South Well	1.8	1.6	-0.051
Saanich North Well	2.7	2.7	0
Mill Bay A	*4.5*	*1.9*	*-0.37*
Mill Bay B	*4.9*	*8.8*	*0.25*

*Italics indicate tests that were interpreted to exhibit a rising/falling static water level.

The two tests that were interpreted to have exhibited a rising static water level are shown in italics. In these cases, the difference in log transmissivity between the pumping and recovery phases is not significantly greater than in other tests, remaining within half an order of magnitude. Even with a more pronounced static water level rise, transmissivity could still be meaningfully estimated from both phases of these pumping tests. If trying to establish a true transmissivity, picking the lower value would be ideal for conservative estimates. If it is necessary to estimate a representative transmissivity, taking an average of the two may be preferred.

For fractured bedrock pumping tests, site-specific characterization of any static water level change is crucial to avoid inaccurate assumptions about pumping responses under non-ideal conditions. To ensure optimal transmissivity estimation, the derivative method should be applied whenever possible as a standard analysis technique.

5.4 Evaluating the Reliability of Q_{100} and Transmissivity

Table 5 summarizes the results of the extended drawdown analysis. The extended drawdown method did not work for all six pumping tests. For two tests (Errington and Mill Bay A), the extended drawdown exhibited a strong upward trend immediately after pump shutoff. For both cases, the water level recovery exceeded 100% after testing and the initially reported “static” water level was rising. The van der Kamp method cannot be used in these cases to extrapolate drawdown to one hundred days to calculate Q_{100} without adjusting for the change in drawdown due to a rising static water level.

Table 5: Interpretation of extended drawdown plot.

Test Name	Rising Static water level?	Extended drawdown applicable?
Errington	yes	no
Galiano	no, (tidal interference)	no
Saanich South Well	no	yes
Saanich North Well	no	yes
Mill Bay A	yes	no
Mill Bay B	no, (dewatering during late recovery)	yes

Q_{100} is intended as the maximum permissible pumping rate for a 100-day period where no recharge occurs (B.C. Ministry of Environment, 1999). For each test in this study, Q_{100} was calculated by straight-line extrapolation. It was assumed that the drawdown rate observed at the end of pumping is consistent with the ideal long-term infinite-acting radial flow response of the aquifer. In the case of the two tests that exhibited a rising static water level, it is important to assess if a straight-line extrapolation for calculating Q_{100} is still reasonable so that the licensed pumping rate is still sustainable. If the rise in static water level is negligible compared to the total drawdown, the estimated Q_{100} may still serve as a reasonable upper bound.

When there is a rising static water level, the observed drawdown is underestimated (Fig 23a). This is due to a change in the background hydraulic head, changing the reference static water level. If the rise in static water level during pumping can be accounted for, the actual drawdown curve will be steeper, leading to a lower Q_{100}. Calculating Q_{100} without accounting for a rising static water level gives an overestimate of Q_{100}.

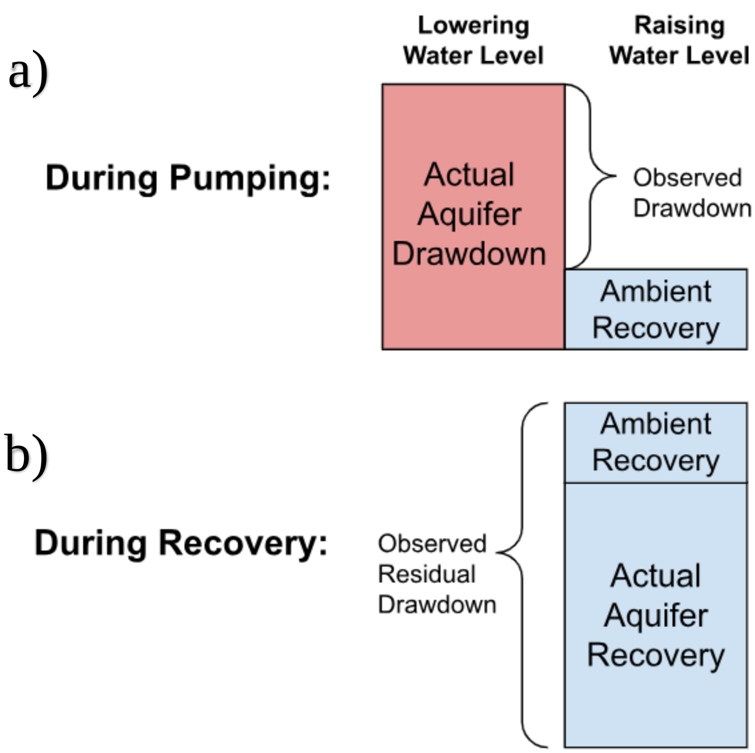

Figure 23: Visualization of the effect of recharge causing a rising static water level: a observed drawdown is less than actual drawdown during pumping; b observed residual drawdown is greater than actual residual drawdown during recovery.

Equation 10 is a formula that can be used to adjust the drawdown data $s_{adj}(t)$ to correct for a set rate of static water level rise ΔSW at each time step t using the drawdown data obtained from the pumping test $s(t)$. Q_{100} can be recalculated using the adjusted drawdown curve and compared to the previous estimate to assess the impact of recovery on long-term sustainable yield across different pumping tests. It is important to note that this technique does not determine the actual Q_{100} but is simply an improvement of the 100-day drawdown. Adjusting the shape of the drawdown curve is merely a pragmatic approach to estimating errors in Q_{100} resulting from a rising static water level being a component of the drawdown rate.

$$s_{adj}(t) = s(t) + \Delta SW \times t \qquad \text{(Eq. 10)}$$

To illustrate how a rising static water level changes the drawdown curve, ΔSW was arbitrarily chosen to be 0.1 m/hour, similar to what may have been occurring during the Errington test. Over the duration of a pumping test, the rate of static water level “rise” will also change. Ideally, the change in the ΔSW rate would also be incorporated into Equation 10. The adjusted drawdown was overlain by the measured drawdown for the Errington test in Figure 24 and the Mill Bay A test in Figure 25.

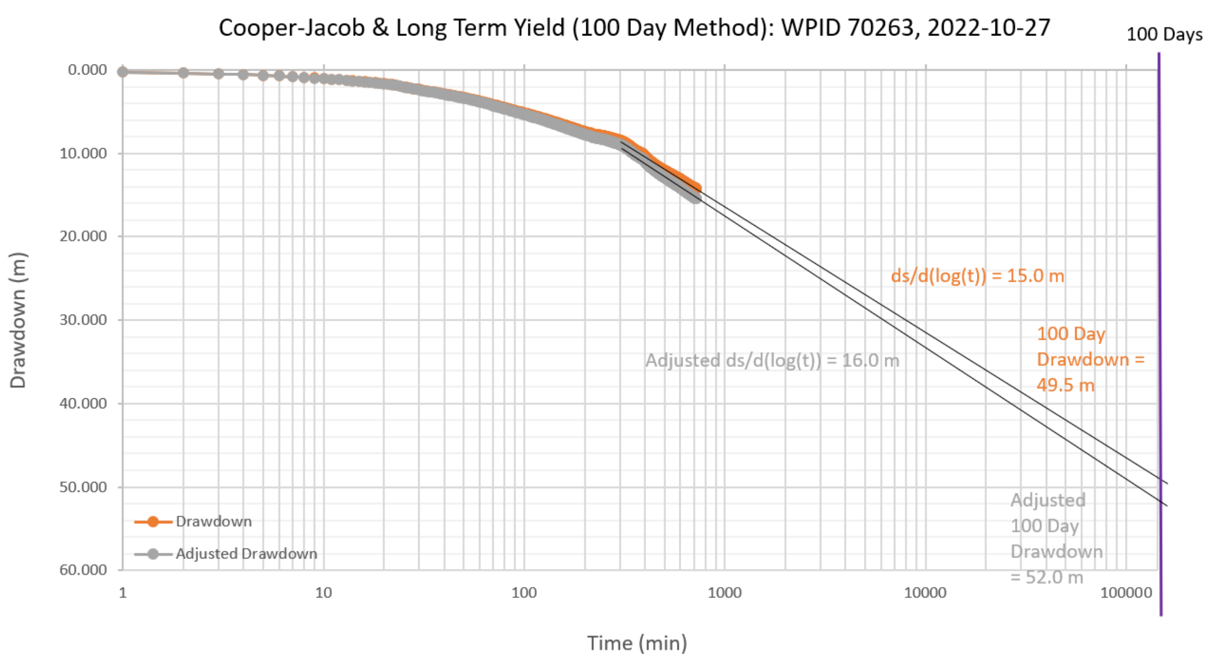

Figure 24: Adjusted 100-day drawdown, Errington WPID 70263, 2022-10-27.

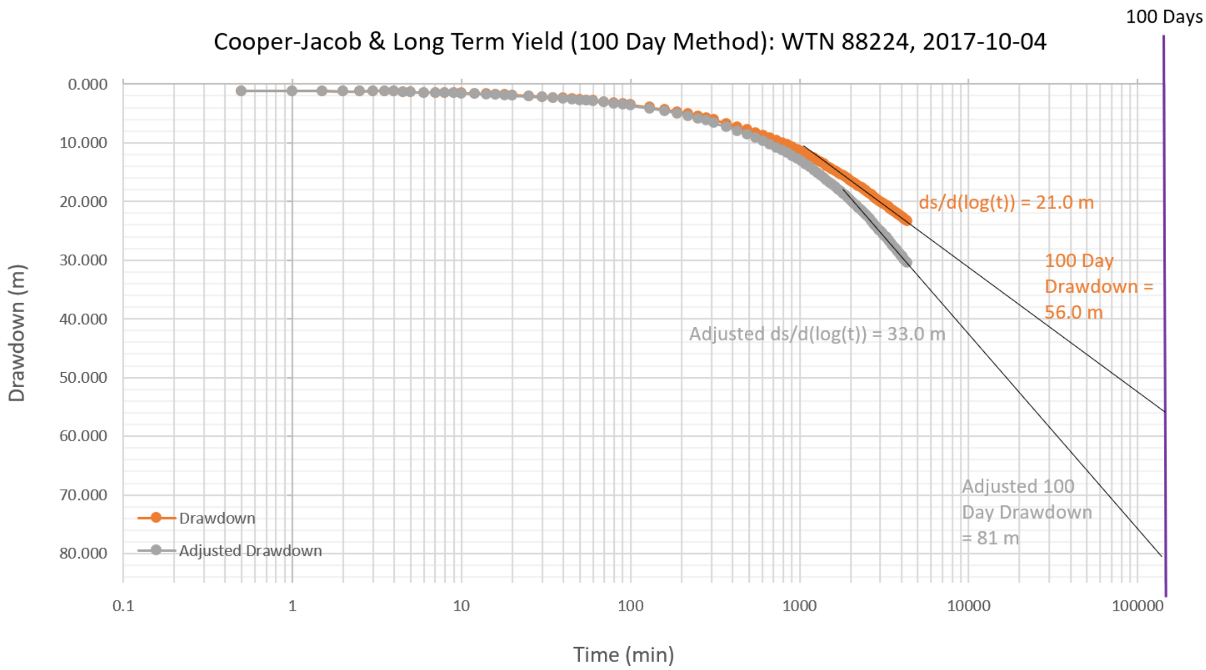

Figure 25: Adjusted 100-day drawdown, Mill Bay A WTN 88224, 2017-10-04.

Using the adjusted 100-day drawdown extrapolation, $s_{100\text{-}day}$, an adjusted Q_{100} was calculated using Equation 1. The values used to calculate the adjusted Q_{100} are provided in Table 6. The percent difference (Equation 11) between the previously calculated Q_{100} and the adjusted Q_{100} indicates how significantly Q_{100} can be off if there is a rising static water level.

$$Percent\ Difference = 100 \times \frac{|Q_{100} - Q_{100,adj}|}{\frac{Q_{100} + Q_{100,adj}}{2}} \qquad \text{(Eq. 11)}$$

Table 6: Comparing adjusted Q_{100} to calculated Q_{100} for pumping tests that exhibited a rising static water level.

Test Name	ΔSW (m/hour)	Slope per Log Cycle of Time (m)	Adjusted Slope per Log Cycle of Time (m)	$s_{100day\ proj}$ (m)	Adjusted $s_{100\text{-}day}$ (m)	Q_{100} (m^3/day)	Adjusted Q_{100} (m^3/day)	Percent Difference
Errington	0.1	15.0	16.0	49.5	55.0	3.2	3.0	6.5
Mill Bay A	0.1	21.0	33.0	56.0	81.0	335	232	36.3

The adjusted Q_{100} turns out to be 36.3% lower in Mill Bay A and 6.5% lower in Errington. Extrapolating the drawdown data is highly dependent on the drawdown rate. For lower yield wells, where the pumping-induced drawdown rate is fast, a rising static water level has less of an influence on the overall pumping response. For higher yield wells, when the pumping-induced drawdown is more gradual, a similar rate of static water level rise will have a larger impact on the drawdown rate and thus on the calculated Q_{100}.

The Errington well is quite low in its potential yield, so the Q_{100} between adjusted and unadjusted drawdown is acceptable (6%). Mill Bay A, being a much higher potential yield, is more susceptible to greater overestimates of Q_{100} and the previously projected Q_{100} is 36% higher. Keep in mind that the static water level rise of 0.1 m/hour was arbitrarily selected for illustrative purposes.

The opposite may also be true during the summer periods after winter recharge. Dewatering, potentially due to seasonal water use, will result in an underestimation of Q_{100}. For fractured bedrock aquifers, which are highly susceptible to static water level shifts, it is advisable to be skeptical of the accuracy of an empirical 100-day drawdown extrapolation, especially for high-yield wells, if the change in static water level has not been well characterized.

For most of the pumping tests, the straight-line extrapolation is fit to the same infinite-acting radial flow regime that is used to calculate transmissivity. It is also worthwhile considering how transmissivity would be affected in this 0.1 m/hour rising static water level scenario. As transmissivity is log-normally distributed, Table 7 shows that it is smaller yield wells that can have a larger discrepancy in the observed transmissivity if there is a rising static water level. Despite this drift, the adjusted transmissivity is still close to 0.5 orders of magnitude from the observed transmissivity and is still reasonable to use.

Table 7: Comparing adjusted T to calculated T for pumping tests that exhibited a rising static water level.

Test Name	Slope per Log Cycle of Time (m)	Adjusted Slope per Log Cycle of Time (m)	Cooper-Jacob Transmissivity (m^2/day)	Adjusted Cooper-Jacob Transmissivity (m^2/day)	Transmissivity Orders of Magnitude Difference, $\log(T_{adj}/T_{C-J})$
Errington	15.0	16.0	0.052	0.19	0.56
Mill Bay A	21.0	33.0	4.5	11	0.39

5.5 Study Limitations

The strength of the results of this study is limited by the number of tests used. It was challenging to source tests that met the desired criteria. Using more than six tests to assess the implications of the derivative method and the van der Kamp method to fractured bedrock aquifers would have been beneficial.

The interpretations of these pumping tests are not comprehensive and depend on other environmental factors that were not considered. Conducting a thorough aquifer interpretation requires an approach in which the derivative and extended drawdown response are analyzed while considering each unique geological environment (Ferroud et al., 2019). Detailed information about each test used in this study was limited, with some tests only containing the raw test data, without any well record (as was the case for the Errington test), or detailed geologic reports of the test sites. Monitoring the static water level prior to pumping is essential, however, this data was not available for any of the tests studied.

6. Conclusions and Recommendations

The implementation of the derivative method and the van der Kamp method has the potential to benefit all pumping tests. Plotting the derivative can easily serve as a cursory check for straight-line fitting or curve matching when calculating transmissivity using traditional infinite-active radial flow models (e.g., Theis, 1935; Cooper-Jacob. 1946). When the principle of superposition is valid and the static water level is constant (or can be adjusted for rise/fall), plotting the extended drawdown can help project long-term drawdown, reducing the uncertainty of the empirical projection of drawdown to 100 days to calculate Q_{100}. It is critical to accurately calculate transmissivity and Q_{100} to ensure sustainable licencing of groundwater use. Routine use of the derivative and van der Kamp methods can help minimize uncertainty in the inherent assumptions when fitting models to pumping test data. By narrowing in on certain assumptions and minimizing the subjective nature of pumping test interpretation, these methods can decrease interpretation variability and improve comparability across regions.

This study has identified the following key insights from applying the derivative method and van der Kamp method to pumping tests in fractured bedrock aquifers on Vancouver Island and Galiano Island, BC:

1) The derivative method effectively identifies various flow regimes and confirms the absence of others.
2) No pumping tests exhibited wellbore storage. Some initially exhibited linear flow for several hundred minutes, but all eventually demonstrated infinite-acting radial flow for at least 0.3 log-cycles of time, limited by the end of pumping.
3) A rising static water level is common if the recovery rime between air lifting during well development, step-test and the final constant rate pumping test is insufficient.
4) A rising static water level negatively impacted the use of the van der Kamp method for extending drawdown and could not facilitate improved Q_{100} calculations because the rate of rise could not be accounted for.
5) A rising static water level increases uncertainty in Q_{100} estimates obtained by straight-line extrapolation, particularly for high-yield wells.
6) While a rising static water level introduces uncertainty in transmissivity estimates, it does not significantly impact results derived from standard methods and remains consistent with past regional aquifer data.

Standardizing the use of the derivative and van der Kamp methods for fractured bedrock aquifers appears to be highly beneficial. These methods complement the current interpretive approach to pumping tests and do not require transformative techniques. The following recommendations should be incorporated into provincial guidance as best practices for pumping tests:

Recommendation 1: Do not assume that the water level at the start of pumping reflects the "static" water level. The water level in the well should be monitored before conducting a pumping test to confirm it is steady or allow changes in the static water level to be accounted for. If the water level is found to be rising, one option is to wait until it stabilizes before proceeding with testing. Alternatively, measuring the rate of water level rise (and the change in the rate of water level rise) before pumping starts can be used to adjust for the drift in static water level and drawdown that occurs throughout the test. Ensuring that the effects of rising static water are accounted for corrects for error in the measured drawdown rate and improves the likelihood that the van der Kamp method can be applied to obtain an estimate of Q_{100}. Otherwise, there is a higher uncertainty in the empirical extrapolation of drawdown to 100 days for calculating Q_{100}, which as demonstrated, can be highly unreliable. If the effects of a rising static water level were not accounted for prior to conducting the pumping test, the estimated Q_{100} should be lowered based on the judgment of a licensed professional.

Recommendation 2: To confidently identify radial flow, a pumping test should be conducted until the derivative is stable for at least 0.3 log-cycles of time, if feasible. Conducting a pumping test for a longer duration will be more optimal for added assurance. A longer pumping test also enables verification of the latter flow regime and confirms that it is not a transitory phase, enhancing confidence that transmissivity value calculations are accurate, though it is costlier.

Recommendation 3: The current recommendation of monitoring until 90% recovery should be revised. If feasible, it is ideal to conduct residual drawdown monitoring for at least as long as the pumping phase. The utility of the extended drawdown and the recovery derivative depend on the recovery phase being long enough to compare the pumping and recovery responses. Stopping recovery measurements at “90% recovery” potentially results in valuable information being missed that is only enabled by the van der Kamp method or recovery derivative.

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APPENDIX

Spreadsheets

Errington, WPID 70263, 2022-10-27.xl

Galiano, WTN 91453, 2020-10-16.xlsx

Saanich South Well, WTN 54024, 2022-08

Saanich North Well, WTN 53884, 2022-08

Mill Bay A, WTN 88224, 2017-10-04.xl

Mill Bay B, WTN 117952, 2019-08-14.:

Glossary

Aquifer: A geological deposit that is permeable and saturated that allows a sufficient supply of water to flow to wells and to springs.

Aquifer storage: Water stored within the voids, pore spaces or fractures within the aquifer.

Confining layer: A geological deposit that is made up of mainly low permeability sediments like till, silt or clay. Also referred to as an aquitard.

Available drawdown: The height of the water column in a well that allows water to be drawn down when the well is pumped. The greater the available drawdown in a well, the greater rate the well can be pumped.

Wellbore storage: The effect that the volume of water stored in a pumping well has on the drawdown in the well; wellbore storage effects drawdown in the pumped well in the early part of a pumping test.

Confining sediments: Sediments composed of typically low permeability sediments like till, silt or clay.

Derivative of drawdown: Refers to the rate of the drawdown over time.

Dewatering: In relation to an aquifer, the draining of water out of the voids, pore spaces or fractures as the groundwater level is lowered.

Diffusivity: The ratio of transmissivity to storativity (confined aquifer) or specific yield (unconfined aquifer) and is a measure of how quickly changes in hydraulic pressure or stress is propagated through the aquifer.

Double porosity: Fluid flow in fractured or porous media, where two distinct porosity systems coexist: primary porosity (matrix porosity) and secondary porosity (fracture or conduit porosity). In this model, the matrix stores most of the fluid, while fractures or conduits provide preferential pathways for rapid flow.

Drawdown: The difference between the pumping water level and the static water level or pre-pumping water level at a given location (e.g., in a well or in an aquifer).

True Drawdown: The portion of observed drawdown that is directly caused by pumping and well losses, after filtering out influences such as recharge, regional water table fluctuations, or atmospheric effects. It provides a more accurate measure of the aquifer's response to pumping.

Fluvial sediments: Unconsolidated sediments (mostly sandy, gravelly sediments) deposited by stream(moving) water.

Glacio-marine sediments: Unconsolidated sediments deposited in the ocean during glacial times.

Homogeneous, homogeneity: In relation to hydrogeology, where geological characteristics (e.g., permeability, storativity, thickness) do not change spatially.

Hydraulic connection: The existence of flow between distinct sources of water such as between an aquifer and a stream or ocean.

Hydraulic head: A measure of energy of groundwater per unit weight of water, expressed in meter or feet above a reference datum (usually sea level).

Lateral intrusion (of saltwater): When well pumping (of fresh groundwater) occurs within a coastal aquifer, the equilibrium that exists between a body of fresh groundwater and salt water is disturbed such that the freshwater-saltwater interface moves inland, towards the pumping well.

Leaky aquifer: Confined aquifer that receives or loses water through semi-permeable layers (aquitards) that bound it. Unlike purely confined or unconfined systems, leaky aquifers experience vertical flow between adjacent layers due to differences in hydraulic head.

Log-log: An X-Y graph where both axes have a logarithmic scale.

Mapped aquifer: Aquifer that has been mapped, digitized and entered in the Province's GWELLS database and assigned an aquifer identification number.

Well Tag Number: A unique file number assigned to the well record in the Province's GWELLS database.

Permeability: Ability for a porous material to allow water to flow through it.

Pumping phase: The part of the pumping test when pumping is occurring.

Pumping test: a flow test of a well in which the well is pumped and the quantity of water pumped, pumping water levels and recovery water levels are measured
(a) to provide an estimate of the capacity of the well to produce groundwater, and
(b) to assess aquifer characteristics (legal definition from the Groundwater Protection Regulation).

Quaternary: The current geological time period dating from 2.6 million years ago to the present.

Recharge: Process where water (from rain, snow, surface water) percolates to the aquifer.

Recovery phase: The part of the pumping test after pumping has stopped and measurements of the recovering water level are occurring.

Registered well: A well whose record is entered into the Province's GWELLS database.
Residual drawdown: The difference between the water level recovering after pumping has stopped and the static water level or pre-pumping water level at a given location (e.g., in a well

Representative Elementary Volume: Smallest volume over which a parameter (e.g. T, S) measurement can be made that will yield a value representative of the whole.

Saltwater intrusion: The incursion of saltwater into freshwater aquifers located in coastal areas. While seawater intrusion occurs seasonally as a natural process, well pumping, sea level rise from climate change and from storm surges can cause significant incursion of saltwater into freshwater aquifers to occur.

Semi-log: An X-Y graph where one axis has a linear scale and the other has a logarithmic scale.

Static water level (SWL): Distance (in meters or feet) from the top of the production casing or the surface of the ground to the groundwater level in the well, when the groundwater level is not affected by pumping activities in the well (legal definition from the *Water Sustainability Act*).

Storativity (S): Volume of water stored or released from a column of aquifer with unit cross section under unit change in groundwater level. Storativity determines how quickly (or slowly) an aquifer responds to hydraulic changes and is reported as a dimensionless number (e.g., 0.0001).

Superposition principle: Characteristic of linear systems in that responses can be summed together to produce an overall response. For example, if pumping Well A causes a drawdown of 1 m in Well C and pumping Well B causes a drawdown of 0.5 m in Well C, then pumping of Wells A and B together should cause a total drawdown of (1 m + 0.5 m) 1.5 m of drawdown in Well C.

Sustainable yield: The long-term balance between the amount of groundwater extraction and the groundwater level, baseflow and other in-situ functions of groundwater; is generally accepted to mean achievement of equilibrium over time.

Till: Primarily a mixture of clay, silt, sand, gravel and boulders ranging widely in size and shape deposited directly by and underneath a glacier.

Transmissivity (T): The rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. Transmissivity is commonly expressed as metres squared per second or day, feet squared per second or day, or gallons per day per foot. Transmissivity reflects the permeability of the aquifer integrated over the thickness of the aquifer.

Unconfined aquifer: An aquifer where the top of the aquifer is the water table.

Unconsolidated sediments: A geological material comprising loose sediments, e.g., sand and gravel. Synonymous with “Surficial sediments”.

Well inefficiency: The percentage of the drawdown in the pumping well attributable to drawdown from well loss compared to the total drawdown.

Well loss: The loss of energy or head of water as water flows from the aquifer through the well intake or screen into the well; well loss is a result of presence of a less permeable layer or “skin” or even turbulent flow at the boundary between the well intake and the aquifer and is indicated by an increased drawdown in the pumping well that occurs at the start of pumping and disappears when pumping stops.

Zone of Influence: An area that experiences drawdown due to well pumping; for pumping of a single well, this zone is typically assumed to be circular.