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Applying the Extended Drawdown Method to Interpret Pumping Tests in British Columbia

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Cover Photograph:
Photo of the 24-hour pumping test at the Hill-Mackenzie Fish Hatchery HM-1 well (WTN 53942) near Nakusp, B.C., conducted by Pacific, Pump and Pressure Ltd., August 1984.

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EXECUTIVE SUMMARY

Extrapolating drawdown from a constant rate pumping test to estimate well capacity and assess impacts from long-term pumping can be fraught with uncertainty because of: 1) the typically limited duration of pumping tests (1-3 days); and 2) any trend in drawdown observed near the end of the pumping phase of the test may be difficult to confirm, especially if that trend may not have been clearly established prior to the end of the pumping phase. The extended drawdown method developed by van der Kamp (1989) allows theoretical drawdown to be calculated using recovery data thereby effectively extending drawdown beyond the pumping phase of the test. The method was applied to data for 20 available pumping tests to evaluate and demonstrate the utility of this method in B.C.'s complex hydrogeological environments.

Calculating the extended drawdown for the 20 pumping tests shows that the method is generally applicable in B.C., so long as the fundamental principle of superposition and the conditions of the constant rate pumping test are satisfied. Examination of the selected pumping tests reveal that the extended drawdown can display a downward shift in those tests where dewatering is suspected to have occurred as a result of the pumping (e.g., a confined sand and gravel transitioning to water table or phreatic conditions, dewatering of water-bearing fractures), which negates the applicability of the principle of superposition. The extended drawdown can also display an upward shift in response to a significant rise in the "static" water level during the test. This can be a common situation where the groundwater level is still recovering from a prior step-test, from being recently taken out of operation for testing, or even from rapid seasonal groundwater level rise.

A short-lived "spike" at the very start of the extended drawdown was commonly observed, from tests of the pumped well. This "spike" appears to be associated with the limited accuracy of recording of drawdown and residual drawdown measurements at the start of the pumping and recovery phases when the rate of change of water level is greatest. The "spike" may also reflect drawdown affected by changes in the pumping rate at the beginning of the pumping phase as minor adjustments are being made to achieve a constant pumping rate.

As part of this study, a list of criteria for ideal pumping test datasets was developed. To facilitate application of the extended drawdown method, an Excel spreadsheet was also developed to input, plot and summarize the pumping test data (Appendix A).

The main lessons and recommendations from this study are:

1. A significant change in the static water level during a pumping test can affect the calculation of drawdown and extended drawdown. The professional hydrogeologist responsible for the pumping test should make every effort to allow the static water level to recover from previous step-testing or operational pumping prior to the start of the constant rate test. If that is not feasible, monitor the static water level prior to the pumping test to allow any changes in the static water level to be accounted for in the drawdown and extended drawdown calculations.
2. The pumping test contractor should record the pumping rate immediately prior to and after the rate has been adjusted and record the pumping rate during checks, even if no adjustments are made. This practice would help explain any sudden changes observed in the rate of drawdown and provide more confidence in interpreting the results.
3. Recovery measurements should be taken for as long as feasible because the data allow extended drawdown to be calculated well into the recovery phase to aid in interpretation of the pumping response. The guideline criteria (Todd et al., 2020; Province of B.C., 2018) to cease recovery measurements when 90% recovery is reached should be clarified to exclude well loss in the pumped well.

4. Calculating and plotting the extended drawdown is beneficial as an overall check on the validity of assumptions related to a constant rate pumping test. Professional hydrogeologists should consider calculating and plotting the extended drawdown as normal practice to continue proving the utility of the method to help with interpretation of constant rate pumping tests.
5. The Province of B.C. should consider uploading pumping test data to the corresponding well records in the GWELLS database so that the data can be securely stored and made readily accessible.

Note that the extended drawdown method is not intended to reduce the length of time pumping occurs during the test, but to provide additional insight from a test of the same length.

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

In 2016, the *Water Sustainability Act* (WSA) was brought into force requiring licensing of groundwater use. Before issuing a licence, a water manager must assess the impacts the withdrawal may have on existing water right holders and the environmental flow needs of nearby streams. To support this assessment, the licence applicant may be expected to submit a pumping test conducted and analyzed by a professional hydrogeologist (Todd et al., 2020). The main objective for a pumping test is to observe the groundwater level response to pumping to:

- assess the adequacy of long-term supply of the well,
- characterize well performance,
- determine aquifer hydraulic properties (e.g., transmissivity, storativity), and
- assess drawdown in the aquifer and in neighbouring wells from long-term pumping.

In order to assess the supply of the well and drawdown in the aquifer and in neighbouring wells from long-term pumping, the drawdown trend observed during the pumping test is extrapolated, typically over months to years. However, extrapolating pumping drawdown can be fraught with uncertainty because of: 1) the typically limited duration of pumping tests (1-3 days); and 2) any trend in drawdown observed near the end of the pumping phase of the test may be difficult to confirm, especially if that trend may not have been clearly established prior to the end of the pumping phase. This uncertainty in interpretation can affect the effectiveness and timeliness of licensing decisions.

Over the past several decades, the Province of B.C. has worked to improve how pumping tests are conducted and interpreted, for example:

- Requiring pumping tests in fractured bedrock aquifers to be conducted only during periods of seasonally low groundwater levels (Ministry of Environment, Lands and Parks, 1999);
- Applying the derivative method for analyzing pumping test data from bedrock wells (Allen, 1999);
- Publishing guidance on best practices for conducting pumping tests (Province of B.C., 2018);
- Requiring a professional hydrogeologist to design and perform or supervise a pumping test and to interpret the results of the test where such a test is part of a licensing application (Groundwater Protection Regulation, Section 32); and
- Providing detailed requirements for a pumping test where required as part of the licensing application (Todd et al., 2020).

In 1989, van der Kamp used the principle of superposition to calculate and extend drawdown into the recovery phase of a pumping test, provided groundwater level data in the recovery phase are available (Figure 1). This method (referred to here as the extended drawdown method) was profiled in more recent papers by Neville and van der Kamp (2009, 2012). This method has not been widely applied in B.C. but holds promise because it can provide greater insight and certainty of expected drawdown for days or even weeks beyond the pumping phase of the test, if data for the recovery period is available. This report presents preliminary results of application of the extended drawdown method to assess its applicability and limitations in B.C.'s complex hydrogeological environments. This study was initiated by the Province of B.C. in its continued effort to improve performance and interpretation of pumping tests to support licensing of groundwater use in B.C.

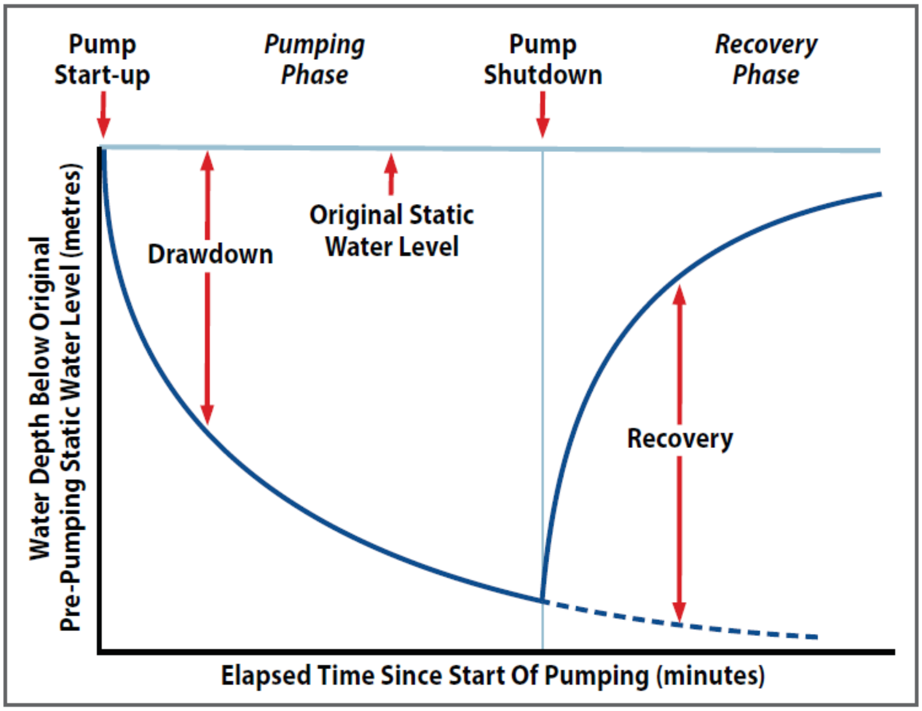

Figure 1. Schematic diagram showing drawdown and recovery of the groundwater level in a well during a pumping test, and the pumping and recovery phases of the test (Province of B.C., 2018). The dashed line is the extended drawdown that would occur if pumping had continued.

The study focussed on applying the extended drawdown method to observe how the extended drawdown would plot for a limited number of tests carried out in different types of aquifers in B.C. For each test, we discussed what general conditions may affect the plot of the extended drawdown. However, it was not within the scope of the study to conduct a comprehensive analysis of the pumping response, nor to comment on the adequacy of the tests for meeting the objectives for which they were originally conducted.

Most of the available pumping tests used in this study were conducted for specific projects. To avoid being too specific about the pumping tests, only the general location and the Well Tag Number (WTN) for the well are reported. For wells that are not in the Province's GWELLS database, the well was given a generic label (e.g., Well 1 or Well R-1).

2. THEORY, METHOD AND APPLICATION

2.1 Theory of extended drawdown

Guidance documents for conducting pumping tests in B.C. (Todd et al., 2020; Province of B.C., 2018) require that recovery of the water levels should be monitored following the end of pumping for a specified time, or for a specific amount of recovery- typically 90%, in the pumped well. Frequently little is done with the recovery data, especially for complex cases. In most cases, the cursory treatment of recovery data represents a genuine loss. Recovery data may provide some of the most valuable information from pumping tests, in part because the effective length of the pumping phase can be extended. The recovery phase of a pumping test should be considered as an integral part of the test since the transient flow and head changes during recovery are part of the aquifer system's response to pumping, and measurement of that response is the reason for carrying out a pumping test in the first place.

Figure 2 provides a theoretical example of how the drawdown cone develops and spreads during the pumping and recovery phases for the case of an ideal confined aquifer. For confined aquifers the drawdown cone spreads out and flattens during the recovery phase. The drawdown at large distances continues to increase for a while after pumping has stopped so as to drive water to flow toward the pumped well to replace the water pumped from aquifer storage. The recovery phase is therefore an integral and important part of a pumping test because it probes more distant portions of the aquifer and thereby can help to detect boundary effects and sources of recharge or leakage. Confined aquifers tend to have large drawdowns and slow recovery. The theoretical drawdown plot in Figure 2 suggests that for confined aquifers it may be advantageous to continue recovery measurements beyond 90 % recovery in both the pumped well and observation wells. An example of such data for a pumping test on a confined aquifer is shown by van der Kamp and Maathuis (2012, Figure 4).

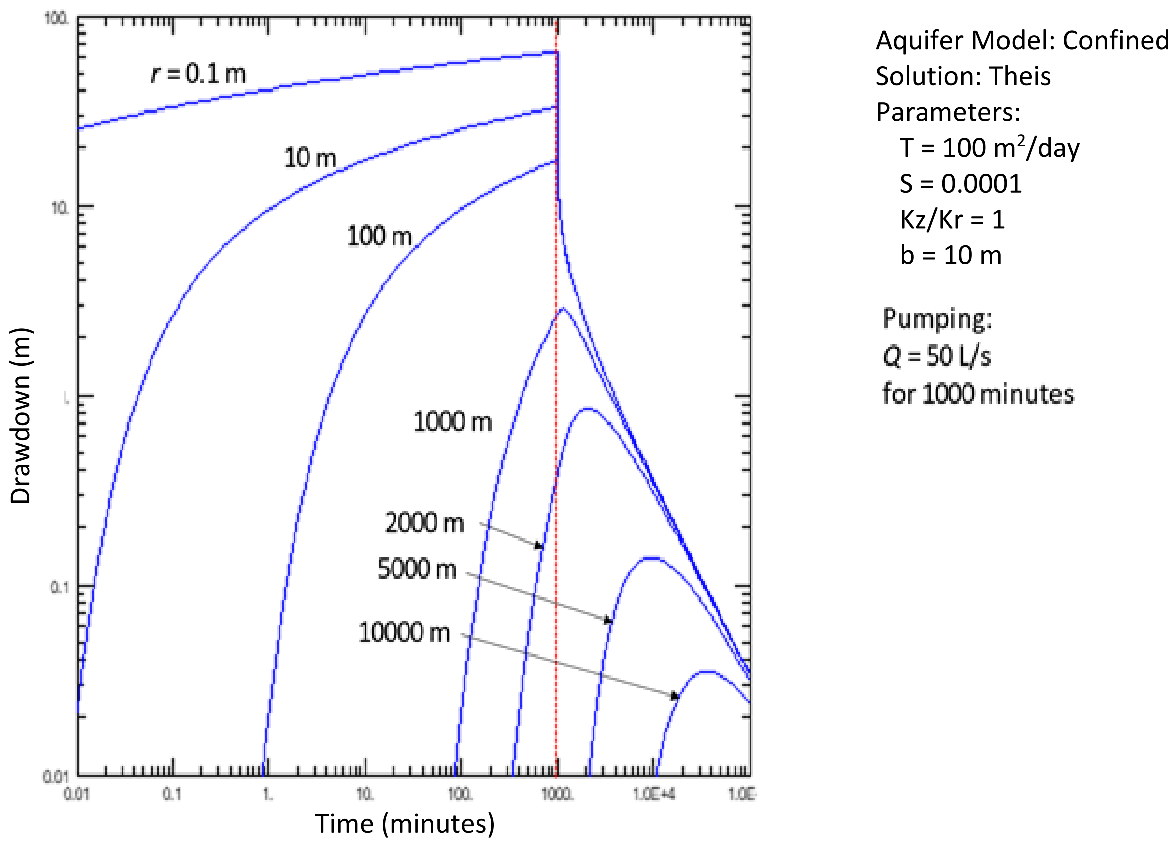

Figure 2. Log-log plot of drawdown changes with time at different distances from the pumped well during the pumping and recovery phases of a 1000-minute pumping test for a confined aquifer (Figure courtesy of C. Neville).

A common approach to interpreting recovery data is based on the Theis model for an ideal confined aquifer which involves plotting the recovery data (i.e., residual drawdown data versus the logarithm of t/t', where t is the total time and t' is the time since pumping was stopped). This approach treats the recovery phase as a separate test, quite independent of the pumping phase. Other approaches, typically included with commercial pumping test analysis software, involve graphing the residual drawdown of the recovery phase continuously with the drawdown of the pumping phase and fitting these plots to various theoretical models for idealized aquifers. Such utilization of recovery data respects the continuity between the pumping and recovery phases. However, the utility of both approaches may be limited for many real-world aquifers which do not conform to the idealised models and for which there is limited hydrogeological information.

The superposition principle allows a much more general use of recovery data which does not depend on a particular idealized model of the aquifer. Figure 3 illustrates the mathematical reasoning: the cessation of pumping can be considered as a continuation of pumping plus an injection at the same rate so that the net withdrawal rate is zero (Theis, 1935).

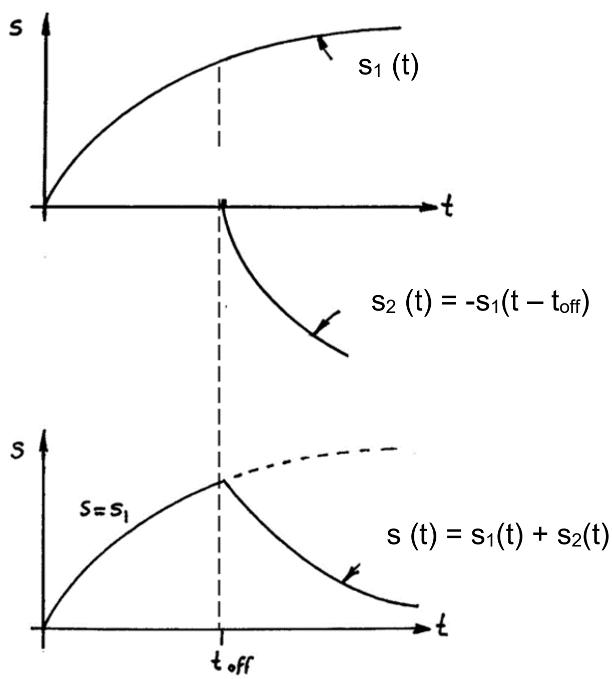

Figure 3. The superposition principle applied to the recovery phase (sketch courtesy of C. Neville).

In Figure 3, t is time, s(t) is the observed drawdown, the dashed line that is continuous with $s_1(t)$ is the drawdown that would have occurred if pumping were continued at a constant rate, and $s_2(t)$ is the negative drawdown (increased head) due to injection starting at t_{off} , the time that pumping stopped. Then by superposition:

$$s(t) = s_1(t) + s_2(t) \qquad [t > t_{off}] \qquad [1]$$

$$s(t) = s_1(t) \qquad [0 \le t \le t_{off}] \qquad [2]$$

But the increase of head resulting from injection at the same rate as the pumping rate is just the inverse of the drawdown resulting from pumping, delayed by the duration of pumping:

$$s_2(t) = -s_1(t - t_{off}) \qquad [t > t_{off}] \qquad [3]$$

Equations [1], [2] and [3] then lead to:

$$s_1(t) = s(t) \qquad [t < t_{off}] \qquad [4a]$$

$$s_1(t) = s(t) + s_1(t - t_{off}) \qquad [t > t_{off}] \qquad [4b]$$

Equation [4b] shows the drawdown that would have occurred ($s_1(t)$) had pumping continued can be calculated by means of the measured residual drawdown (s(t)) after pumping is stopped. What is more, this calculation of the extended drawdown can be carried on for more than one pumping phase duration after pumping has stopped. In fact it can be carried on for as long as water-level measurements are continued and the residual drawdown is large enough to be distinguishable from other effects on the background water level.

Equation [4b] is subject only to the applicability of the principle of superposition, and the condition that the pumping rate was constant (although this latter restriction can be generalized). Recall that the principle of superposition is based on the mathematical linearity of the basic differential equation for transient groundwater flow and the associated boundary conditions. Thus, the principle of superposition requires that equations governing groundwater flow are linear and this requirement of linearity is based on the following conditions:

- Darcy's Law applies, water is released from storage without delay and in proportion to the change of head,
- Aquifer and aquitard hydraulic properties do not change over time, and
- Aquifer saturated thickness does not change (e.g., no dewatering).

Importantly, there is no restriction on aquifer type such as confined or semi-confined and on spatial variability of the aquifer hydraulic properties and the presence of boundaries, nor the magnitude of the hydraulic properties of the aquifer/confining units, so that the principle is equally applicable to flow in aquitards.

The restriction that Darcy's Law is applicable precludes cases in which turbulent flow occurs, as in cavernous karst, large fractures, or perhaps near a pumped well where the flow velocity may lead to turbulence. As we shall see, for practical applications it is also important that the drawdown resulting from pumping can be reliably calculated from the measured groundwater levels. In other words, that other changes of the so-called "static" water level are either very small compared to the residual drawdown or can be identified and removed from the water level record.

The drawdown measured during the pumping phase can be plotted together with the extended drawdown that has been calculated from the residual drawdown measured during the recovery phase, using equation [4]. These can then be analyzed by any of the usual models for analysis of pumping test data or can be the basis for extrapolating the drawdown plot to estimate the drawdowns that would occur for long-term operational pumping. In this way the effective duration of the pumping test can be lengthened at very low cost.

Figure 4 illustrates an application of this method for a large confined buried-channel aquifer, the Estevan Aquifer in south-east Saskatchewan, Canada. This aquifer consists of several intersecting deeply buried channels filled with alluvial sand and gravel. The aquifer is confined by 50 to 100 m of dense clay-rich Pleistocene glacial till and incised into much less permeable Tertiary sedimentary materials (Walton, 1970). At several locations the hydraulic continuity of the channels is much reduced by the presence of transverse barriers of unknown provenance. This aquifer/aquitard system is not homogeneous and continuous in all directions and an approach to the drawdown and recovery data based on the Theis model could not be expected to be useful. However, van der Kamp and Maathuis, (2012) showed that the extended drawdown conforms closely to the drawdown that would be expected far away from the pumping well in a buried-channel aquifer.

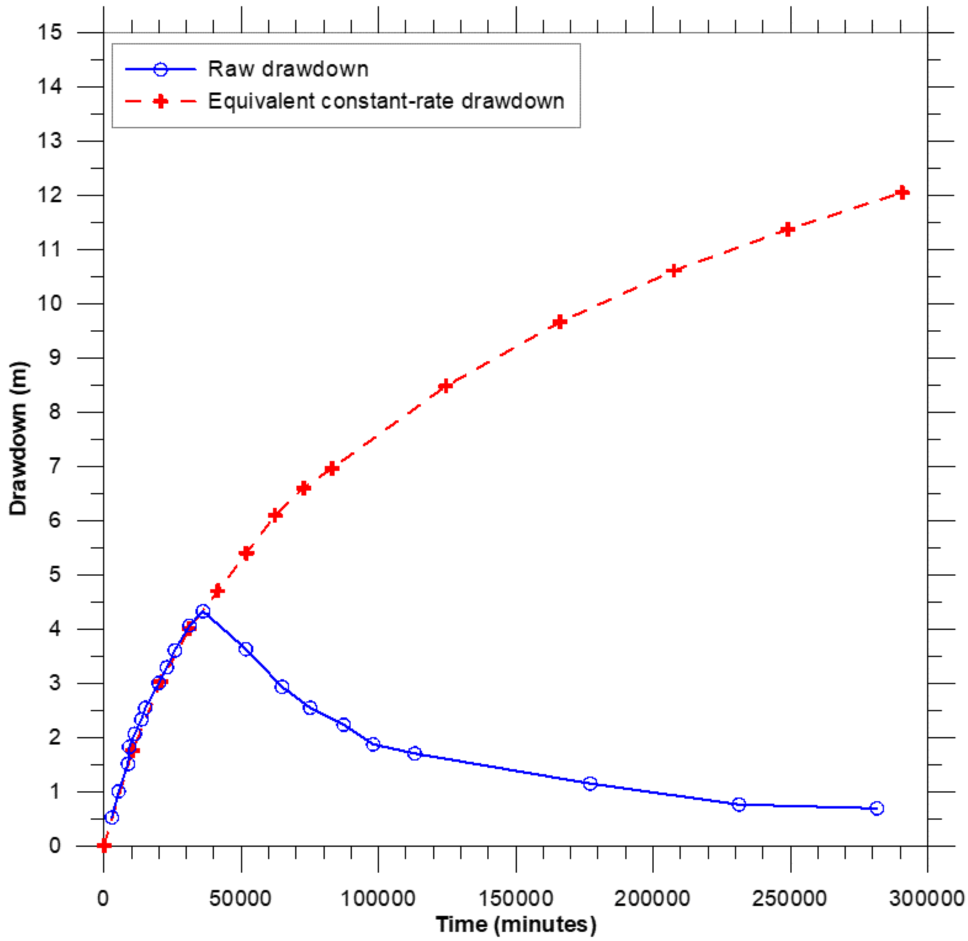

Figure 4. Measured drawdown and extended drawdown at observation well 11L-85, 5,285 m distant from the pumped well, during and after a 29-day pumping test of the Estevan Valley aquifer in Saskatchewan.

Because of the low hydraulic conductivity and continuity of the overlying aquitard, the Estevan Aquifer is highly confined as indicated by the very slow recovery, suggesting recharge to the aquifer through the aquitard and the adjacent geological units is very slow. Measurable residual recovery persisted for at least 170 days after pumping stopped and this allowed extension of the effective pumping duration to 200 days. This continued measurement of the recovery phase and the slow recovery led to a large reduction of the estimated sustainable yield of the aquifer that had been arrived at in previous studies, which was confirmed by subsequent production pumping.

The extended drawdown can also be useful for detecting or confirming hydrogeological conditions that do not meet the conditions of the superposition principle, or for giving warning of possible unreported changes of the pumping rate and changes in the initial ("static") water level. The diffusive character of transient groundwater flow implies that there should be a smooth transition from the measured drawdown during pumping to the extended drawdown during the recovery phase, as illustrated in Figure 1. A "dog leg" kink in the extended drawdown plot at the point when pumping ceases, or an upward or downward shift, are indications that one or more of the conditions for the extended drawdown calculation are not met. Since these conditions underlie most of the standard methods for analyzing pumping test data, the lack of a smooth transition implies that interpretation of the data on the basis of any such standard analysis should be treated with caution or even discarded entirely.

Figure 5 shows drawdown and recovery data for a 700-minute pumping test carried out on an unconfined aquifer. This was an initial test for the design of a dewatering system. There is a clear shift between the measured drawdown data up to t = 700 minutes, and the extended drawdown data after 700 minutes, which were calculated assuming the applicability of the superposition principle. This discontinuity reflects the fact that the recovery was slower than would be expected judging by the initial drawdown during the pumping phase. The discontinuity shows that the principle of superposition is not applicable. Therefore, the groundwater system is either not linear (i.e., groundwater flow not adequately described by linear differential equations) or not time-invariant (i.e., the system dimensions and/or its hydraulic properties changed during the pumping test). In this case it is likely that the water table was drawn down significantly compared to the total saturated thickness of the aquifer so that by the end of the pumping the transmissivity was reduced, leading to slower recovery.

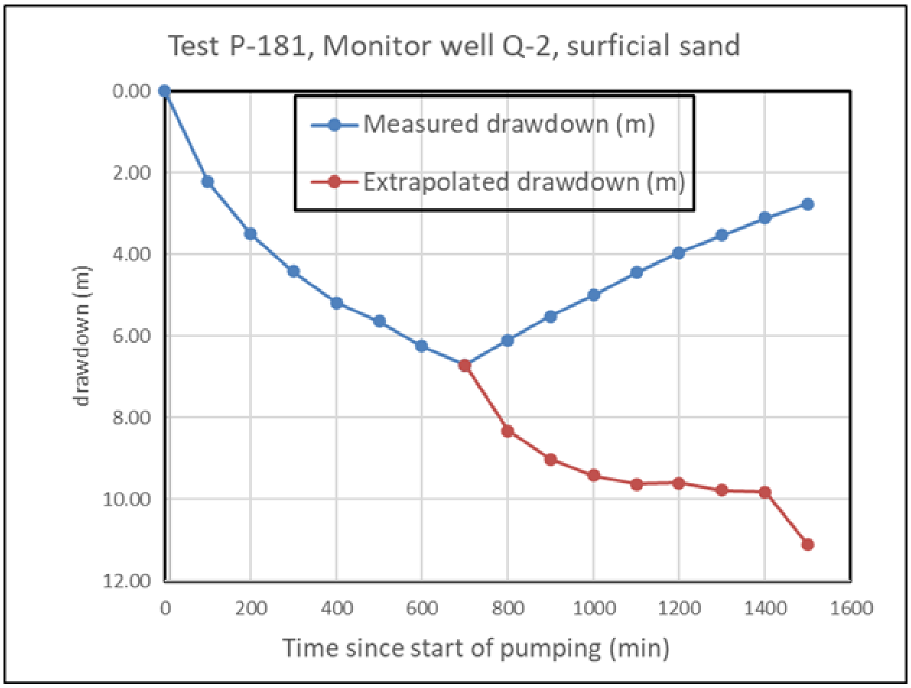

Figure 5. Extended drawdown for a 700-minute pumping test of an unconfined aquifer.

In addition, the recovery analysis assumes that the pumping rate was kept constant and that the "static" water level used to calculate the drawdown was in fact static and not changing. This assumption becomes particularly important as the recovery carries on and the residual drawdown is small so that small changes of the background "static" level can result in apparently anomalous results such as the recovering water level rising above the original "static" level. Plotting of the extended drawdown will help to identify such effects so that they can be taken into account.

Anomalous results such as a rising extended drawdown or a "shift" in the extended drawdown plot should be considered as a "red flag" that something is amiss with the assumptions upon which an interpretation might be based. The anomaly could signal a large unreported change of the pumping rate; a changing "static" water level; dewatering of the aquifer; or interference from other pumping wells in the area. Any of these would have implications for the interpretation of the pumping test data, including estimate of long-term well capacity.

It is important to consider whether the extended drawdown method can be used with data only from the pumped well. In many cases of pumping tests in B.C. there are no observation wells and the only available data is the drawdown in the pumped well. The drawdown in a pumping well commonly includes the head losses due to turbulent flow near the well screen that result from high rates of flow. Such well losses occur rapidly during start of pumping. Drawdown in the pumped well may also reflect the effect of water storage in the well bore during the early time of the pumping test. During the recovery phase, the effect of well losses on residual drawdown will rapidly become negligible once pumping stops. The borehole storage effects will affect the recovery just as they affect the drawdown at the start of the test.

It turns out that the extended drawdown calculation automatically includes the effects of any well losses and well-bore storage in the extended drawdown for the pumped well because those effects are reflected in the drawdown which, in turn, is incorporated in the extended drawdown calculation. The only restriction is that the well losses are not changing during the pumping test as a result of clogging or further cleaning out of the well screen and its surroundings. In other words, well losses and well-bore storage do not lead to lack of continuity in the extended drawdown when pumping is stopped. This conclusion, reached on the basis of theoretical considerations, is born out by the extended drawdown calculations for pumping-test case histories in this study where smooth continuity of the extended drawdown is found even where well losses are known to be significant.

2.2 Method

2.2.1 Criteria for ideal datasets

As part of the project, we developed criteria for selecting datasets to examine. The model constant rate pumping test dataset for this project would include the following criteria:

- If a step test has been conducted beforehand, the water level should be fully recovered before the pumping test starts.
- Any change in the static water level prior to and after the pumping test should be measured in the well.
- A pumping test should last at least 24-72 hours to allow for sufficient time to characterize the aquifer and pumping response.
- The pumping rate should be constant (variation of less than ±5%) and should be recorded every 15 minutes in the first hour of the test and every hour for the remainder of the test; when the pumping is adjusted (to maintain a constant rate), the rate before and after the adjustment should also be recorded.
- Pumping should not stop at any time during the test.
- The water level should be measured before, after, and at regular intervals throughout the pumping test to allow plotting of drawdown and recovery water levels on a logarithmic time axis (e.g., every 30 seconds for the first 5 minutes, every minute from 5-10 minutes, every 2 minutes from 10-20 minutes, every 5 minutes from 20-60 minutes, every 10 minutes from 60-120 minutes, every 100 minutes from thereafter after pumping starts and also after pumping stops).
- The water level during the recovery period should be measured until the water level is at least 90% recovered, or for the same length of time as the pumping test lasted. In the pumped well; the 90% recovery should not include recovery from well loss.

- The pumping test should not be affected by precipitation and is ideally conducted during the dry season (summer on the coast, winter in the interior); this is especially important for fractured bedrock aquifers.
- Ideally, water level data is also collected at an observation well.
- Information should be available on the construction of the well (well record indicating depths of lithology, depths of screen or depths and estimated flow of water-bearing fractures).
- Interpretation of the pumping test data should be done by the professional hydrogeologist who has familiarity of the local hydrogeology.

Additionally, for water supply development:

- The well should be pump tested at or above the rate of its intended use.

These criteria were followed as closely as possible when selecting pumping test datasets for this study, although some exceptions were made for the purpose of including different types of hydrogeological settings.

2.2.2 How are the data plotted?

A Microsoft Excel spreadsheet template was designed to plot pumping test data and calculate the extended drawdown. The spreadsheet template and user guidance can be found in Appendix A. The spreadsheet template contains five tabs for information about the pumping well and observation well(s), data from each well in the pumping test, and a summary of the plotted data. The user of the spreadsheet enters data of the time since pumping started, time since pumping stopped, pumping rate, and water level. Using this information, the derivative, t/t', drawdown, and extended drawdown are calculated within the spreadsheet.

Several plots are set up on the spreadsheet template to display the pumping test data. These include:

- Water Level vs Time,
- Derivative vs Time,
- Pumping Rate vs Time,
- Drawdown vs log Time,
- Residual Drawdown vs log t/t',
- Extended Drawdown vs Time,
- Extended Drawdown vs log Time, and
- Water Level and Extended Drawdown vs Time.

The first five plots are standard plots typically used for interpretation of pumping test data. The last three plots are various ways to show the calculated extended drawdown.

The calculation of extended drawdown requires the drawdown at a given time since pumping started and the residual drawdown at the corresponding time since pumping stopped to be summed (see Equation [1]). However, for a variety of logistical reasons, the water level measurements after pumping stopped may not follow exactly the same time schedule as the measurements during the pumping phase. This typically happens for manual water level measurements. When these times of measurement do not correspond exactly, linear interpolation of the drawdown during the pumping phase is used to calculate the extended drawdown at a given time since pumping started.

In cases where many data points required linear interpolation to calculate extended drawdown, we used Excel functions to determine the values needed for the calculations. A detailed explanation of the use of these functions and linear interpolation can be found in Appendix A.

2.3 Application

All pumping test data analyzed in this study were from tests conducted in B.C. Pumping test datasets were selected from the following sources:

- B.C. government's nearly 280 water utility[1] files. Candidate tests were screened based on their pumping test attributes. From those candidate tests, a review of the specific files to inspect the data and plots was done to choose the most likely useable datasets.
- Pumping test data published in Vicki Carmichael's compendia of re-evaluated pumping tests on the east coast of Vancouver Island and in the Okanagan Basin (Carmichael (2014), Carmichael (2013), Carmichael et al (2009a) and Carmichael et al (2009b)). These publications were reviewed to select the most useable tests, based on the criteria for ideal pumping test datasets (see Section 2.2.1). The pumping test data in Excel format were obtained from the BC Ministry of Environment and Climate Change Strategy. Unfortunately, the consultants' reports associated with these tests were not always available to provide complete context around the original purpose of the tests.
- Select pumping tests provided by Elanco Ltd, GW Solutions, and Western Water Associates Ltd.

In our search, we attempted to select pumping tests that reflect the various aquifer types and boundary conditions in B.C. but encountered the following challenges:

- Accessing pumping test data from government stored on internal drives for specific projects, or in paper files stored off-site.
- Some tests, including tests with observation wells, had excellent drawdown data but limited or no recovery data.
- In some 24- or 72-hour tests, the pumping rate was not held constant.
- Some tests had noisy data (pumping rate was not rigorously controlled) or may be affected by pumping of another well nearby.

In all, extended drawdown was calculated for 20 pumping tests. Fourteen tests were from unconsolidated aquifers and six tests were from fractured bedrock. Nine of the pumping tests had at least one observation well with recovery data to apply the extended drawdown method. A summary of the pumping tests for which the extended drawdown was calculated is shown in Table 1.

[1] A water utility is a private entity that supplies water to a subdivision where local government is not prepared to do so. Private water utilities are regulated by the Province of B.C. under the *Water Utility Act* and *Utilities Commission Act*. To obtain a Certificate of Public Convenience and Necessity to operate a private water utility, a pumping test is typically required in support of the application.

Table 1. Summary of pumping tests chosen for this study.

General Location	Well Tag Number (WTN)	Date of Start of Test (yyyy-mm-dd)	Duration of pumping (min)	Duration of recovery (t/t')	No. of Obs. Well(s)*	Aquifer No.**	Aquifer Type***	T (m^2/day)	S (-)	Site Hydrogeology
Armstrong	63166	1996-02-03	4000	4	0	N/M	6b	0.07	N/C	Well record indicates that this well is drilled into fractured granitic bedrock of varying composition. The well is located at the base of a northwest-facing rocky slope.
Cowichan Lake	90027	2003-11-05	1440	2.2	0	190	2	60	N/C	The aquifer is likely in hydraulic connection with Cowichan Lake (~65 m away) and a tributary creek (~95 m away). The probable direction of flow is southwest towards Cowichan Lake. Recharge occurs from infiltration of runoff from precipitation, but also from infiltration of water from the tributary creek. Pumping could also induce infiltration from the creek and Cowichan Lake.
Fernie	59365	1990-06-28	1440	2.1	0	532	4b	408	N/C	Well is completed into a confined floodplain sand and gravel aquifer beside the Elk River.
Golden	78362	2000-03-07	5760	2	1	N/M	5a	14	$1.3\times(10^{-4})$	The pumped and observation wells are drilled into fractured sedimentary (slate, calcareous slate, limestone) bedrock. The site is located at an elevation of ~1350 m asl, on a NE-facing ski slope.
Keremeos	83151	1994-09-22	517	1.6	0	261	4a	N/C	N/C	The aquifer beneath the golf course consists of coarse-grained sand and gravel glacial outwash within a glacial-carved, "U"-shaped bedrock valley. Reported depths to bedrock vary between 22 m and 76 m and the average thickness of the saturated aquifer is estimated to be 300 m. There is no surface water flow and the valley is infilled with hummocky glacial outwash sands and gravels. Twin Lakes are approximately 900 m to the south of the well (Carmichael et al., 2009b)
Lantzville	NR	2011-07-04	2880	1.6	1	167	4b	384	$2\times(10^{-2})$	The site is underlain by a thin, shallow layer of silt (4.6 m depth) overlying interbedded layers of sand and gravel. Shale bedrock is found at 27.4 m depth.
Lantzville	NR	2011-07-11	4320	2	1	167	4b	738	$3.4\times(10^{-3})$	The site is underlain by a thin, shallow layer of silt (2.7 m depth) overlying interbedded layers of sand and gravel. Blue clay is found at 21.3 m depth.
Lantzville	NR	2012-07-09	4320	1.2	2	215	4b	10	$4.2\times(10^{-3})$	The aquifer beneath the site comprises sand and gravel from 77 m to 84 m depth. The aquifer is overlain by silty sand, silty clay and sand and underlain by argillite bedrock.
Mill Bay	88224	2017-10-04	4320	2.1	0	208	6b	3.7		Well is completed into a fractured crystalline bedrock aquifer. Anecdotal information suggests fracture thicknesses can be significant (drill rods dropping in boreholes). The test was also done after a season of operational pumping.
Mill Bay	119110	2019-10-29	4320	4	1	208	6b	3.2	$\sim5\times(10^{-5})$	Well is drilled into a fractured crystalline bedrock aquifer in a little explored area of the aquifer.
Nakusp	113356	1987-10-01	1440	2	1	N/M	3	35-553	$8.3\times(10^{-4})$	Well completed in an alluvial fan complex. Based on Wei (1988)'s conceptual understanding of the alluvial fan, the alluvial sand and gravel aquifer may be confined at the site but possibly becomes unconfined further uphill (see Figure 14 of Wei (1988)).
Nakusp	53942	1987-10-27	1440	2	1	N/M	3	333	$9.6\times(10^{-4})$	Well completed in an alluvial fan complex. Based on Wei (1988)'s conceptual understanding of the alluvial fan, the alluvial sand and gravel aquifer may be confined at the site but possibly becomes unconfined further uphill (see Figure 14 of Wei (1988)).
Nanoose	NR	1988-05-22	4260	3.8	0	218	6b	2	N/C	Well drilled into fractured meta-sedimentary and other crystalline bedrock. No overburden material.
New Denver	86235	2006-09-29	1200	11	0	1116	3	N/C	N/C	The pumped well is drilled into an alluvial fan of Wilson Creek (hydraulically connected). The well is located ~320 m from Wilson Creek and ~470 m from Slocan Lake.
Osoyoos	83016	1986-08-15	2880	1.7	0	193	4a	1366	$7.8\times(10^{-2})$	The well is completed into a shallow, thin unconfined, unconsolidated aquifer. The pumping well is located 40 m from Osoyoos Lake.
Powell River	49911	1982-02-01	600	2.3	1	838	4b	82	N/C	The sand and gravel aquifer is confined below clay and till and may be an aquifer unit within the till or pre-till (Quadra Sands?). There is an upper gravel unit from 13.7 to 38.1 m depth that may exist under unconfined conditions. Locally, the unconsolidated sediments reach over 110 m thick and the sands and gravels, though lithologically confined by till/clay, may be hydraulically unconfined (in places).
Prince George	39604	1978-05-04	14000	1.9	2	86	4b	N/C	N/C	Pumped and obs well #1 (and likely obs well #2) are completed into a confined sand and gravel aquifer beneath ~25m of clay. Of the 4 wells drilled for Autumn Estates in GWELLS (WTNs 38135, 39604, 72883, and 72884), well WTN 72883 did not encounter the aquifer.
Qualicum Beach	41896	1979-03-13	1500	2.0	0	217	4b	385	N/C	Although the Quadra Sands forms an extensive sub-till aquifer, it is very likely heterogeneous. There is a complex mixture of till, lenses of gravel, sand and silt which overlie the Quadra Sands (Carmichael, 2013).
Qualicum Beach	113212	2017-05-24	2880	1.7	0	662	4b	12	N/C	Well is drilled through silt and clay into a confined sand and gravel aquifer (Quadra Sands).
Salt Spring Island	75537	2000-07-04	5760	2.4	0	722	5a	1.3	$4.2\times(10^{-4})$	Pumped well drilled into fractured sandstone and shale of the Nanaimo Group. The upper-most major water-bearing fracture is reported at 34 feet (10.4 m) depth. The well is located ~100 m from the ocean.

*With recovery measurements; **Aquifer No. is the number assigned to a mapped aquifer in the GWELLS database; ***Aquifer types in B.C. are explained in Wei et al. (2009); T=transmissivity; S=storativity or specific yield (only calculated where data from an observation well available); NR=no record in GWELLS; N/M = not mapped; N/C=not calculated.

3. RESULTS

Of the 20 pumping tests reviewed in this study, the calculated extended drawdown appears to work reasonably well for just over half of the tests (i.e., rate of drawdown at late pumping times seems to continue as expected into the recovery phase). Examples of these tests are presented in Section 3.1. For all the tests presented in Section 3.1, the assumption of a linear system holds where superposition is applicable, the assumed conditions of the test (constant pumping rate and no changes of the static water level) also appear to hold.

For the remainder of the tests, the calculated extended drawdown did not plot as expected. Some examples are presented below in Section 3.2. In these tests, either the assumption of a linear system or conditions of the test were not valid. Calculating and plotting the extended drawdown indicated that these assumptions needed to be critically re-evaluated.

A summary of analysis for each of the 20 pumping tests can be found in Appendix B, along with the Excel files containing the data and plots for each of the tests.

3.1 Tests where calculated extended drawdowns plot as expected

3.1.1 Unconsolidated aquifers

Figures 6 and 7 show the calculated extended drawdown for wells drilled into an unconfined, unconsolidated sand and gravel aquifer; and a confined, unconsolidated sand and gravel aquifer, respectively. The downward arrow shows when the pumping phase of the test ended and when the recovery phase began (right of arrow). Both semi-log plots show data from the pumped well. Figures 6 and 7 show that there is continuity in the drawdown and extended drawdown. In these cases, drawdown can be extended through the duration of the recovery phase using the recovery data. The plots show that a spike at the start of the recovery phase is evident. This will be further discussed in Section 3.1.4. Extended drawdown for pumping tests for wells WTN 53942 (Nakusp) and WTN 113212 (Qualicum Beach) also show extended drawdown plots as expected (see Appendix B for write-ups).

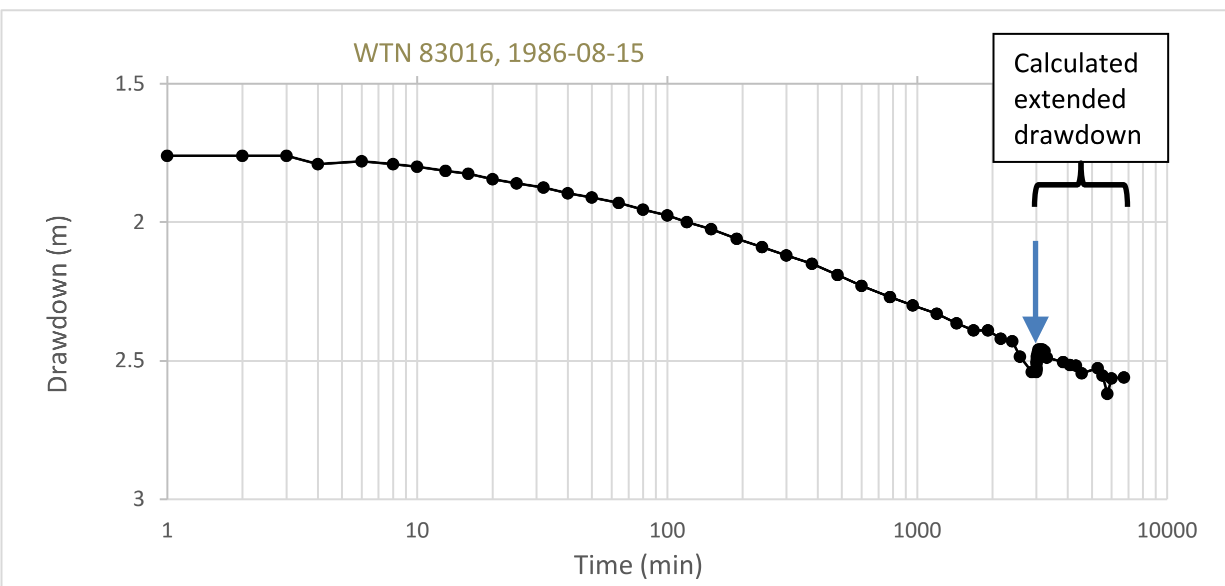

Figure 6. Plot of drawdown and calculated extended drawdown from recovery data for a well drilled into an unconfined, unconsolidated sand and gravel aquifer in Osoyoos.

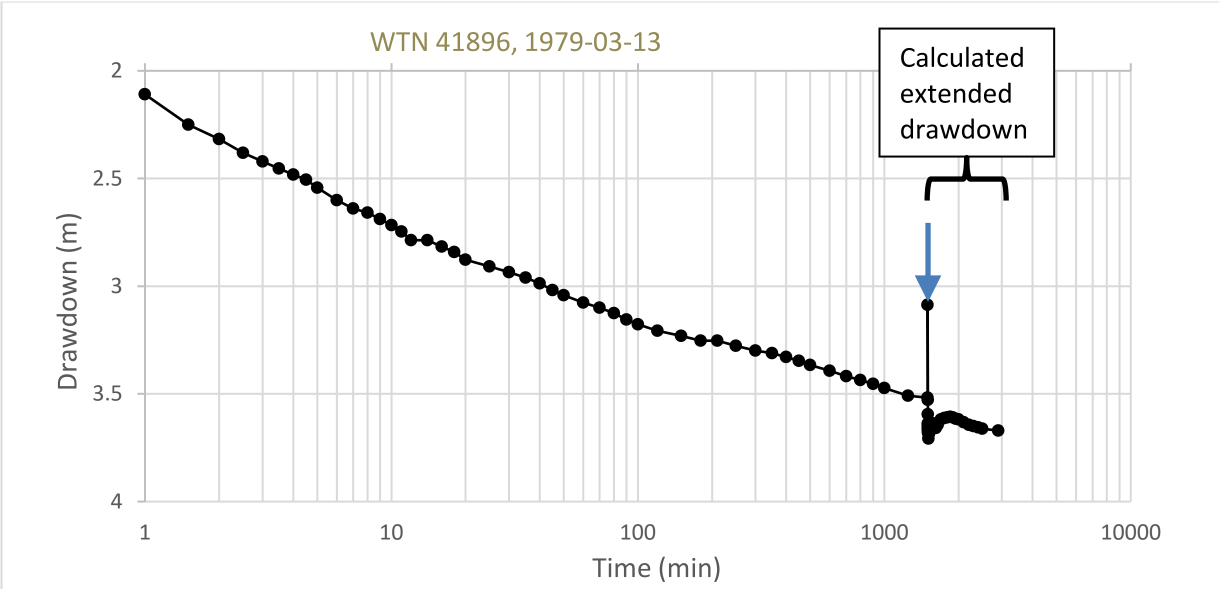

Figure 7. Plot of drawdown and calculated extended drawdown from recovery data for a well drilled into a confined, unconsolidated sand and gravel aquifer in Qualicum Beach.

3.1.2 Fractured bedrock aquifers

Figure 8 is a plot for a pumping well in a fractured granitic bedrock aquifer. The calculated extended recovery shows the drawdown is expected to continue (drawdown extends similarly in the nearby observation well – see Appendix B). The calculated extended drawdown declines at a steeper rate on the semi-log plot compared to the rate of drawdown near the end of pumping. The steeper rate of drawdown reflects that conditions may have changed between the pumping phase and the recovery phase (draining of fractures?) or that the aquifer may be bounded. The pumping test of another fractured bedrock aquifer in Nanoose showed similar results (see Appendix B) in that the method was able to extend the drawdown with recovery data.

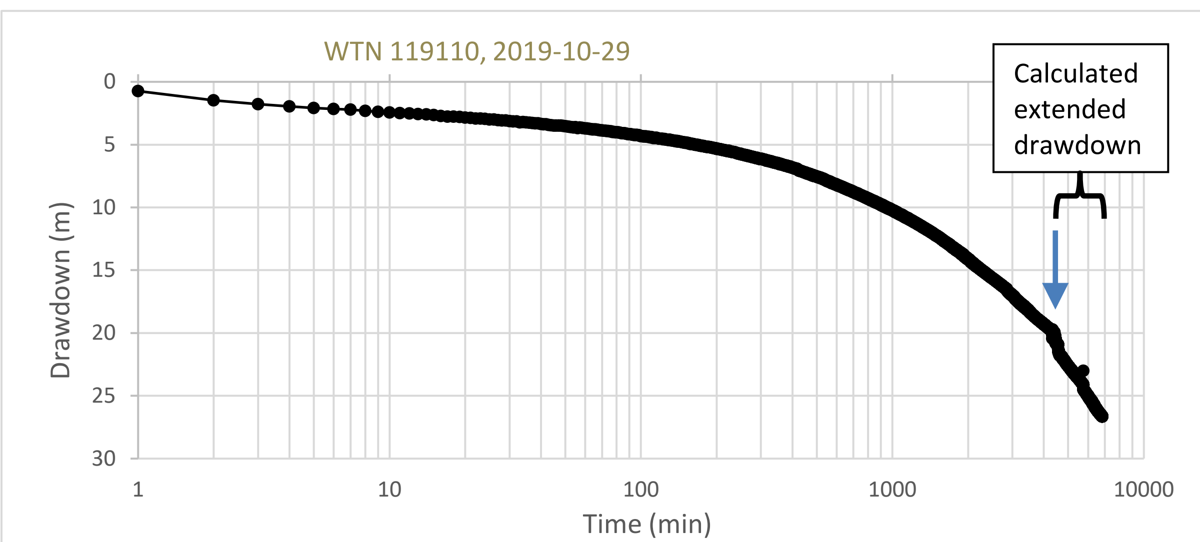

Figure 8. Plot of drawdown and calculated extended drawdown from recovery data for a well drilled into a fractured granitic aquifer in Mill Bay.

3.1.3 Positive boundary condition

Figure 9 shows the calculated extended drawdown for a well drilled into an unconfined, unconsolidated (deltaic) sand and gravel aquifer. Drawdown stabilized after ~1000-1200 minutes of pumping, and the condition of stabilization is supported by the calculated extended drawdown. The stabilization is interpreted to be enduring, with the source of water from a hydraulically connected stream or from Cowichan Lake.

Stabilization in drawdown was also observed for tests of wells WTN 75537 (sedimentary bedrock on Salt Spring Island), WTN 86235 (alluvial sand and gravel aquifer in New Denver), and two wells drilled into confined sand and gravel in Lantzville (no WTNs; see Lantzville (2 wells) in Appendix B).

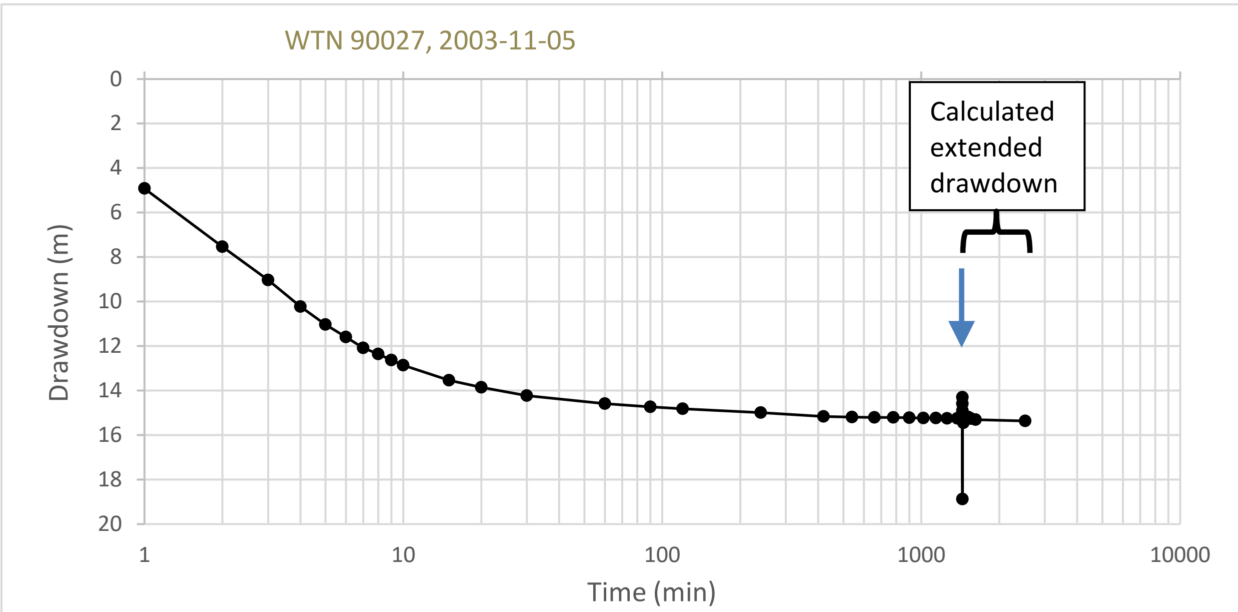

Figure 9. Plot of drawdown and calculated extended drawdown from recovery data for a well drilled into an unconfined, unconsolidated sand and gravel aquifer near Lake Cowichan.

3.1.4 The "spike"

For most of the plots of calculated extended drawdown, a "spike" appears in the plot for the pumped well that generally occurs within the first couple of minutes into the recovery phase and lasts about half an hour (see Figure 7 and Figure 9, for example). The cause of the "spike" can not be confirmed at this time but could potentially be related to the limited accuracy of the recording of drawdown and residual drawdown measurements at the start of the pumping and recovery phases when the rate of change of water level is greatest. The "spike" could also reflect drawdown affected by changes in pumping rate at the beginning of the pumping phase as the contractor made adjustments to achieve a constant pumping rate. The former (measurement inaccuracies) should not be an issue with data measured with a transducer and datalogger. However, the latter (drawdown affected by initial adjustments of pumping rate) would appear regardless of whether the data was collected manually or with a transducer and datalogger. Most "spikes" in the pumped well are short-lived and do not appear to affect the interpretation of the calculated extended drawdown viewed over a longer period of time.

3.2 Tests where calculated extended drawdowns do not plot as expected

For many of the tests, the calculated extended drawdown did not plot as expected. There appear to be two main phenomena observed: 1) the background "static water level" may have changed significantly during the pumping test and 2) dewatering may have occurred as a result of the pumping. These phenomena are briefly discussed below. To our knowledge, these phenomena have not been previously reported in reviewed literature.

3.2.1 Pumping tests where the static water level changed significantly

There were a number pumping tests examined in this study where application of the extended drawdown method showed the extended drawdown declining. One such test (WTN 88224) was conducted at the end of a summer of operational pumping from a bedrock aquifer. The test was conducted mainly to assess well performance. The effect of the recovering (rising) static water level produced an extended drawdown that was recovering (Figure 10), which is not possible if the assumed conditions hold, because the extended drawdown applies for continued pumping of the well. A similar result was observed for another test in sand and gravel (test of well R-1 in Lantzville-see Appendix B). In both tests, the static water level was rising prior to and during the constant rate pumping test. A similar result is suspected for the test in Keremeos (WTN 83151).

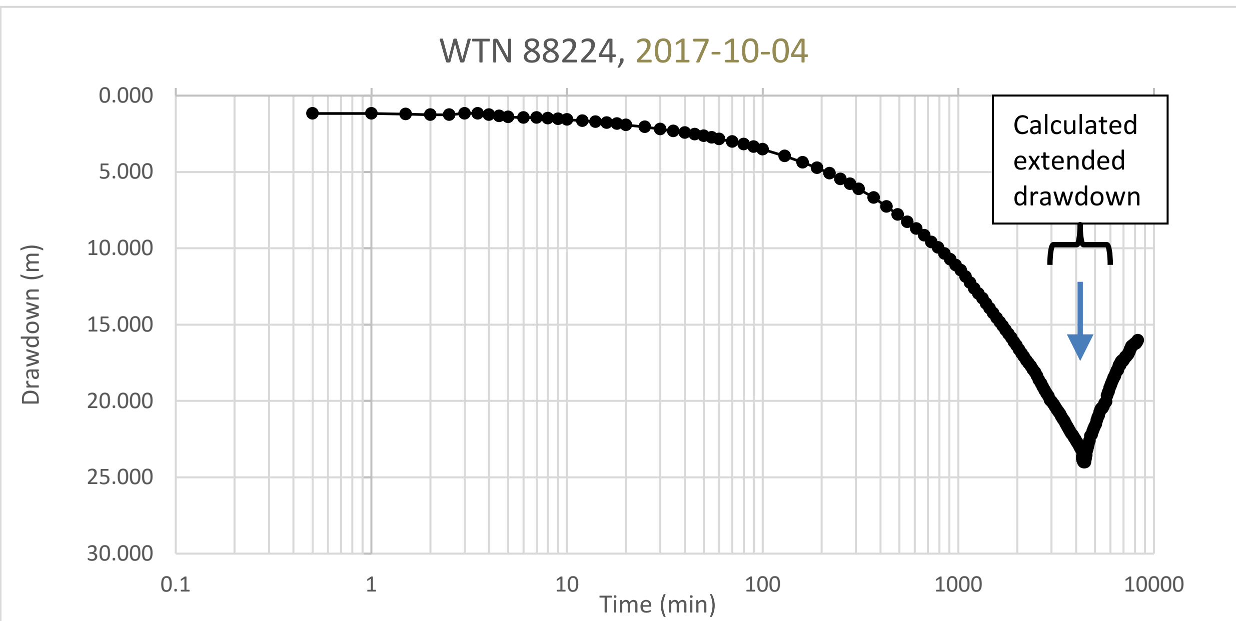

Figure 10. Plot of drawdown and extended drawdown showing affect of a rising "static" water level on the extended drawdown calculation.

A rising static water level prior to a constant rate pumping test is not uncommon because testing typically occurs after a previous short-term step test or when a well is taken out of production for testing. In both cases, the groundwater level is still recovering. Waiting for the static water level to fully recover before conducting a pumping test is especially challenging for fractured bedrock wells where the season for testing is limited and recovery from prior pumping is typically slower.

3.2.2 Pumping tests that showed evidence of dewatering or slow recovery

In some of the tests examined pumping may have caused dewatering of the aquifer; that is, draining of the water out of the aquifer pores have occurred. This is suspected to be occurring when the pumping water level drops to below the top of the confined sand and gravel aquifer. In fractured bedrock, very slow recovery initially after pumping stops was observed in some of the tests. The slow recovery may reflect draining of fractures (at the water table).

Dewatering can be detected as a downward shift in the extended drawdown plot. The shift means the recovery immediately after pumping stopped was slower than drawdown immediately after pumping started. This slow recovery is attributable to the longer time it takes to fill the dewatered pores or fractures following a lowered water table, versus the time it takes to raise the pressure in saturated pores or fractures following a reduction of the piezometric level. The available drawdown above the top of a confined sand and gravel aquifer can provide an indication of how likely a transition to water table conditions and dewatering may be. The pumping water level relative to the top of the confined sand and gravel aquifer and a decrease in the rate of drawdown may be evidence of dewatering occurring during the pumping test. A transition from confined to water table conditions in the aquifer is the interpretation for the 10-day pumping test in Prince George (WTN 39604 - Figure 11). For this case the drawdown caused the water level at one of the observation wells to decline about 6 m below the top of the aquifer and below the top of the well screen. In Figure 11, the downward shift appears to re-occur after an interval of time equal to the duration of pumping because the extended drawdown calculation then refers to the extended drawdown during the first interval after pumping stopped. A similar recurrent downward shift is also evident in the pumping test for well WTN 113356 in Nakusp.

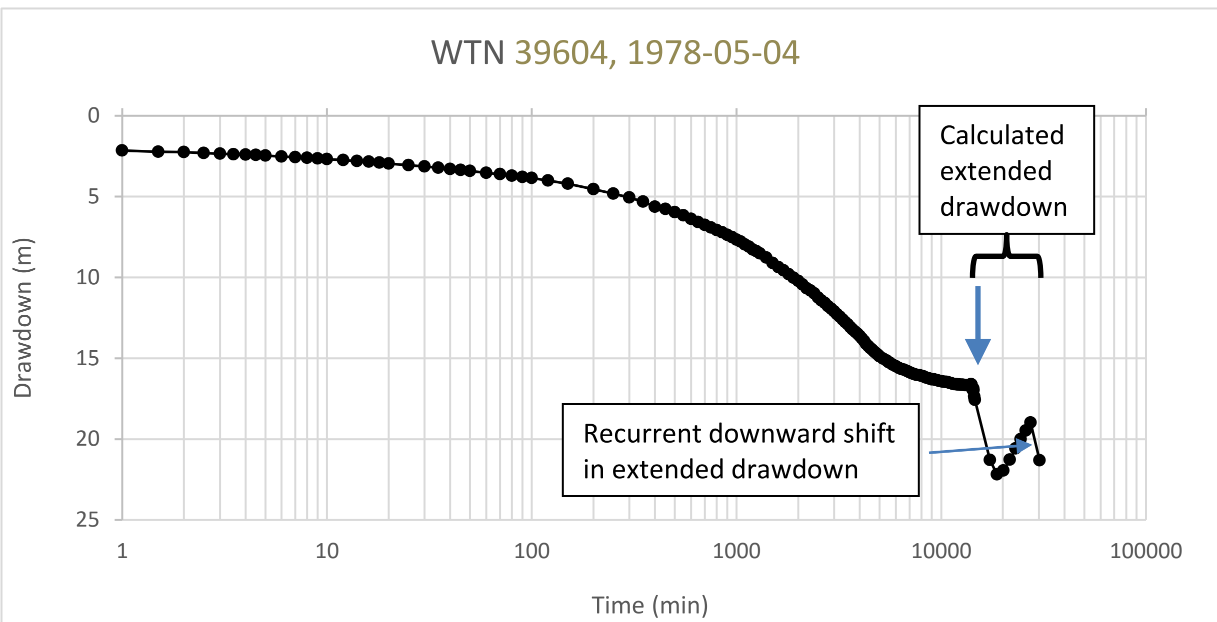

Figure 11. Plot of drawdown and extended drawdown showing the affect of dewatering as a result of pumping and slow recovery.

4. LESSONS LEARNED AND RECOMMENDATIONS

This study highlights some of the important details related to a pumping test, including the following:

4.1 Significant change in the static water level

Significant changes in the static water level during testing can affect calculations of drawdown and extended drawdown over the duration of the test. Accuracy of drawdown calculations in turn impacts estimates of well capacity and aquifer hydraulic properties (i.e., transmissivity and storativity). The static water level is commonly assumed to be unchanging, but, in fact, is commonly subject to change (e.g., from prior step-testing, from seasonal fluctuation (especially in fractured bedrock aquifers) or from recovery of operational pumping).

In aquifers that respond slowly after pumping, as is common for deep confined aquifers or bedrock aquifers, it may be worth considering shortening the step-test durations or by scheduling the step-test and pumping test on either side of a weekend, to allow as much time as feasible for the static water level to recover.

Recommendation 1: Allow sufficient time for the static water level to recover from any prior pumping but at a minimum, measure and report the static water level prior to any step tests and the constant rate pumping test in the well to be pumped (and any observation well). That would help to detect and characterize the change and allow any change in the static water level to at least be taken into consideration in the interpretation of the drawdown and extended drawdown calculations. This practice would remove uncertainty in interpretation caused by changing static water levels.

4.2 Documenting adjustments of the pumping rate

In many of the pumping tests, the constant pumping rate was only stated once at the beginning. In other tests, the rate was periodically recorded throughout the pumping phase of the test. Neither practice is sufficient to determine whether the pumping rate was adjusted to keep the rate constant to help explain any changes in the rate of drawdown.

Recommendation 2: The pumping test contractor should record the pumping rate immediately prior to and after the rate has been adjusted and record the pumping rate during checks, even if no adjustments are made. This practice would help explain any sudden changes observed in the rate of drawdown and provide more confidence in interpreting the results.

4.3 Adequate recovery measurements

Some of the tests plotted in this study had drawdown measurements from observation wells but not recovery measurements. The reason for the lack of recovery measurements is unknown but reflects the priority usually given to obtaining drawdown measurements over recovery measurements. Recovery measurements should be taken for as long as feasible but the current criteria to cease recovery measurements when 90% recovery is reached (Todd et al., 2020 and Province of B.C., 2018) needs to be clarified so recovery is not prematurely ended. The current provincial guidelines do not clearly distinguish recovery of aquifer loss from well loss in the pumped well. Well loss in the pumping well can result in significant drawdown at the start of the pumping phase but that loss disappears immediately after pumping stops while recovery from aquifer loss continues. In highly inefficient wells, drawdown from well loss can be so high that “90%” recovery is attained minutes after pumping has stopped, even though the percent recovery in the aquifer is still less than 90%. It is important to clarify that in the pumped well, percent recovery should refer to the aquifer loss only, not well loss.

<u>Recommendation 3:</u> The Province's guidelines (Todd et al., 2020 and Province of B.C., 2018) should clarify that, in the pumped well, percent recovery should refer to the aquifer loss only, not well loss.

4.4 Calculate extended recovery as normal practice

Perhaps the main lesson from this study is that calculating and plotting the extended drawdown is beneficial as an overall check on the validity of assumptions related to a constant rate pumping test. The method not only allows drawdown to be extended using recovery data but can help confirm whether the typical assumptions related to interpretation of the data are satisfied.

<u>Recommendation 4:</u> Professional hydrogeologists should consider calculating and plotting the extended drawdown as normal practice to continue proving the utility of the method to help with interpretation of constant rate pumping tests.

4.5 Archiving pumping test data in GWELLS

Finally, the Province of B.C.'s GWELLS database has the capability to store electronic files, including data from pumping tests. Storing pumping test data in GWELLS would allow the data to be securely stored and also made more widely accessible.

<u>Recommendation 5:</u> The pumping test data from this study and those from the compendia by Carmichael (2013, 2014) and Carmichael et al. (2009a) and Carmichael et al. (2009b) and any pumping test data made available to the Province of B.C. should be uploaded to the corresponding well records in GWELLS so that the data can be properly stored and made readily accessible.

5. <u>CLOSING REMARK</u>

Pumping tests are conducted to answer questions about the capacity of the well for long-term supply, to ascertain aquifer hydraulic properties and to help identify the potential long-term impacts from pumping. The extended drawdown method is not meant to reduce the duration of the pumping portion of the test, but to enhance the interpretation of data recorded during and after pumping. It can not only help extrapolate drawdown behaviour with more confidence but also serve as a check of the typical assumptions related to interpretation of the data. Where assumptions of test conditions (e.g., stable static water level) or principle of superposition are not satisfied, that does not automatically render a test worthless or require a test to be re-done; those ramifications must be considered within the specific context and weighed against the overall risks and benefits of the proposed water use.

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APPENDIX A. HOW TO USE THE EXCEL SPREADSHEET

Extended Drawdown Template.xlsx

The spreadsheet template is a Microsoft (MS) Excel file with five tabs, as can be seen in Figure A-1 (included as separate attachment and as a link). The first tab, “Pumped Well Info,” contains information on the pumping well, pumping test, and aquifer. The second tab, “Summary Plots,” contains general information about the pumping and observation wells, and Water Level vs Time and Extended Drawdown vs log Time plots for each well. The third tab, “Pumped Well Data,” contains a layout for pumping test data and automated plots. The fourth tab, “Obs Well Info,” contains information on the observation well and pumping test. The fifth tab, “Obs Well Data,” contains a layout for pumping test data and automated plots. The fourth and fifth tabs can be duplicated if there is more than one observation well for a pumping test.

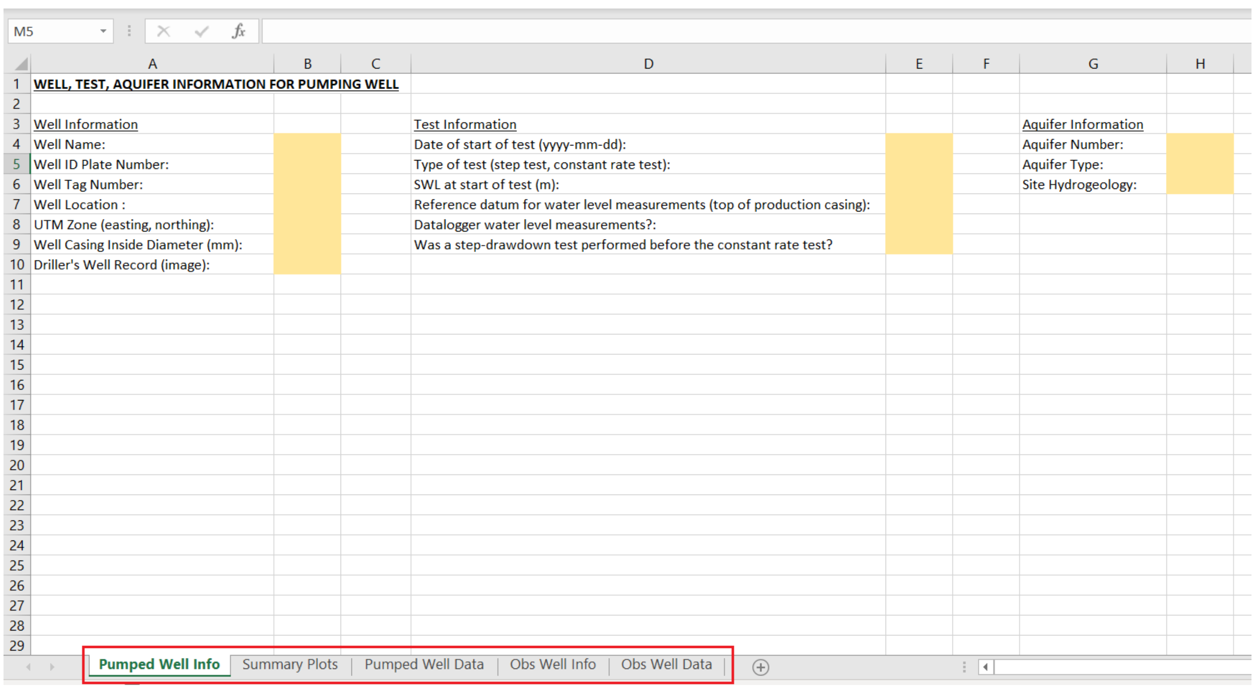
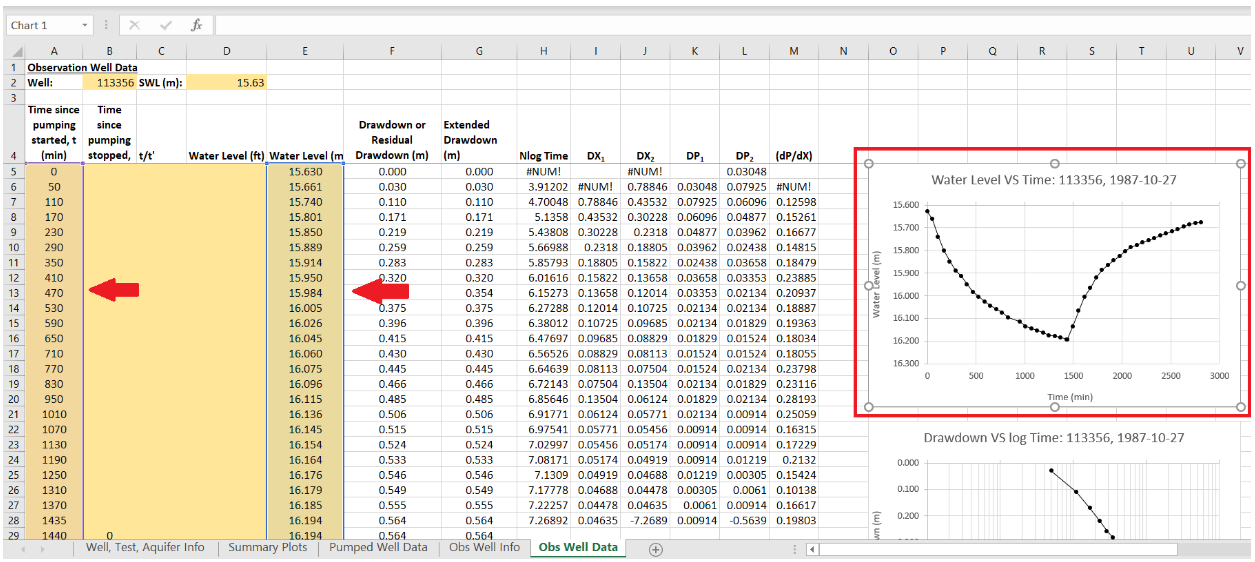


Figure A-1. The five tabs are found at the bottom of the spreadsheet and are outlined here in red.

Cells or columns where the user must enter information or data are highlighted in beige. Cells and columns that are left white contain calculated values, such as the columns in the “Pumped Well Data” and “Obs Well Data” tabs for Drawdown, Extended Drawdown, and the Derivative calculations. Depending on the data collected for a test, the data in some beige columns, such as t/t’ or Water Level in metres or feet, may also be calculated.

The Derivative calculations are performed in columns H through M in Figure A-2. The components of this calculation (in columns H through L) include the natural log of Time, differences between the ln(Time) values, and differences between the corresponding drawdown values. The final derivative, dP/dX (in column M), is calculated using these values. This method was adapted from Allen (1999) and Spane and Wurstner (1993).



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Observation Well Data												
2	Well:	113356	SWL (m):	15.63									
3													
4	Time since pumping started, t (min)	Time since pumping stopped,	t/t'	Water Level (ft)	Water Level (m	Drawdown or Residual Drawdown (m)	Extended Drawdown (m)	Nlog Time	DX_1	DX_2	DP_1	DP_2	(dP/dX)
5	0				15.630	0.000	0.000	#NUM!		#NUM!		0.03048	
6	50				15.661	0.030	0.030	3.91202	#NUM!	0.78846	0.03048	0.07925	#NUM!
7	110				15.740	0.110	0.110	4.70048	0.78846	0.43532	0.07925	0.06096	0.12598
8	170				15.801	0.171	0.171	5.1358	0.43532	0.30228	0.06096	0.04877	0.15261
9	230				15.850	0.219	0.219	5.43808	0.30228	0.2318	0.04877	0.03962	0.16677
10	290				15.889	0.259	0.259	5.66988	0.2318	0.18805	0.03962	0.02438	0.14815
11	350				15.914	0.283	0.283	5.85793	0.18805	0.15822	0.02438	0.03658	0.18479
12	410				15.950	0.320	0.320	6.01616	0.15822	0.13658	0.03658	0.03353	0.23885
13	470				15.984		0.354	6.15273	0.13658	0.12014	0.03353	0.02134	0.20937
14	530				16.005	0.375	0.375	6.27288	0.12014	0.10725	0.02134	0.02134	0.18887
15	590				16.026	0.396	0.396	6.38012	0.10725	0.09685	0.02134	0.01829	0.19363
16	650				16.045	0.415	0.415	6.47697	0.09685	0.08829	0.01829	0.01524	0.18034
17	710				16.060	0.430	0.430	6.56526	0.08829	0.08113	0.01524	0.01524	0.18055
18	770				16.075	0.445	0.445	6.64639	0.08113	0.07504	0.01524	0.02134	0.23798
19	830				16.096	0.466	0.466	6.72143	0.07504	0.13504	0.02134	0.01829	0.23116
20	950				16.115	0.485	0.485	6.85646	0.13504	0.06124	0.01829	0.02134	0.28193
21	1010				16.136	0.506	0.506	6.91771	0.06124	0.05771	0.02134	0.00914	0.25059
22	1070				16.145	0.515	0.515	6.97541	0.05771	0.05456	0.00914	0.00914	0.16315
23	1130				16.154	0.524	0.524	7.02997	0.05456	0.05174	0.00914	0.00914	0.17229
24	1190				16.164	0.533	0.533	7.08171	0.05174	0.04919	0.00914	0.01219	0.2132
25	1250				16.176	0.546	0.546	7.1309	0.04919	0.04688	0.01219	0.00305	0.15424
26	1310				16.179	0.549	0.549	7.17778	0.04688	0.04478	0.00305	0.0061	0.10138
27	1370				16.185	0.555	0.555	7.22257	0.04478	0.04635	0.0061	0.00914	0.16617
28	1435				16.194	0.564	0.564	7.26892	0.04635	-7.2689	0.00914	-0.5639	0.19803
29	1440	0			16.194	0.564	0.564						

Figure A-2. The selected plot is outlined in red. Once a plot is selected, the X and Y values (next to the red arrows) become highlighted in purple and blue. They can be dragged from the corner to adjust the range to include the data required for the plot. The derivative calculation is performed in column M, using the data in columns H through L.

The plots in each tab, positioned to the right of the data, will plot datasets automatically once data has been entered into a column. In the template, the plots have been set up to use the data in rows 5-52 as the duration of the pumping phase and rows 53-100 as the recovery period. These ranges can be edited by clicking on a plot and then dragging the highlighted ranges to contain the required value, as can be seen in Figure A-2, or by right clicking on the plot and choosing “Select Data” from the drop-down menu.

Extended drawdown can be calculated by superimposing the residual drawdown after pumping has stopped on the drawdown during pumping. To perform this calculation in the spreadsheet, sum the residual drawdown at a given time since pumping stopped (t’) and the drawdown at the equivalent time since pumping started (t) and in the Extended Drawdown column, as show in Figure A-3. The Extended Drawdown column should contain the same drawdown values as the Drawdown or Residual Drawdown for the pumping phase of the test.

If the pumping phase was shorter than the length of time the recovery phase was recorded for (t/t’ < 2), the drawdown value at a given t should be selected from the Extended Drawdown column for the calculation. This ensures that when t/t’ < 2 the residual drawdown at a given t’ is superimposed over the extended drawdown rather than the residual drawdown.

CODE =I77+J21

	A	B	C	D	E	F	G	H	I	J	K
1	Pumped Well Data										
2	Well:	63166	SWL (m):	1.570		Average Pumping Rate (m3/day):			5.041		
3											
4	Time since pumping started, t (min)	Time since pumping stopped, t' (min)	t/t'	Pumping rate, Q (USgpm)	Pumping rate, Q (L/s)	Pumping Rate, Q (m3/day)	Water Level (ft)	Water Level (m)	Drawdown or Residual Drawdown (m)	Extended Drawdown (m)	Nlog Time
12	6						14.200	4.328	2.758	2.758	1.792
13	7						14.500	4.420	2.850	2.850	1.946
14	8						14.800	4.511	2.941	2.941	2.079
15	9						15.150	4.618	3.048	3.048	2.197
16	10						15.450	4.709	3.139	3.139	2.303
17	12						16.000	4.877	3.307	3.307	2.485
18	14						16.500	5.029	3.459	3.459	2.639
19	16						17.000	5.182	3.612	3.612	2.773
20	18						17.550	5.349	3.780	3.780	2.890
21	20						18.500	5.639	4.069	4.069	2.996
22	25						19.900	6.066	4.496	4.496	3.219
23	30						21.600	6.584	5.014	5.014	3.401
24	35						22.850	6.965	5.395	5.395	3.555
25	40						24.200	7.376	5.806	5.806	3.689
⋮	⋮						⋮	⋮	⋮	⋮	⋮
73	4012	12	334.333				83.100	25.329	23.759	27.066	
74	4014	14	286.714				82.100	25.024	23.454	26.914	
75	4016	16	251.000				81.100	24.719	23.150	26.761	
76	4018	18	223.222				80.150	24.430	22.860	26.640	
77	4020	20	201.000				79.200	24.140	22.570	=I77+J21	
78	4025	25	161.000				76.750	23.393	21.824	26.319	
79	4030	30	134.333				74.450	22.692	21.123	26.137	
80	4040	40	101.000				70.000	21.336	19.766	25.573	
81	4050	50	81.000				65.500	19.964	18.395	25.390	
82	4060	60	67.667				61.100	18.623	17.054	24.902	
83	4070	70	58.143				56.950	17.358	15.789	24.341	
84	4080	80	51.000				53.050	16.170	14.600	23.774	
85	4090	90	45.444				49.700	15.149	13.579	23.317	

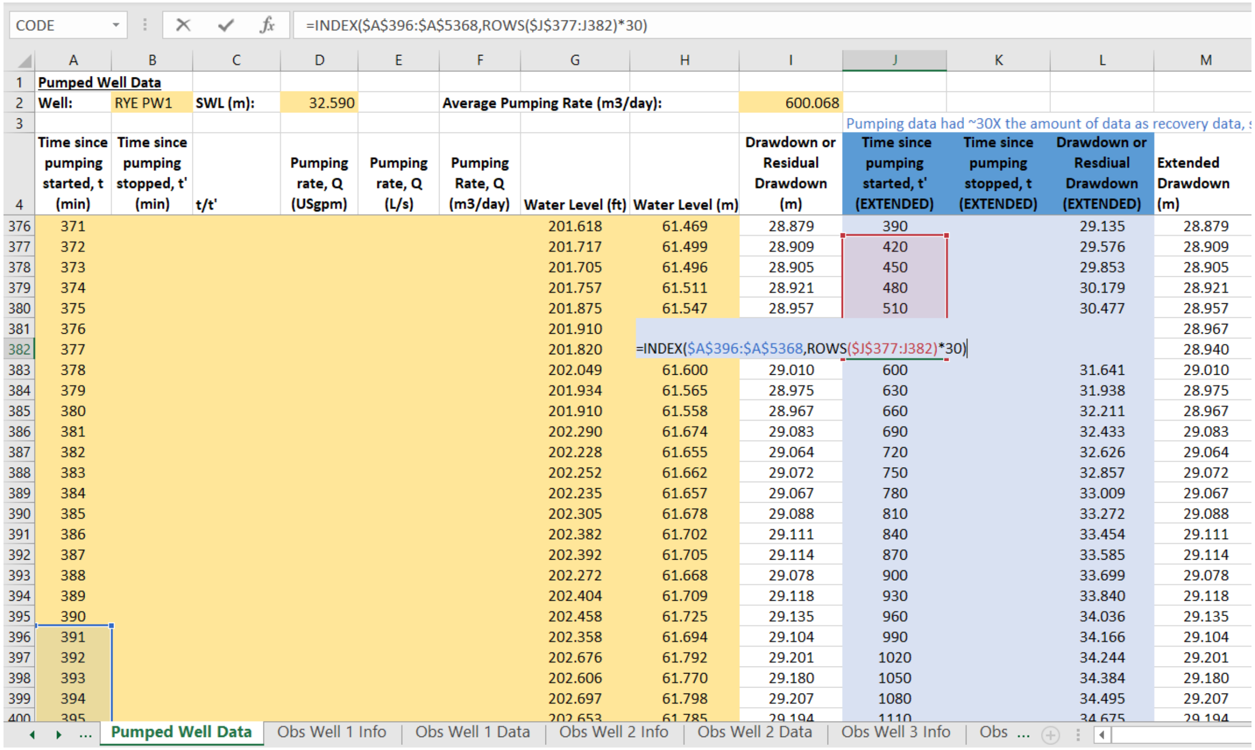
Figure A-3. The "Extended Drawdown" column (J) contains the same values as the "Drawdown or Residual Drawdown" column (I) during the pumping phase, shown here in rows 12-25. During the recovery phase, extended drawdown is calculated by adding the residual drawdown at a given t' with the drawdown when t = t'. In this example, the residual drawdown at t' = 20 is added with the drawdown when t = 20.

For some pumping tests with datalogger data there may be several times more data during one phase of the test than the other. In such cases the phase with more data can be condensed to match the less frequent intervals at which data was recorded in the phase with less data, using the INDEX function in Excel:

> =INDEX([range which values will be selected from], ROWS([range from first cell using INDEX function to current cell])*[interval at which values should be selected from])

An example of this function in use can be seen in Figure A-4.

If there is more recovery data than pumping data, this technique can be used to condense the range of times in the recovery data at which extended drawdown is calculated. If there is more pumping data than recovery data, this technique can be used to condense the pumping data used to calculate the extended drawdown.



CODE =INDEX($A$396:$A$5368,ROWS($J$377:J382)*30)

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	Pumped Well Data												
2	Well:	RYE PW1	SWL (m):	32.590		Average Pumping Rate (m3/day):			600.068				
3										Pumping data had ~30X the amount of data as recovery data,			
4	Time since pumping started, t (min)	Time since pumping stopped, t' (min)	t/t'	Pumping rate, Q (USgpm)	Pumping rate, Q (L/s)	Pumping Rate, Q (m3/day)	Water Level (ft)	Water Level (m)	Drawdown or Residual Drawdown (m)	Time since pumping started, t' (EXTENDED)	Time since pumping stopped, t (EXTENDED)	Drawdown or Resdiual Drawdown (EXTENDED)	Extended Drawdown (m)
376	371						201.618	61.469	28.879	390		29.135	28.879
377	372						201.717	61.499	28.909	420		29.576	28.909
378	373						201.705	61.496	28.905	450		29.853	28.905
379	374						201.757	61.511	28.921	480		30.179	28.921
380	375						201.875	61.547	28.957	510		30.477	28.957
381	376						201.910						28.967
382	377						201.820	=INDEX($A$396:$A$5368,ROWS($J$377:J382)*30)					28.940
383	378						202.049	61.600	29.010	600		31.641	29.010
384	379						201.934	61.565	28.975	630		31.938	28.975
385	380						201.910	61.558	28.967	660		32.211	28.967
386	381						202.290	61.674	29.083	690		32.433	29.083
387	382						202.228	61.655	29.064	720		32.626	29.064
388	383						202.252	61.662	29.072	750		32.857	29.072
389	384						202.235	61.657	29.067	780		33.009	29.067
390	385						202.305	61.678	29.088	810		33.272	29.088
391	386						202.382	61.702	29.111	840		33.454	29.111
392	387						202.392	61.705	29.114	870		33.585	29.114
393	388						202.272	61.668	29.078	900		33.699	29.078
394	389						202.404	61.709	29.118	930		33.840	29.118
395	390						202.458	61.725	29.135	960		34.036	29.135
396	391						202.358	61.694	29.104	990		34.166	29.104
397	392						202.676	61.792	29.201	1020		34.244	29.201
398	393						202.606	61.770	29.180	1050		34.384	29.180
399	394						202.697	61.798	29.207	1080		34.495	29.207
400	395						202.653	61.785	29.194	1110		34.675	29.194

Pumped Well Data | Obs Well 1 Info | Obs Well 1 Data | Obs Well 2 Info | Obs Well 2 Data | Obs Well 3 Info | Obs ...

Figure A-4. In this example, data was collected at much more frequent intervals during the pumping phase than the recovery phase. The INDEX function is used to condense the pumping phase data to match the intervals at which data was collected during the recovery phase. The INDEX function requires setting the range of data to draw from (highlighted in blue here), the interval at which data is taken at (30 here), and the number of data points collected using the INDEX function (highlighted in red here, using the ROWS function).

When a t' value does not have an equivalent t value, linear interpolation between the two nearest t values can be used to calculate the drawdown required for the extended drawdown. If there are only a few cases in the dataset where linear interpolation is needed, they can be calculated manually. If a more systematic approach is needed to calculate the drawdown using linear interpolation, a set of functions can be coded and employed with the following steps:

- Ensure that the file is saved as a "macro-enabled worksheet." The file type should be .xlsm.
- The next steps can be seen in Figure A-5. Click on the "Developer" tab in the ribbon at the top of the Excel window. If the Developer tab is not available in the Ribbon-bar select File, Options and from the Customize Ribbon check the Developer box.

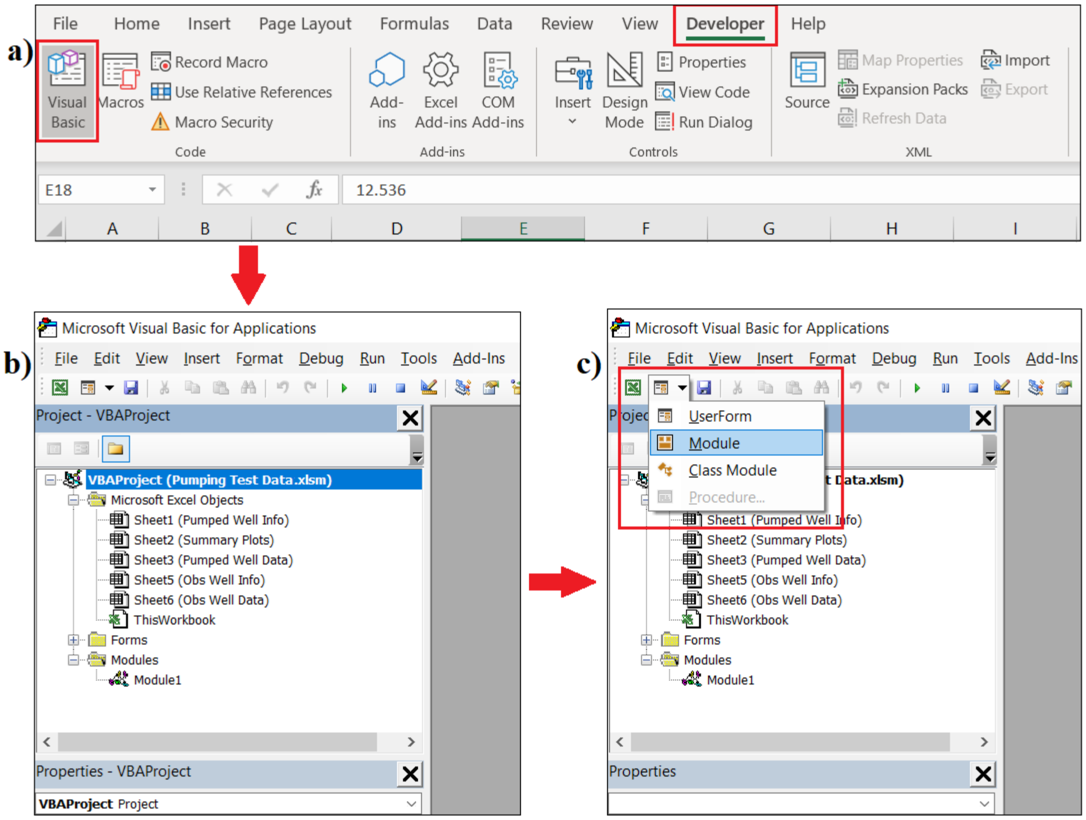


Figure A-5. To code the FindFirstLower and FindFirstHigher functions a) open the Developer tab and select Visual Basic, which will open the Visual Basic window, b) click on the title of your file in the Project window to select it (highlighted in blue), c) open the Insert UserForm dropdown menu and select Module. This will create a module for the file and open a module window, where the code for the two functions can be entered.

- Click on "Visual Basic" in the upper left corner, which will open a new window.
- Select the current file (VBAProject) in the "Project" window on the left.
- Open the dropdown "Insert UserForm" and select "Module." A module window should appear, and can be accessed being closed by clicking on the Module in the "Project" window. Insert the following text into the module window and then save the module:

```
Function FindFirstHigher(target As Double, range As range) As range
  Dim found As Boolean
  found = False
  For Each cell In range
    If cell.Value >= target And found = False Then
      Set FindFirstHigher = cell
      found = True
    End If
  Next cell
End Function
Function FindFirstLower(target As Double, rng As range) As range
  Dim found As Boolean
  found = False
```

```
    Dim prev As range
    For Each cell In rng
      If cell.Value > target And found = False Then
        Set FindFirstLower = prev
        found = True
      Else
        Set prev = cell
      End If
    Next cell
  End Function
```

This code creates two new functions, FindFirstLower and FindFirstHigher, which will be used to simplify the linear interpolation calculations. These functions were developed by Robert Tulip.

- Returning to the main Excel spreadsheet, insert four new columns between the "Drawdown or Residual Drawdown" and "Extended Drawdown" columns. The first column will contain the closest t value below a given t' value for the lower end of the linear interpolation, using the FindFirstLower function:

  =FindFirstLower([selected t' value], [range of all t values])

  The second column will contain the closest t value above a given t' value for the upper end of the linear interpolation, using the FindFirstHigher function:

  =FindFirstHigher([selected t' value], [range of all t values])

  The third and fourth columns will contain the corresponding drawdown values to the lower t and upper t values respectively, using the LOOKUP function:

  =LOOKUP([t value], [range of all t values], [range of all drawdown and extended drawdown values])

  Examples of these functions can be seen in Figure A-6.

a)

CODE | =FindFirstLower(B65,$A$5:$A$69)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Pumped Well Data													
2	Well:	59365	SWL (m):	4.66		Average Pumping Rate (m3/day):			294.6					
3														
4	Time since pumping started, t (min)	Time since pumping stopped, t' (min)	t/t'	Pumping rate, Q (USgpm)	Pumping rate, Q (L/s)	Pumping Rate, Q (m3/day)	Water Level (ft)	Water Level (m)	Drawdown or Residual Drawdown (m)	Linear interpolation, time1	Linear interpolation, time3	Linear interpolation, drawdown1	Linear interpolation, drawdown3	Extended Drawdown (m)
50	1448	8	181.000				16.371	4.990	0.330	7	9	1.110	1.140	1.455
51	1449	9	161.000				16.306	4.970	0.310					1.450
52	1450	10	145.000				16.273	4.960	0.300	9	12	1.140	1.190	1.457
53	1455	15	97.000				16.109	4.910	0.250	12	16	1.190	1.210	1.455
54	1460	20	73.000				16.076	4.900	0.240					1.470
55	1465	25	58.600				15.978	4.870	0.210					1.450
56	1470	30	49.000				15.945	4.860	0.200	25	35	1.240	1.265	1.453
57	1480	40	37.000				15.912	4.850	0.190					1.465
58	1490	50	29.800				15.879	4.840	0.180					1.465
59	1500	60	25.000				15.846	4.830	0.170					1.465
60	1515	75	20.200				15.846	4.830	0.170	70	80	1.300	1.310	1.475
61	1530	90	17.000				15.846	4.830	0.170					1.490
62	1545	105	14.714				15.781	4.810	0.150	100	120	1.325	1.335	1.478
63	1560	120	13.000				15.584	4.750	0.090					1.425
64	1590	150	10.600				15.551	4.740	0.080	140	160	1.345	1.365	1.435
65	1690	250	6.760				15.518	4.730		=FindFirstLower(B65,$A$5:$A$69)		1.405	1.420	1.480
66	1745	305	5.721				15.387	4.690	0.030	300	330	1.430	1.450	1.463
67	2005	565	3.549				15.322	4.670	0.010	540	600	1.525	1.540	1.541
68	2665	1225	2.176				15.289	4.660	0.000	890	1260	1.590	1.700	1.690
69	2790	1350	2.067				15.092	4.600	-0.060	1260	1440	1.700	1.730	1.655
70														

b)

CODE | =LOOKUP(J65,$A$5:$A$69,$N$5:$N$69)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Pumped Well Data													
2	Well:	59365	SWL (m):	4.66		Average Pumping Rate (m3/day):			294.6					
3														
4	Time since pumping started, t (min)	Time since pumping stopped, t' (min)	t/t'	Pumping rate, Q (USgpm)	Pumping rate, Q (L/s)	Pumping Rate, Q (m3/day)	Water Level (ft)	Water Level (m)	Drawdown or Residual Drawdown (m)	Linear interpolation, time1	Linear interpolation, time3	Linear interpolation, drawdown1	Linear interpolation, drawdown3	Extended Drawdown (m)
50	1448	8	181.000				16.371	4.990	0.330	7	9	1.110	1.140	1.455
51	1449	9	161.000				16.306	4.970	0.310					1.450
52	1450	10	145.000				16.273	4.960	0.300	9	12	1.140	1.190	1.457
53	1455	15	97.000				16.109	4.910	0.250	12	16	1.190	1.210	1.455
54	1460	20	73.000				16.076	4.900	0.240					1.470
55	1465	25	58.600				15.978	4.870	0.210					1.450
56	1470	30	49.000				15.945	4.860	0.200	25	35	1.240	1.265	1.453
57	1480	40	37.000				15.912	4.850	0.190					1.465
58	1490	50	29.800				15.879	4.840	0.180					1.465
59	1500	60	25.000				15.846	4.830	0.170					1.465
60	1515	75	20.200				15.846	4.830	0.170	70	80	1.300	1.310	1.475
61	1530	90	17.000				15.846	4.830	0.170					1.490
62	1545	105	14.714				15.781	4.810	0.150	100	120	1.325	1.335	1.478
63	1560	120	13.000				15.584	4.750	0.090					1.425
64	1590	150	10.600				15.551	4.740	0.080	140	160	1.345	1.365	1.435
65	1690	250	6.760				15.518	4.730	0.070	240		=LOOKUP(J65,$A$5:$A$69,$N$5:$N$69)		1.480
66	1745	305	5.721				15.387	4.690	0.030	300	330	1.430	1.450	1.463
67	2005	565	3.549				15.322	4.670	0.010	540	600	1.525	1.540	1.541
68	2665	1225	2.176				15.289	4.660	0.000	890	1260	1.590	1.700	1.690
69	2790	1350	2.067				15.092	4.600	-0.060	1260	1440	1.700	1.730	1.655
70														

Figure A-6. a) The FindFirstLower function in column J requires the chosen t' value (highlighted in blue) and the entire range of t values in the test (highlighted in red). The FindFirstHigher function in column K has the same requirements. b) The LOOKUP function in column L requires the value found by the FindFirstLower function in column J (highlighted in blue), the entire range t values (highlighted in red), and the range of drawdown and extended drawdown values in column N (highlighted in purple). The LOOKUP function in column M has nearly the same requirements, replacing the FindFirstLower value in column J with the value found by the FindFirstHigher function in column K.

In the Extended Drawdown column, calculate the linear interpolation using values selected by the FindFirstLower, FindFirstHigher, and LOOKUP functions, and add the residual drawdown value for the given t' as shown in Figure A-7. These calculations can be dragged down to be applied to the remaining rows.

CODE | =L69+(((M69-L69)*(B69-J69))/(K69-J69))+I69

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Pumped Well Data														
2	Well:	113356	SWL (m):	14.98092		Average Pumping Rate (m3/day):			623.047						
3															
4	Time since pumping started, t (min)	Time since pumping stopped, t' (min)	t/t'	Pumping rate, Q (USgpm)	Pumping rate, Q (L/s)	Pumping Rate, Q (m3/day)	Water Level (ft)	Water Level (m)	Drawdown or Residual Drawdown (m)	Linear interpolation, t1	Linear interpolation, t3	Linear interpolation, drawdown1	Linear interpolation, drawdown 3	Extended Drawdown (m)	Nlog Time
58	1480	40	37.000				101.960	31.077	16.096					31.595	
59	1485	45	33.000				101.270	30.867	15.886					31.638	
60	1490	50	29.800				100.690	30.690	15.709					31.912	
61	1500	60	25.000				99.710	30.392	15.411					32.275	
62	1510	70	21.571				98.790	30.111	15.130					32.650	
63	1520	80	19.000				97.980	29.864	14.883					32.839	
64	1530	90	17.000				97.040	29.578	14.597					33.132	
65	1540	100	15.400				96.460	29.401	14.420					33.183	
66	1565	125	12.520				94.580	28.828	13.847					33.817	
67	1595	155	10.290				93.080	28.371	13.390	150	175	20.745	21.482	34.282	
68	1673.5	233.5	7.167				89.270	27.209	12.228	200	250	22.110	23.226	35.086	
69	1720	280	6.143				87.330	26.618	11.637	250	300	23.226		=L69+(((M69-L69)*(B69-J69))/(K69-J69))+I69	
70	1760	320	5.500				85.880	26.176	11.195	300	350	24.033	24.847	35.554	
71	1780	340	5.235				84.880	25.871	10.890	300	350	24.033	24.847	35.575	
72	1840	400	4.600				83.330	25.399	10.418					35.738	
73	2780	1340	2.075				64.810	19.754	4.773	1300	1400	28.002	28.160	32.838	
74	2793	1353	2.064				64.540	19.672	4.691	1300	1400	28.002	28.160	32.777	
75	3360	1920	1.750				60.060	18.306	3.325	1840	2780	35.738	32.838	38.816	
76	4193	2753	1.523				56.650	17.267	2.286	1840	2780	35.738	32.838	35.208	
77	4288	2848	1.506				56.410	17.194	2.213	2793	3360	32.777	38.816	35.575	
78	4575	3135	1.459				55.870	17.029	2.048	2793	3360	32.777	38.816	38.468	
79	5670	4230	1.340				54.040	16.471	1.490	4193	4288	35.208	35.575	36.841	

Pumped Well Info | Summary Plots | Pumped Well Data | Obs Well Info | Obs Well Data

Figure A-7. The extended drawdown is calculated using linear interpolation to find the drawdown at t when t = t' and the residual drawdown for a given t'. Linear interpolation of the drawdown is calculated using the data in columns J through M and the corresponding t' value. In the same cell, this interpolated drawdown value is summed with the residual drawdown (highlighted in orange) to calculate extended drawdown.

Note: If the recovery phase was recorded for longer than the pumping phase and data was recorded with increasingly longer intervals in between measurements, it is possible that the linear interpolation calculation will become circular and will not work. An example of this can be seen in Figure A-8, where the t' value corresponds with the t value at the upper end of the linear interpolation. In addition to the possibility of circular calculations, linear interpolation will yield less accurate results where there are large gaps between data points and depending on the quality of data.

Others are welcome to use the spreadsheet template, but should do so using their own caution and judgement, as it was developed solely for this study.

A80 | 8637

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Pumped Well Data													
2	Well:	113356	SWL (m):	14.98092		Average Pumping Rate (m3/day):			623.047					
3														
4	Time since pumping started, t (min)	Time since pumping stopped, t' (min)	t/t'	Pumping rate, Q (USgpm)	Pumping rate, Q (L/s)	Pumping Rate, Q (m3/day)	Water Level (ft)	Water Level (m)	Drawdown or Residual Drawdown (m)	Linear interpolation, t1	Linear interpolation, t3	Linear interpolation, drawdown1	Linear interpolation, drawdown 3	Extended Drawdown (m)
73	2780	1340	2.075				64.810	19.754	4.773	1300	1400	28.002	28.160	32.838
74	2793	1353	2.064				64.540	19.672	4.691	1300	1400	28.002	28.160	32.777
75	3360	1920	1.750				60.060	18.306	3.325	1840	2780	35.738	32.838	38.816
76	4193	2753	1.523				56.650	17.267	2.286	1840	2780	35.738	32.838	35.208
77	4288	2848	1.506				56.410	17.194	2.213	2793	3360	32.777	38.816	35.575
78	4575	3135	1.459				55.870	17.029	2.048	2793	3360	32.777	38.816	38.468
79	5670	4230	1.340				54.040	16.471	1.490	4193	4288	35.208	35.575	36.841
80	8637	7197	1.200				51.910	15.822	0.841	5670	8637	36.841	0.000	0.000
81	10107	8667	1.166				51.610	15.731	0.750	8637	10107	4.771	32.838	5.439

Figure A-8. Here is an example where linear interpolation becomes self-referential and fails. The t' value outlined in red does not have a corresponding t value and requires linear interpolation. However, the closest greater t value is in the same row as the t' value and has not been calculated yet, making the linear interpolation impossible, as well as disrupting the linear interpolation in the subsequent line.

APPENDIX B. PUMPING TESTS AND INTERPRETATION OF EXTENDED DRAWDOWNS

Appendix B contains write-ups for each pumping test examined in this study. Each write-up includes:

- A brief description of the aquifer geology,
- Brief description of the pumped well (and any observation well(s) used in the analysis),
- Summary of the pumping test, and
- Interpretation of the application of the extended drawdown method.

Included with each write-up is a link to the Excel file containing the data and standard plots, including a tab of summary plots.

Armstrong, WTN 63166

Aquifer geology: Well (WTN 63166) indicates that this well is drilled into fractured granitic bedrock of varying composition from 3 m to 211 m depth. Brown clay, rock and weathered granite occur from 0 m to 3 m depth. The well is located at the base of a northwest-facing rocky slope.

Pumped well and any observation well(s) summary: The well is cased to 3 m depth with 152 mm (6-inch) diameter steel casing and is a 152 mm (6-inch) open hole below that. The static water level was 1.57 m below top of casing (btoc) at the start of the test on February 3, 1996. The well record does not report location and flow of any discrete water-bearing fractures.

Pumping test summary: Well WTN 63166 was pumped at a reported constant rate of 5.0 m^3/day for 4000 minutes, followed by 1270 minutes of recovery (t/t'=4.2). The drawdown at the end of the pumping phase was 25.5 m. The initial drawdown of about 2 m after just 1 minute of pumping is not possible at the pumping rate of 5 m^3/day and is probably caused by the well either being pumped or bailed some time before the start of this test. Drawdown in the first 500 minutes of pumping reflects wellbore storage. Aquifer response is seen after about 500 minutes of pumping, and after 500 minutes of recovery.

The rise of the water level during the last 1000 minutes of pumping may be due to a rain or snowmelt event which would tend to infiltrate water to shallow fractures and increase flow out of such fractures (it was early February).

Interpretation: The complex response of the water level in the pumped well to pumping prevents any straightforward interpretation of the response of the well-fracture system to pumping. The long-duration upward anomaly of the extended drawdown indicates that the recovery was faster than the initial drawdown, possibly reflecting recharge to fractures as suggested by the water-level rise during the last 1000 minutes of pumping.

This appears to be the kind of water supply well that relies on storage of water in the well bore to provide water for short bursts of pumping. The well then slowly fills again.

63166, Armstrong, 1996-02-03.xlsx

Cowichan Lake, WTN 90027

Aquifer geology: Well WTN 90027 is completed into sand and gravel at 28.3 m to 31.7 m (93 feet - 104 feet). The aquifer is overlain by clay and glacial till.

The aquifer is likely in hydraulic connection with Cowichan Lake (~65 m away) and the tributary creek (~95 m away). The probable direction of flow is southwest towards Cowichan Lake. Recharge likely occurs from infiltration of runoff from precipitation, but also from infiltration of water from the tributary creek. Pumping could also induce infiltration from the creek and Cowichan Lake.

Pumped well and any observation well(s) summary: The well is screened from 28.7 m – 31.4 m below ground level (bgl) (94 feet – 103 feet). The casing is 152 mm (6-inch) in diameter.

Pumping test summary: The well was pumped at a reported constant rate of 196 m^3/day for 1440 minutes. Recovery was measured for 1080 minutes (t/t'=2.2) although only one measurement was recorded after 180 minutes after pumping stopped. The static water level was 5.68 m btoc. Drawdown stabilized at 15.25 m after about 700 minutes of pumping to the end of the pumping phase. Borehole storage was evident for the first hour of pumping. The residual drawdown was 0.14 m at the end of the recovery phase.

Interpretation: The extended drawdown is consistent with the stabilization of the drawdown after about 700 minutes during the pumping phase. The short-term "spikes" of the extended drawdown, lasting for about 10 minutes after pumping stopped (see 3.1.4 for a discussion of the "spike") are likely the result of small errors in the data at the start and end of pumping.

The well-bore storage effects (evident in the first 100 minutes of the pumping phase) do not have an effect on the extended drawdown.

90027, Cowichan Lake, 2003-11-05.xlsx

Fernie, WTN 59365

Aquifer geology: Well WTN 59365 is completed into a confined floodplain sand and gravel aquifer beside the Elk River. Gravel and fine sand are encountered from 5.5 m to 8.5 m (18 feet to 28 feet). Silty clay with sand lenses overlies the aquifer. At least 4 m of clay till underlies the aquifer. The static level is at 4.66 m bgl, less than 1 m above the top of the aquifer. The pumped well is located about 90 m from the Elk River.

Pumped well and any observation well(s) summary: The well casing is 254 mm (10 inches) in diameter. The length of casing is not specified but can be assumed to be to the top of the screen. The screen extends from 5.5 m to 8.5 m depth.

Pumping test summary: The well was pumped for one day with one day of recovery measurements (t/t'=2.1). Pumping rate was reported to be a constant rate of 295 m^3/day. The static water level was 4.66 m. Borehole storage was evident for the first 20 minutes of pumping. The water level at end of pumping was at 6.4 m or 21 feet, about 1 m below the top of the aquifer at the pumped well. The last recovery measurement has water level 0.06 m above static, so the last two data points of recovery should not be used to calculate extended drawdown.

Interpretation: The upward shift of the extended drawdown may have been the result of changing "static" water level as indicated by the rise of the water level above the initial static at the end of the recovery phase. The small drawdown together with the changing ambient level, plus possible dewatering makes recovery hard to interpret. However, this also applies to interpretation of the drawdown during the pumping phase, which is likely affected by changes of the "static" water level.

59365, Fernie, 1990-06-28.xlsm

Golden, WTN 78362

Aquifer geology: The pumped and observation wells are drilled into fractured sedimentary (slate, calcareous slate, limestone) bedrock. The site is located at an elevation of ~1350 m above sea level on a NE-facing ski slope. At the well site the clay overburden is 1.8 m thick. Several water-bearing fractures were encountered between 54.3, 70.1 and 77.1 m depth. The observation well encountered water-bearing fractures at 22.6 to 33.5 m and 54.8 to 57.3 m depth bgl.

Pumped well and any observation well(s) summary: The pumped well (WTN 78362) was drilled to 80.77 m. It is lined with 6-inch PVC casing, perforated from 53.34 m to the bottom of the hole at 80.77 m.

The observation well is 50 m from the pumped well and is lined with 8-inch PVC, perforated from 42.2 m to the bottom of the hole at 65.5 m.

Pumping test summary: The well was pumped at 473 m^3/day for 4 days, starting March 7, 2000 and recovery was measured for 4 days (t/t'=2.0). The static water level in the pumped well was 23.0 m btoc, maximum drawdown was 36.72 m (56.7 m below ground level) and residual drawdown after 4 days recovery was 4.69 m. In the observation well the static water level was 26.83 m btoc, the maximum drawdown was 20.28 m (47.1 m below ground level) and residual drawdown after 4 days was 4.74 m.

The pumping water levels in both the pumped well and observation well indicate that drawdown in both wells dropped below the upper-most water bearing fractures at 54.1 m and 22.6 m depth, respectively.

Interpretation: The long-lasting downward shift of the extended drawdown means that the recovery was slower than indicated by the drawdown during the pumping phase. The most likely explanation for the slow recovery is that the upper-most water-bearing fractures were dewatered during the test and yielded little water until the water level again rose above them, to near the original static level. The shallow water-bearing fractures in the observation well were 15 to 5 m above the water level in the observation well during the pumping phase. It may also be possible that some of the deeper water-bearing fractures closed somewhat because of the large drawdown of the pore pressure and the resultant greater effective stress on the fractures.

In any case, the extended drawdown downward shift occurred at the pumped well and at the observation well, indicating that the anomalous change of the aquifer properties extended well beyond the pumped well. And the downward shift, whether caused by fractures being dewatered or closed, suggests that the water level in the well might have continued to decline at an increasing rate, as shown by an increasing slope on a plot of drawdown versus log time.

The extended drawdown plot thus draws attention in this case to the likely diminishing effective permeability of the formation as the drawdown increased (dewatering of water-bearing fractures or closing of fractures) and may help to better understand the initial slow recovery. This, in turn, suggests that the long-term well yield is probably smaller than would be surmised from just the drawdown measured during the pumping phase.

78362, Golden,
2000-03-07.xlsx

Keremeos, WTN 83151

Aquifer geology: The aquifer consists of coarse-grained sand and gravel glacial outwash within a glacial-carved, "U"-shaped bedrock valley. Reported depths to bedrock vary between 22 m and 76 m. There is no surface water flow and the valley is infilled with hummocky glacial outwash sands and gravels. The pumped well (WTN 83151) encountered sand and gravel to 29.5 m. Twin Lakes is approximately 900 m to the south of the well (Carmichael et al., 2009a)

Pumped well and any observation well(s) summary: The well is cased with 152 mm (6-inch) diameter steel casing to 18.3 m and screened from 18.3 m to 24.4 m bgl.

Pumping test summary: The well was pumped at a reported constant rate of 2160 m^3/day for 517 minutes. Drawdown reached 1.55 m btoc after 517 minutes and did not stabilize. Recovery was monitored for 877 minutes (t/t'=1.6), but the last measurement of the water level was 0.15 m above the initial static water level of 7.65 m.

Interpretation: The initial downward "spike" of the extended drawdown lasted for a few minutes (see Section 3.1.4 for a discussion of the "spike"). The late-time extended drawdown cannot be meaningfully interpreted because of the rising "static" water level. Was the original static water level at the start of the pumping phase affected by on-going recovery after prior step-drawdown testing? Or was the background level changing as a result of recovery of nearby pumping? A reliable measurement of the unaffected static water level is needed for the recovery data to be more useful.

This lack of knowledge of how the static water level is affected by the effects of prior pumping (e.g., step-test, seasonal fluctuation or after operational pumping) or nearby pumping severely limits the utility of late-time drawdown measurements during the pumping phase as well as the value of residual drawdown measurements to estimate extended drawdown.

83151, Keremeos,
1994-09-22.xlsm

Lantzville (2 wells)

There are two wells 80 m apart at this site. Both wells were tested in July 2011. The geology and pumping test for both wells are summarized together in this write-up.

Aquifer geology: At Well 1 the aquifer consists of 27.4 m of gravel, sand and silt overlying shale bedrock. At Well 2 the aquifer is similar but is reported to overlie "blue clay" (instead of bedrock) at 21 m depth. At both wells, the sand and gravel aquifer is overlain by a thin layer of silt (4.6 m at Well 1 and 2.7 m at Well 2). The permeable zones in which the wells are completed are separated by a silt layer. The static water level in both wells were within the silt layer, less than 1 m below ground.

Pumped wells and any observation wells summary: Well 1 is cased to 18.1 m, with a screen from 18.1 – 21.1 m and backfilled with pea gravel below the screen to the shale bedrock. Well 2 is cased to 12.3 m, screened from 12.3 – 15.3 m and backfilled with pea gravel below the screen.

Pumping test summary of Well 1: A 2-hour step test was done on June 28, 2011. Well 1 was pumped starting July 2, 2011 at an average constant rate of 946 m^3/day for 2 days with recovery measured for 4.5 days (t/t'=1.6). The pumping rate was lower and varied during the first few minutes of the test and steady afterwards. The static water level at the start of the test was 0.93 m btoc and the water level was at 1.00 m btoc at the end of the recovery, a small residual drawdown of 0.07 m. Drawdown at the end of the pumping phase was 13.5 m. Well 2 was used as observation well and recovery was monitored for 1 day. Water level in Well 2 was 1.35 m btoc at the start of the test and 1.44 m after 1 day of recovery: 0.09 m of residual drawdown.

Interpretation for Well 1: The "spike" was evident in the extended drawdown plot (see Section 3.1.4 for a discussion of the "spike"). After that the extended drawdown in the pumped well is consistent with the pumping phase drawdown and indicates that the drawdown would have been almost constant if pumping had continued. The drawdown in the observation well was much smaller and delayed in response.

Pumping test summary of Well 2: A 2-hour step pumping test was carried out on June 27, 2011. Well 2 was pumped for 3 days starting July 11, 2011 at an average constant pumping rate of 920 m^3/day and recovery was monitored for 3 days (t/t'=2). The pumping rate was slightly erratic at the start, then remained steady. The water level was 1.44 m at the start of the test and 1.44 m at the end of recovery.

The observation well (Well 1), was monitored for the 3 days of pumping and 3 days of recovery. The water level in the well was 1.00 m at the start of pumping and 1.02 m at the end of recovery monitoring.

Interpretation for Well 2: The extended drawdown data for the Well 2 pumping test are consistent with the test for Well 1, including the near steady-state of the extended drawdown after 3 days of recovery. The drawdown in the observation well (Well 1) was subject to what appears to be daily influences of a few centimetres but otherwise mirrors the drawdown in Well 2 during the Well 1 test, as expected from the reciprocity principle. For both tests, the extended drawdown calculated from the residual drawdown measurements, served to further the extrapolation of drawdown into the recovery phase.

The pumping test responses could be interpreted as the response of a layered aquifer consisting of highly permeable zones separated by zones of less permeable silt and fine sand, so that each permeable zone responds like a semiconfined aquifer. The drawdown approached quasi-steady state after about 2 to 3 days of pumping in each case, possibly because of the increasing effect of the drawdown cone extending to overlying or underlying permeable zones.

Lantzville, 2011-07-02.xlsm   Lantzville, 2011-07-11.xlsx

Lantzville, Well R-1

Aquifer geology: The aquifer consists of sand and gravel extending from 77.4 m bgl to about 84 m bgl and is underlain by argillite bedrock. The aquifer is overlain by grey silty sand with some layers of silty clay between 52.7 m bgl and 62.2 m bgl. The static water level as reported to be at 32.7 m btoc on July 7, 2012, in loose wet sand. Above the water table at 11.6 m bgl, the sand is reported as "dry".

Pumped well and any observation well(s) summary: The well screen extends from 78.3 m bgl to 81.1 m bgl in sand and gravel. Two observation wells were completed at similar depths into the same aquifer, at 15 m and 145 m distance from the pumped well. The observation well at 15 m distance is completed into the unconsolidated sand and gravel aquifer with an outer 203 mm diameter steel casing to about 78 m depth with an open section to just above the bedrock at 83.9 m. A deeper inner 52 mm diameter PVC casing (slotted from 85.5 m to 88.6 m depth) set into the argillite bedrock acts as a second observation well at 15 m distance to observe drawdown in the underlying bedrock. The inner PVC casing is sealed from the overlying sand and gravel aquifer by a bentonite seal.

Pumping test summary: The well was pumped at 600 m^3/day for 3 days starting July 9, followed by 15 days of recovery measurements in the pumped well and the three observation wells (t/t'=1.2). The "static" water level at the beginning of the pumping test was at 32.59 m and the water level was 32.01 at end of recovery, higher than the "static" level by 0.58 m. The drawdown in the pumped well was 40.72 m at the end of the pumping phase and drawdown was still increasing.

The consultant's hydrograph plot of all the water levels (not shown) shows that the water levels in the pumped well and three observation wells were still rising prior to the constant rate pumping test, so that true "static" level is not known and could be up to 1 m or more higher than was reported. Consequently, the true drawdown is not certain and the residual drawdown towards the end of the 15-day recovery phase may reflect this rising static water level.

Interpretation: The uncertainty about the true static water level means that the residual drawdown data in the pumped well and Observation wells 2 and 3 after about the first day of recovery may reflect the rising background water level and, therefore, is not useful in calculating the extended drawdown (data for Observation well 1 (15 m away monitoring the aquifer) show the residual drawdown at the end of the recovery phase was lower than the static water level at the start of pumping, so the extended drawdown for that well does not show an anomalous rise). Use of these data would require that the true "static" water level in the wells is known. It is not known whether a step pumping test was performed before the 3-day constant rate test and whether a true static level was reported.

The extended drawdown plots are smoothly continuous through the pumping and recovery phases, indicating the assumption of the principle of superposition is met. The anomalous rise of the extended drawdown towards the end of the recovery phase indicates the assumption that the "static" level did not change throughout the test was not satisfied, at least not for the pumped well and Observation wells 2 and 3.

The recovery during the first day or two of the recovery phase is consistent with the continuing increase of the drawdown during the pumping phase and indicates that the aquifer responded to the pumping like a highly confined aquifer with little leakage from above. The time required to reach stabilization cannot be estimated in spite of the long duration of recovery measurements because the actual starting "static" level is unknown. This case illustrates that the usefulness of an extended period of recovery measurements is dependent on the measurement of a true "static" level.

Lantzville,
2012-07-09.xlsx

Mill Bay WTN 88224

Aquifer geology: Well WTN 88224 is completed into a fractured crystalline bedrock aquifer, overlain by sand and gravel from 0 m to 18.3 m (60 feet) and clay from 18.3 m (60 feet) – 21.3 m (70 feet). Anecdotal information suggests fracture thicknesses can be significant (driller notes drill rods dropping in a nearby borehole). The main water-bearing fractures were encountered at 121 m (397 feet) and 130.8 m (429 feet).

The ambient groundwater level in this aquifer may be subject to large seasonal changes, as indicated by B.C. Observation Well #380 drilled into the same aquifer, which show annual variations of up to 15 m, from 30 to 45 m bgl, the same depth range in static water levels as those measured in well WTN 88224.

Pumped well and any observation well(s) summary: The pumped well WTN 88224 was installed April 4-11, 2007. It is cased with 203 mm (8-inch) diameter steel casing to 21.3 m (70 feet) and 203 mm (8-inch) open hole below that. The original 2007 static was reported as 34.5 m bgl (112 feet). The well was drilled to 183.5 m (602 feet) and backfilled with gravel and bentonite to 135.6 m (445 feet).

Pumping test summary: Well WTN 88224 was retested in the fall of 2017 after a season of operational pumping to quantify well performance. The well was pumped at an average constant pumping rate of 519 m^3/day for 3 days, with 3 days of recovery measurements (t/t'=2.1). The "static" water level at the start of the test was reported as 80.88 m (266 feet).

The hydrograph for well WTN 88224 and a nearby production well show the groundwater in both wells may have still been recovering from a season of operation (well WTN 88224 was taken out of operation on September 25 and the nearby production well was taken out of operation on September 29, 2017). At the time of the October 2017 test the "static" level in the well was about 45 m below the original static 34.5 m level in April 2007 when the well was first drilled. Very little rain fell at the Victoria Airport during the period of the constant rate test (only small amounts of rain fell on October 4 (2 mm), October 6 (0.5 mm) and October 9 (0.8 mm)), so it's unlikely that rain affected the static water level.

Interpretation of the water level response and extended drawdown calculations: Drawdown in well WTN 88224 did not show signs of stabilization during the pumping phase. The recovery data show that the recovery was slow and that the groundwater level prior to the pumping test was still recovering from operational pumping and perhaps also from recovery of the nearby production well (prior to its shutdown before the test). Therefore, the water level at the start of the constant rate test was likely not a true "static" level, which cannot be defined. By the end of the recovery phase the water level in the well had risen almost 6 m above the level at the beginning of the test, and clearly would have continued to rise.

The monitoring of the recovery in this case, and the upward rise of the extended drawdown in this case provides the very important message that the background "static" level was not static but changing significantly, thus it was also doing so during the pumping phase. This means that the drawdown data collected during the pumping phase should not be interpreted or analyzed with the usual assumption that the static water level is not changing during the test. In other words, a changing static water level imparts a level of uncertainty about the actual slope of the drawdown curve. This is another important reason for monitoring recovery: it gives a check on whether the background level might have changed significantly during the pumping phase.

88224, Mill Bay,
2017-10-04.xlsx

Mill Bay WTN 119110

Aquifer geology: Well WTN 119110 is completed a fractured crystalline bedrock aquifer bedrock, overlain by mostly gravel with a layer of dense till to a depth of 28.0 m (92 feet). Bedrock was encountered from 28.0 – 91.4 m (92--300 feet). The main water-bearing fracture in the well is reported at 76.8 m (252 feet).

Pumped well and any observation well(s) summary: The pumped well WTN 119110 has 254 mm (10-inch) casing installed to 28.3 m (93 feet), and 254 mm (10-inch) open hole from 28.3-91 m (93-300 feet). A 203 mm (8-inch) PVC liner was installed from 0 m to 91.4 m (300 feet). The liner is perforated from 67.1 m – 91.4 m (220 – 300 feet).

The observation well WTN 117952 was drilled to 92 m (301 ft) and has 152 mm (6-inch) diameter steel casing installed to 28 m (92 feet). Drilling encountered a water-bearing fracture zone from 81-84 m (267-275 feet). WTN 117952 is located 6.1 m from the pumped well.

The step drawdown test on the pumped well indicates about 2 or 3 m of drawdown in the well due to well losses during the pumping test.

Pumping test summary: Well WTN 119110 was pumped at a reported constant rate of 322 m^3/day for 3 days with 1.75 days of recovery (t/t'=4). Observation well WTN 117952 experienced almost the exact same drawdown as the pumped well, but 2 m less. The water levels before the pumping test started are tabulated below.

Date and time	SWL (m bgl)	Note
10/28/2019 9:30	27.48	Start of 5-hour step drawdown test
10/28/2019 15:30	30.83	After 1 hour recovery after step test
10/29/2019 12:00	29.69	Start of 72-hour pump test

The above table shows there was still (29.69 - 27.48 m) 2.21 m of residual drawdown at start of pumping test due to step drawdown test from the previous day.

Interpretation: The slow recovery suggests a finite aquifer with downward trend on slope of semilog drawdown plot. The extended drawdown corroborates this pattern of increasingly steep slope on the semilog plot and is useful in this case to inform extrapolation of the drawdown to obtain a more realistic estimate of the well's capacity. A log-log plot of the extended drawdown shows a late-time straight-line behavior with a slope of ½, such as would be expected for a strip aquifer with linear rather than radial flow to the well (Butler & Liu, 1991; van der Kamp and Maathuis, 2012).

As might be expected from the slow recovery during the constant rate pumping test, there was still 2.21 m of residual drawdown at the start of the pumping test due to the step drawdown test of the previous day. This means that by the end of the 3 days of pumping the "static" level was probably about 2 m higher than at the start of pumping and therefore the drawdown at the end of the test, and during the recovery was likely about 2 m greater than shown in the plot. This is not a large effect compared to the reported 20 m of drawdown, but it does mean that on this basis alone any estimate of the well capacity, based on extrapolation of a straight line on a semilog plot would be about 10 % higher than actual. This is another example of the importance of allowing the static to recover fully after a step drawdown test. However, this is not always feasible because pumping tests of fractured bedrock aquifers in B.C. is only limited to a specific time of year when the seasonal water level is low. In such situations, taking the remaining residual drawdown into account would be prudent in the analysis.

The drawdown in the well remained above the water-bearing fracture zone (at 76.8 m) so the aquifer was not dewatered. The extended drawdown analysis gives a useful result with no anomaly after pumping stopped such as would be expected if the aquifer is dewatered during the pumping test.

119110, Mill Bay, 2019-10-29.xlsx

Nakusp, WTNs 113356 & 53942

Note: The pumping tests for wells WTNs 113356 and 53942 are discussed together here because the same wells were used for both tests except that the roles of pumped well and observation well were reversed with the test on well WTN 113356 being carried out first.

Pumping test for WTN 113356, October 19, 1987

Aquifer geology: Well WTN 113356 is drilled into an alluvial fan complex. Based on Figure 14 of Wei's 1988 report, the alluvial sand and gravel aquifer may be confined at the site but possibly exists under water-table conditions further uphill within the alluvial fan. At well WTN 113356, the aquifer was encountered at 78 m - 86 m depth consisting of "dirty sand and gravel and till chunks" overlain by clay and till.

Well WTN 53942 is also completed into a sand and gravel aquifer confined above by clay and till. The depth of the screen (39.6 m – 45.7 m) is distinctly shallower. Hence, Wei (1988) hypothesized that even though wells WTN 113356 and WTN 53942 may be completed into the same alluvial fan complex, they may be screening different water-bearing zones (Wei, 1988; Figure 14). Inferring from topography, well WTN 53942 is located downgradient from well WTN 113356.

Pumped well and any observation well(s) summary: Well WTN 113356 was drilled and cased with a 305 mm (12-inch) steel casing to 47 m depth. Drilling continued inside the 305 mm casing with a 204 mm (8-inch) diameter steel casing to 91.4 m depth. The well was completed with a screen from 78.3 m - 86.0 m.

The observation well (WTN 53942) is screened from 39.6 m - 45.7 m in sand and gravel layer, overlain by clay and till. A deeper sand and gravel aquifer at 60.4 m to 73.2 m depth was also encountered but according to the driller, was not as productive.

Pumping test summary of well WTN 113356: The static water level in the pumped well WTN 113356 was 14.98 m at start of test, on October 19, 1987. The well was pumped at an average constant rate of 623 m^3/day for 1,440 minutes. Recovery was measured for 6 days (8667 minutes – t/t'=1.2). At the end of recovery residual drawdown was 0.75 m and the next day, October 27 it was 0.65 m at the start of the test on well WTN 53942. The static water level in observation well WTN 53942 was 12.30 m.

Interpretation: The short upward "spike" anomaly of the extended drawdown for the pumped well was evident in the first few minutes of the extended drawdown (see Section 3.1.4 for a discussion of the "spike"). The longer-term downward shift of up to 7 m shows that the recovery was slower than would be expected judging by the initial drawdown at the start of pumping. A possible reason for this shift is that successively larger portions of the aquifer, likely in the uphill portion of the aquifer, were dewatered during the pumping, resulting in the aquifer transitioning from confined to water table conditions. Such transition from confined conditions to water-table conditions, and the dewatering of the aquifer both contravene the conditions for applicability of the superposition principle (no change of hydraulic properties and no change in the aquifer's saturated thickness). The transition to water-table conditions is consistent with the slight leveling out of the drawdown curve on the semilog plot during the latter part of the pumping phase.

The slow recovery shows up in the extended drawdown as recurrent anomalies after each interval of time equal to the duration of pumping. However, the steepened overall slope of the extended drawdown is anomalous and does not represent the actual drawdown regime if pumping had continued.

The drawdown in the observation well WTN 53942 was much smaller (0.276 m) than in the pumped well and the slope of the drawdown curve on the semi-log plot is also much smaller, indicating that the sand

and gravel layer in which the observation well is completed is not directly connected to the aquifer in which the pumped well is completed.

The extended drawdown plot for the observation well exhibits a long-term downward shift which is similar to that for the pumped well drawdown. It may be that the drawdown in this separate aquifer unit is reacting to the drawdown in the main aquifer that was pumped.

Note that the extended drawdown in the observation well shows no sign of the short-term upward "spike" that is seen for the pumped well extended drawdown. That is expected because the short "spike" is interpreted as being caused by variations of the pumping rate at the start of pumping or by errors in the drawdown data at early times during the pumping and recovery phases. Irregularities in pumping would not significantly affect the far-away observation well. Also, the first recovery reading was not taken until 88 minutes after pumping stopped.

Pumping test for WTN 53942 – October 27, 1987

Pumped well and any observation well(s) summary: The pumped well (WTN 53942) is screened from 39.6 m - 45.7 m opposite a sand and gravel layer, confined above and below by till. The well has a 305 mm (12-inch) diameter steel casing.

The observation well (WTN 113356) is screened from 78.3 m - 86.0 m depth. It is 216 m distant from the pumped well.

Pumping test summary of WTN 53942: Well WTN 53942 was pumped for one day at an average constant rate of 889 m^3/day, starting October 27, 1987. Recovery was measured for one day (t/t'=2.0). The static water level was 12.16 m and the residual drawdown at the end of the recovery was 0.24 m. The first 30 minutes of drawdown were affected by well-bore storage.

The observation well static water level was 15.63 m at the start of the test, with 0.65 m of residual drawdown remaining from the pumping test of October 19-20 carried out on this well, meaning that the water level in this well was still rising slowly at about 0.05 to 0.1 m per day.

Interpretation: The small short-lived upward "spike" of the extended drawdown plot was evident in the first few minutes of the pumping and recovery phases (see 3.1.4 for a discussion of the "spike"). After that the longer-term extended drawdown indicates further continued drawdown if pumping had continued. The extended drawdown lengthened the effective duration of the pumping test from 1 day to 2 days and draws attention to the fact that the first few minutes of the pumping test data are not reliable for extended drawdown analysis.

The extended drawdown for the observation well WTN 113356 is affected by the slow rise of the static level, at about 0.05 m per day, caused by the lingering recovery effects of the pumping test carried out on this well previously. Allowing for this effect, the extended observation well drawdown is consistent with the drawdown during the pumping phase and indicated continuing drawdown if pumping had continued.

Discussion of both tests

Comparison of the two test results is informative since the tests involved reversal of the pumped and observation wells. The results of the first test on the deeper well (WTN 113152) indicate that a portion of the aquifer, likely further uphill, was under water-table conditions or transitioned from confined to water-table conditions, thereby leading to a long-term downward shift of the extended drawdown curve. The second test on the shallower well (WTN 53942) gave no indication of anomalous effects, suggesting that there was no significant dewatering of this aquifer or other change of aquifer conditions. The observed response from the pumping test of well WTN 53942 is consistent with confined aquifer conditions. It appears therefore the shallower aquifer does not connect to uphill portions of aquifer under water-table conditions, as was hypothesized in Figure 14 of Wei (1988).

For such a pair of wells with pumping and observation roles reversed the reciprocity principle would apply if the conditions for the superposition principle are met. Comparison of the observation well data for the two tests, allowing for the greater pumping rate of the second test (889 m^3/day /623 m^3/day = 1.43), shows that the drawdowns are both small as expected. However, the observation well drawdown for the first test (0.276 m x 1.43 = 0.39 m) appears to be smaller than would be expected judging by the data for the second test (0.56 m maximum drawdown). Probably the difference is related to the hypothesis that the deeper aquifer of the first test has a water-table portion that invalidates the reciprocity principle as well as the superposition principle.

113356, Nakusp, 1987-10-01.xlsm

53942, Nakusp, 1987-10-27.xlsm

Nanoose, No WTN

Aquifer geology: The pumped well is drilled into fractured meta-sedimentary and other crystalline bedrock. There is no overburden material encountered at the well site.

Pumped well and any observation well(s) summary: The well has 4.45 m of 152 mm (6-inch) diameter steel casing installed into bedrock. The remainder of the well is open hole from 4.45 m to 99 m. The main water-bearing fracture zone was encountered between 97.7 m and 99 m.

Pumping test summary: The well was tested starting on May 22, 1988 at an average constant rate of 83.4 m^3/day for 3 days. Recovery readings were measured for one day (t/t'=3.8). The static water level was 3.06 m. The nature of the drawdown is typical of fractured bedrock, showing linear flow at early times and transitioning to more radial flow after about 400 minutes of pumping. The rate of drawdown decreased after about 600 minutes of pumping but did not stabilize. The drawdown at the end of pumping was 15.91 m.

Recovery was initially slow but increased with time. Residual drawdown reached 2.11 m, 1,540 minutes after pumping stopped.

Interpretation: The extended drawdown indicates continuing drawdown if pumping continued after 3 days. Slight irregularities in the extended drawdown are likely caused by small discrepancies in recording the time and pumping rate.

Nanoose, 1988-05-33.xlsx

New Denver, WTN 86235

Aquifer geology: Pumped well WTN 86235 is drilled into an unconfined alluvial fan aquifer comprised of boulders, sand and gravel from 0 m to 48 m (0 feet to 156 feet). The aquifer likely exists in hydraulic connection with Wilson Creek (~320 m away) and Slocan Lake (~470 m away).

Pumped well and any observation well(s) summary: The pumped well is a 152 mm (6-inch) diameter well with the screen located at 46.3 m to 47.5 m (152 feet to 156 feet) depth.

Pumping test summary: The well was pumped at a reported constant rate of 273 m^3/day for 1200 minutes. Recovery was measured for 120 minutes (t/t'=11). The initial static water level was at 38.99 m. The drawdown during the pumping stabilized within a few minutes. Total drawdown reached 1.01 m and recovered completely in less than 2 minutes after pumping stopped.

Interpretation: The extended drawdown showed that recovery closely matched the drawdown but was slightly faster as indicated by the small upward "spike" during the first few minutes after pumping had stopped (see 3.1.4 for a discussion of the "spike").

86235, New Denver, 2006-09-29.xlsx

Osoyoos, WTN 83016

Aquifer geology: The pumped well WTN 83016 is drilled into an unconfined, unconsolidated sand and gravel aquifer. The well is located approximately 50 m from Osoyoos Lake. The static water level is about 6 m bgl. Grey clay was encountered at 13.4 m, indicating a saturated thickness of 7.4 m.

Pumped well and any observation well(s) summary: The pumped well has a 254 mm (10-inch) diameter casing installed to 10.2 m and screened from 10.36 m to 13.4 m. The observation well is 55 m from the pumped well.

Pumping test summary: Well WTN 83016 was pumped at 3542 m^3/day for 2 days and recovery was measured for 3 days (t/t'=1.7). The initial static level was 6.06 m, the drawdown at the end of pumping was 2.49 m and the residual drawdown after 3 days of recovery was 0.05 m. The maximum recorded drawdown of 2.49 m represents 34% of the initial saturated thickness but some of the drawdown (1-1.5 m) may reflect well inefficiency (i.e., well loss), considering the very high pumping rate from only 3 m of screens.

The observation well drawdown at the end of pumping phase was 0.65 m. Unfortunately, there is no recovery data for the observation well.

Interpretation: The extended drawdown lines up with the pumping-phase drawdown and shows little sign of stabilization. This permeable gravel aquifer is only 7.4 m thick. It is likely that the continuing drawdown after about 200 minutes represents dewatering of the gravel at the water table. The observation well has same semilog slope as the pumped well, indicating similar transmissivity. A Cooper-Jacob (1946) analysis of the drawdown in the observation well shows a storativity more representative of the specific yield of an unconfined aquifer ($7.8\times(10^{-2}$); see Table 1).

It is notable that the drawdown and extended drawdown did not show much sign if any of drawdown stabilization as might be expected from induced infiltration from Osoyoos Lake only 50 m away. Drawdown in the observation well 55 m away also did not stabilize. Given the proximity of the well to the lake, the lake's influence was expected to be felt sooner, well within the 2 days of pumping. The reason for the lack of drawdown stabilization is unknown.

83016, Osoyoos, 1986-08-15.xlsm

Powell River, WTN 49911

Aquifer geology: At well WTN 49911, the aquifer is at 13.7 m to 38.1 m depth and consists of sand and gravel with some layers of clay and boulder till. It is overlain by 13.7 m of clay and boulder till. The static water level was at 20.86 m btoc at the start of the pumping test on February 18, 1982, about 7 m below the top of the aquifer, which indicates that the aquifer is under water table conditions.

Pumped well and any observation well(s) summary: Well is cased with 152 mm (6-inch) diameter steel casing and screened from 30.5 m – 42.7 m (100 feet – 140 feet) and from 61 – 67 m (200 feet – 220 feet). There is no information on the location, depth, and lithology of the observation well.

Pumping test summary: Well WTN 49911 was pumped at an average constant rate of 186 m^3/day for 6 hours, followed by 5 hours of recovery (t/t'=2.3). Well borehole storage was evident only for the first 5 minutes of pumping. The drawdown at the end of the pumping phase was 8.66 m so the water level had dropped to 29.52 m, to just 1 m above the top of the well screen and drawdown did not appear to stabilize. Given the drawdown level, there likely was dewatering of the aquifer near the well. At the end of recovery the residual drawdown was 0.17 m.

The observation well had a small drawdown of 0.34 m at end of pumping, and slow response to end of pumping.

Interpretation: The upward shift of the extended drawdown means that the recovery was faster then would be expected judging by the drawdown at the start of pumping. The reason for this upward shift, which persists for several hundred minutes, is not clear especially since dewatering of the aquifer was expected (this would lead to a downward shift reflecting slowed recovery due slow refilling of drained pores at the water table and to the reduction of aquifer transmissivity near the well). The late-time extended drawdown suggests continuing drawdown if pumping continued, consistent with the understanding of the hydrogeology. The extended drawdown behavior in the observation well showed a downward shift, which appears to be related to anomalous drawdown data for the first minutes of the pumping phase, suggesting that the reported static water level may not be correct.

49911, Powell River, 1982-02-01.xlsm

Prince George, WTN 39604

Aquifer geology: The pumped (WTN 39604) and observation wells #1 (WTN 38135) and #2 (WTN 72884) are completed in a sand and gravel aquifer, probably in a buried channel, confined beneath ~25 m of clay. Of the 4 wells drilled for the project (WTNs 38135, 39604, 72883, and 72884), well WTN 72883 did not encounter the aquifer. The aquifer thickness is about 20 m at the pumped well and includes some thin layers of silt and clay. The channel is reported in the consultant's report to be about 1.6 km wide and at least 4.8 km long.

Pumped well and any observation well(s) summary: The pumped well's production casing is 203 mm in diameter and the well is screened at the bottom of the aquifer from 38.7 to 46.3 m (127 to 152 feet). The static water level was 5.2 m bgl. Two observation wells were installed at 50 m (165 feet-WTN 38135) and 233 m (765 feet-WTN 72884) from the pumped well (WTN 39604). The top of the well screen in the near and distant observation wells were 26.5 and at 27.1 m bgl, respectively (about 19.5 and 5.5 m below the static water level).

Pumping test summary: The well was pumped for 14,000 minutes at a reported constant rate of 1744 m^3/day. The original pumping test data sheets list the pumping rate as being the same (320 USgpm) throughout the test, suggesting that the pumping rate was checked regularly. Recovery was measured for 16,000 minutes (t/t' = 1.9).

The static water level was 8.38 m, 7.01 m and 21.63 m btoc for the pumped well, observation well 1 and observation well 2, respectively. Drawdowns at the end of the pumping phase were 16.68 m, 14.59 m, and 12.84 m in the pumped well, observation well 1 and observation well 2, respectively.

Interpretation: Plots of the water level and semi-log plots of the extended drawdown are shown in the accompanying spreadsheet for each of the three wells. The nature of the drawdown with time (increasing in rate from early to mid-time) supports the concept of a bounded aquifer. However, the slower rate of drawdown on the semi-log plot after about 4 days of pumping is the opposite of what would be expected if the drawdown cone had simply intercepted impermeable boundaries.

Since the overlying clay at observation well 2 is about 26 m thick and the static water level was 21.63 m btoc, it follows that at observation well 2, the aquifer transitioned from confined to water table conditions after about 2000 minutes of pumping when the drawdown was about 5 or 6 m at which point the top of the screen became exposed so that air could enter the aquifer. At the pumped well itself the water level had declined to almost the top of the aquifer by the end of the pumping phase. In other words, an increasing portion of the aquifer likely transitioned from confined conditions to water-table conditions as the test proceeded. This transition would have been gradual depending on the interplay between negative water pressures (suction) at the top of the aquifer, air entry through the observation well screen and drainage of the pores. The transition is the likely explanation for the flattening out of the drawdown. The specific yield (S_y) associated with drainage of pores of the sand and gravel at the water table is much larger than the elastic storativity (S), hence the rate of drawdown would then decrease when dewatering begins to occur.

The transition from confined to water-table conditions also is the likely reason for the long-lasting downward anomaly of the extended drawdown for each of the 3 wells. Because the anomaly is downward the recovery was slower than would be expected judging by the initial drawdown from pumping. The slow recovery may reflect the depleted water storage at the water table which would need to be re-filled before the aquifer returns to confined conditions at a later time in the recovery phase. Because the anomaly occurred for all three wells it is believed that the anomaly was an aquifer-wide phenomenon rather than conditions only at the pumped well such as change of well efficiency.

The transition from confined to water-table conditions would mean that the superposition principle does not hold because the storage properties of the aquifer have changed during the course of the test. One of the basic conditions for the applicability of superposition is that the hydraulic properties of the aquifer does not change with time. That would explain the large anomaly of the extended drawdown. This finding also illustrates how the calculation and plotting of the extended drawdown can indicate the occurrence of conditions that invalidate the superposition principle and therefore also call into question interpretations of the test results that are based on the same assumptions as those which underlie the superposition principle.

39604, Prince George,1978-05-04.x

Qualicum Beach, WTN 41896

Aquifer geology: Well WTN 41896 is completed into a confined sand and gravel aquifer from 43.9 m – 47.2 m (144 feet to 155 feet) depth. The aquifer is confined above by compact till with another sand and gravel layer at 37.2 m – 40.5 m (122 feet to 133 feet). Although the sand and gravel form an extensive sub-till aquifer, it is very likely heterogeneous (Carmichael, 2013).

Pumped well and any observation well(s) summary: Well WTN 41896 is cased with 152 mm diameter steel casing and is screened from 43.9 m - 47.2 m (144 feet -155 feet).

Pumping test summary: The well was pumped for 1500 minutes at a reported constant rate of 736 m^3/day. Recovery was measured for 1400 minutes (t/t'=2.0). The static water level was at 5.24 m at the start of the test and recovered to 5.39 m. The drawdown at the end of the pumping phase was 3.52 m, approximately 30 m above the top of the confined aquifer.

Interpretation: The "spike" at 0.25 min of recovery is caused by an anomalously small drawdown data point at 0.25 min of pumping (see 3.1.4 for a discussion of the "spike"). There is a small downward anomaly for the first 300 minutes of recovery (0.2 m in 3.5 m total drawdown). After that the extended drawdown shows continued increase consistent with pumping phase drawdown and indicates that the aquifer is strongly confined.

The downward shift of the extended drawdown means that the recovery was slower than would be expected judging by the drawdown during the first 300 minutes of pumping. The cause of this shift is not known. It could be caused by a decrease of the pumping rate later in the test, but there is no data to show or support this and this seems unlikely considering the relatively small drawdown. There was no aquifer dewatering during the test. Compaction of the aquitard material above and below the aquifer could also be the cause.

41896, Qualicum Beach, 1979-03-13.xl

Qualicum Beach, WTN 113212

Aquifer geology: The pumped well (WTN 113212) is drilled into a gravel and silty sand aquifer at 69 m – 76.8 m bgl, confined above by grey sandy silt and clay.

Pumped well and any observation well(s) summary: The 152 mm (6-inch) diameter well is screened from 74.2 m to 77.0 m (243.5 feet to 252.5 feet).

Pumping test summary: Well WTN 113212 was pumped at an average constant rate of 509 m^3/day for 2,880 minutes (2 days), followed by 4,110 minutes (almost 3 days) of recovery (t/t'=1.7). The pumping rate was adjusted upward several times during the test and these adjustments show up in the drawdown record. The static water level at the beginning of the test was 21.9 m, followed by drawdown of 36.67 m at the end of the pumping phase, still about 10 m above the top of the aquifer. Drawdown did not stabilize. After 3 days recovery the residual drawdown was 3.90 m.

Interpretation: The extended drawdown indicates continued drawdown had the test continued. The extended drawdown has in effect lengthened the duration of the test from 2 days to 5 days. In fact, the extended drawdown follows the steepening downward line on the semi-log plot that is indicative of a bounded aquifer. On a log-log plot of the extended drawdown the data plot as a straight line.

The small upward “spike” on the extended drawdown plot is noted (see 3.1.4 for a discussion of the “spike”). It is an indication that the first few minutes of the drawdown data are questionable and should be de-emphasized for interpretation of the extended drawdown.

113212, Qualicum Beach, 2017-05-24.xl

Salt Spring, WTN 75537

Aquifer geology: The pumped well (WTN 75537) is drilled into fractured sandstone and shale of the Nanaimo Group. Water occurs in discrete fractures in the sedimentary bedrock. The well is located ~100 m from the ocean, at an elevation of ~10 m asl.

Pumped well and any observation well(s) summary: The well is cased to 6.1 m (20 feet) depth and completed open hole to 30.5 m (100 feet). The upper-most major water-bearing fracture is reported at 10.4 m (34 feet) depth in the well, with additional water-bearing fractures reported at 17.7 m (58 feet), 28.0 m (92 feet). There were two observation wells located 25 m and 100 m away from the pumped well but unfortunately no recovery measurements were taken from these wells.

Pumping test summary: The well was pumped for 4 days at a reported constant rate of 21.3 m^3/day, followed by 2.8 days of recovery (t/t’=2.4). The static water level was 5.27 m. After 1 day of pumping the drawdown in the pumped well stabilized at 8.05 m. Drawdown stabilization was also observed in the observation well 25 m away (very little drawdown (0.03 m) was noted in the observation well 100 m away).

The drawdown of 8.05 m means the upper-most water-bearing fracture at 10.4 m depth was dewatered at the pumped well, after about 6 hours of pumping. 0.52 m of residual drawdown remained after 2.8 days of recovery.

Interpretation: The extended drawdown results are anomalous. The downward shift may reflect dewatering of the upper-most water-bearing fracture at 10.4 m depth. The recovery was initially slow, suggesting low inflow to the well, but drawdown also stabilized after 1 day of pumping. The stabilization appears to reflect aquifer conditions because it was also observed in the observation well 25 m away and may reflect the area of drawdown reaching the ocean. Had recovery been monitored for a longer period, the extended drawdown may eventually approach a constant drawdown.

75537, Saltspring Island, 2000-07-04.xl

APPENDIX C. GLOSSARY

Alluvial: Process by which sediments are deposited by a stream as the stream enter a larger valley.

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.

Aquitard: A geological deposit that is made up of mainly low permeability sediments like till, silt or clay. Also sometimes referred to as a confining layer.

Available drawdown: The height of 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.

Bore-hole storage: The effect that the volume of water stored in a pumping well has on the drawdown in the well; bore-hole storage effects drawdown in the pumped well in the early part of a pumping test. Synonymous with "wellbore storage".

Confined aquifer: An aquifer that is overlain by confining sediments or confining layer; groundwater in a confined aquifer is commonly under pressure.

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

Deltaic sediments: Unconsolidated sediments (mostly permeable sandy sediments) deposited at the mouth of a river or stream.

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.

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).

Down-gradient: The direction of maximum decrease in the groundwater elevation; often inferred as the direction of groundwater flow.

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

Piezometric level: Refers to the groundwater level elevation or hydraulic head in a confined aquifer.

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).

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.

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 or in an aquifer).

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

Specific yield (Sy): The volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline in the water table.

Static water level (SWL): Distance (in metres 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.

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.

Turbulent flow: Flow where inertial forces relative to viscous forces of water becomes significant and flow is no longer parallel but chaotic. Turbulent groundwater flow usually only happens where groundwater velocities are high, such as at a well pumping at a high rate.

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”.

Water table: The top of the saturated zone in the ground where the water pressure is equivalent to atmospheric pressure.

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.

Well tag number (WTN): the file number assigned in the government’s GWELLS database to the record of a particular well.