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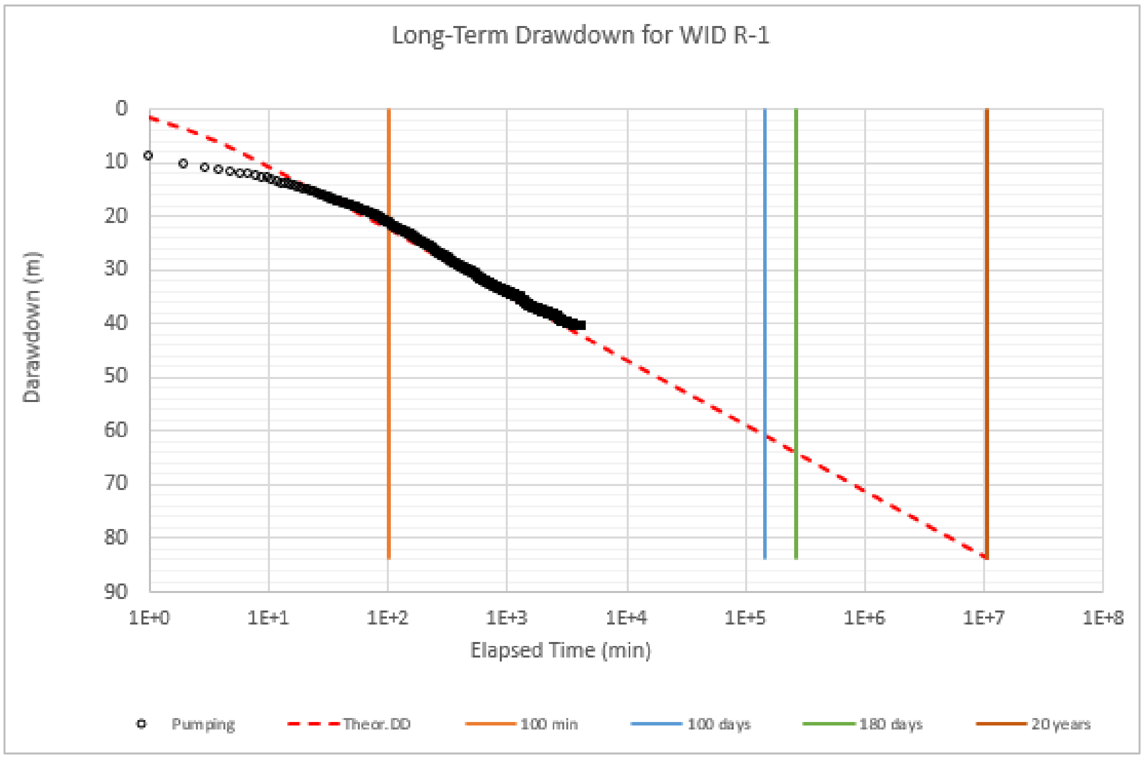
Comparison of Two Methods For Determining Long-Term Well Yield in British Columbia

David van Everdingen



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Cover Image:
Time drawdown, semi-log graph, showing 100-minute, projected 100-day, 180-day and 20-year drawdowns using pumping well data.

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EXECUTIVE SUMMARY

Well performance and aquifer capabilities must be assessed to Provincial standards when providing supplementary information for groundwater licence applications in British Columbia. Two acceptable methods for evaluating long-term capacities for water supply wells are the 100-day and the modified Moell Q_{20} methods.

The 100-day method is the safe available drawdown multiplied by the specific capacity (SC) of the well. SC is the pumping rate divided by the projected drawdown at 100 days using the Cooper-Jacob straight line semi-log plot. This assumes Theis' assumptions are valid. The 100-days of pumping represent a period where no recharge occurs (e.g., typically summer months in coastal regions and winter months in the interior). It was originally designed to be a graphical solution to calculating long-term well yield. Because it uses an extrapolation of the actual drawdown data from the pumping test, monitored in the pumping well, it implicitly accounts for well loss. This method was developed in British Columbia where precipitation is expected to occur after a temporary period when groundwater recharge is minimal.

The Q_{20} is used to calculate the sustainable yield of the well based on the projected drawdown after 20 years using a proven mathematical model (e.g., Theis but can also use any other model), assuming continuous pumping for the duration. The sustainable well yield (Q_{20}) equation is essentially the same as the 100-day equation, except that SC equals test pumping rate divided by the projected drawdown after 20 years modified by the well loss during the first 100 minutes of pumping. This method was developed for aquifers in the prairie provinces where recharge is likely much lower.

The choice of method should be dictated by the conceptual model (i.e., aquifer characteristics) and both current and predicted future climatic conditions. If the methods are applied correctly, the 100-day estimated long-term well yield will always be greater than that of the Q_{20} method.

Comparison of the methods is shown in following table.

100-day Method	Q_{20} Modified Moell Method
Better for wells pumped on a seasonal basis e.g., irrigation wells	Better for municipal wells and other wells which are pumped year-round
Conditions with recharge (precipitation) after 100 or 180 days	Drier conditions (precipitation not guaranteed) or deeper, highly confined aquifers without annual recharge
As written is dependent on Theis ideal aquifer assumptions being valid	Can use any suitable analytical method
Implicitly assumes recharge occurs annually	Assumes exhaustion of supply after 20 years
Late-time drawdown trend must plot as straight line on semi-log plot prior to extension	Doesn't specify which portion of curve to use. Absence of boundaries and relatively flat derivative must be confirmed
Must be updated if pattern of decline in water levels changes	

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1. INTRODUCTION

Well performance and aquifer capabilities must be assessed to Provincial standards when providing supplementary information for groundwater licence applications in British Columbia (B.C.) (Todd et al., 2020). The two acceptable methods for evaluating long-term capacities for water supply wells are the 100-day (Ministry of Environment, 1999) and the modified Moell Q_{20} (Maathuis and van der Kamp, 2006) methods.

A comparison of these methods has been carried out with the purpose of clarifying the conditions under which the methods are appropriate for use. Comparison of these methods includes consideration of:

1. Safe available drawdown in the well;
2. Assessing where and when these methods apply;
3. Prerequisites and assumptions underlying the methods; and
4. Other factors that may impact long-term well yield, such as boundary conditions and well interference.

Adequate pumping test procedures are critical to defensible results, but are not specifically addressed in this document and can be found elsewhere (e.g., Todd et al., 2020).

2. BACKGROUND

The most widely used of the quantitative methods of assessing long-term well yield in North America were all developed in western Canada. These include Q_{20} methods first used in the prairie provinces of Alberta and Saskatchewan (Farvolden, 1959 and Moell, 1975); and the 100-day method developed in B.C. (Moncur, 1974; Wei and Kohut, 1986 and MoE, 1999).

van der Kamp and Maathuis (2006) recommended adoption of a modified Moell Method to replace the older (Farvolden and Moell) methods.

The 100-day method was developed in B.C. in the late 1970's to address the assessment of bedrock wells in coastal areas such as the Gulf Islands. The method was discussed by Wei and Kohut (1986) who incorporated it in a revision of Guidelines for Groundwater Reports and Well Testing in Support of a Certificate of Public Convenience and Necessity sometime after 1982. While it was originally intended for bedrock well assessments, it evolved by 1999 to be the standard (conservative) approach in BC for assessing wells also completed in unconsolidated deposits.

Safe Available Drawdown

Long-term well yield is dependent, in part, on the safe available drawdown (SAD) in a well which is the total available drawdown (TAD or $\Delta s_{available}$) measured from the non-pumping water level (NPWL)[1] (the NPWL is usually taken just prior to the pumping tests commencement) to the top of the aquifer (alternatively, screen top, upper-most major water-bearing fracture zone, or pump intake) multiplied by a safety factor (S_f) (Figure 1).

Note that the safety factor of 30%, is typically used to offset over-estimates of sustained yield which can result from assuming the aquifer to be of infinite extent, constant thickness, homogenous and isotropic (Moell, 1975). Low seasonal water levels and interference from nearby wells is accounted for in the assessment of water level when determining the total available drawdown.

[1] To determine SAD, the NPWL should be adjusted for the lowest seasonal water level as well as for interference from other wells.

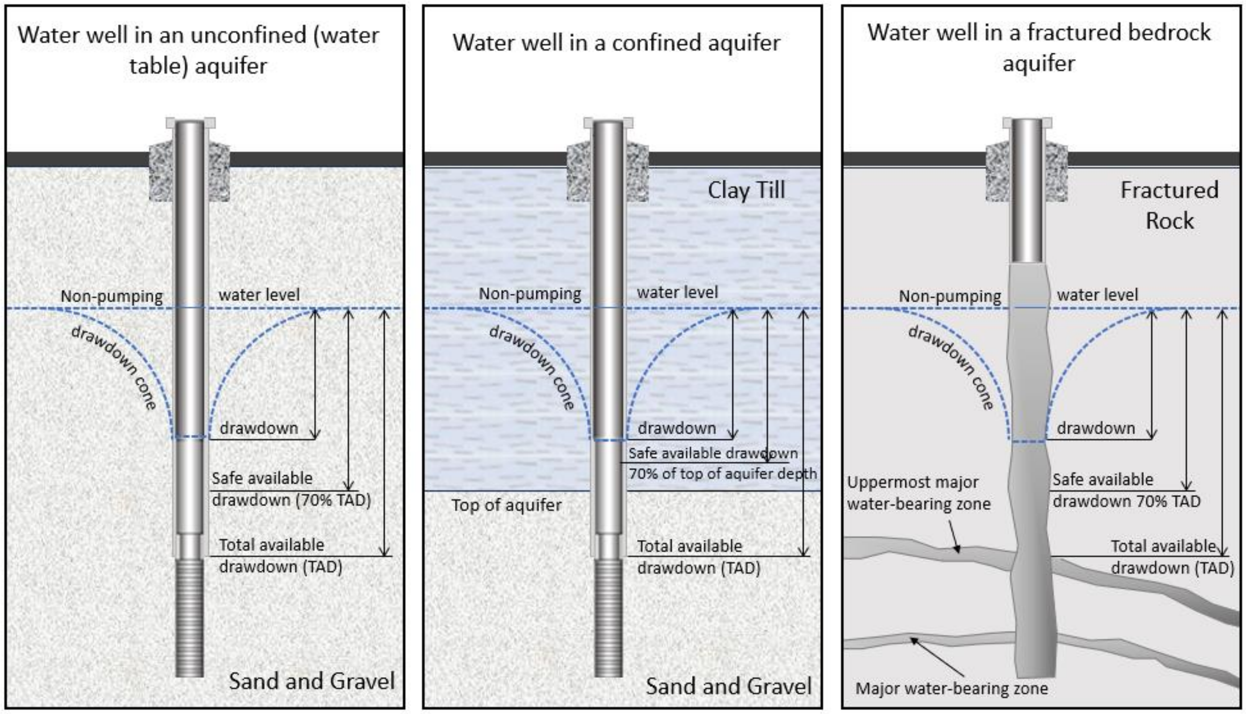

Figure 1. Calculation of safe available drawdown for different aquifer types (i.e., unconfined - unconsolidated, confined-consolidated and fractured bedrock). Modified from MOE (1999) which had SAD set at the top of the aquifer leaving little room for error.

It is recommended that pumping tests take place during the driest part of the year to reduce or eliminate the potential effects of a precipitation event on drawdown water levels and for assessing yield using the minimum TAD.

2.1 One Hundred Day Method

The 100-day method, described by MoE (1999), used to determine a theoretical long-term pumping rate ($Q_{100\ day}$) from a well, is the safe available drawdown (SAD) times the specific capacity (SC) of the well (Equation 1). The method was derived from the Theis and Jacob solutions to groundwater flow to a pumping well (Wei and Kohut, 1986). SC is the pumping rate divided by the straight-line projection of the drawdown to 100 days using the Cooper-Jacob log-linear plot.

$$Q_{100day} = SAD \times SC = \left[s_{available} \times S_f\right] \times \frac{Q_t}{s_{100day\ proj}} \quad (1)$$

where $s_{100day\ proj}$ refers to drawdown projected to 100 days and Q_t is the pumping rate during a pumping test. This method assumes the validity of the Theis (1935) assumptions[2].

The long-term yield of the well is based on extrapolating the straight-line drawdown, on a semi-log graph, from the period of steady-state drawdown near the end of the test to 100 days. The projected drawdown at 100-days is used to determine the long-term specific capacity of the well (Figure 2).

[2] Theis' assumptions include: the aquifer is of infinite areal extent, uniform thickness, homogenous, confined, and non-leaky. The control well is fully or partially penetrating; flow is unsteady; flow to control well is horizontal when control well is fully penetrating; diameter of pumping well is very small so that storage in the well can be neglected and water is released instantaneously from storage with decline in hydraulic head.

Extrapolation to 100 days was selected because recharge is assumed to occur annually after 100 days. MoE (1999) states "The 100 days of continuous pumping represent a period where no recharge occurs (summer and fall months in coastal areas and fall and winter months in the interior). Recharge is assumed to occur annually with winter rains or snow melt". This is taken to mean that the well is pumped for 100 days, typically the duration of the regional irrigation season during the summer months.

A safety factor, usually using 70% of TAD (30% reduction), is factored into the capacity rating by multiplying the SC at 100 days with the SAD (which incorporates the safety factor).

Other factors that may impact the long-term capacity of the well include interference from other nearby pumping wells, surface water-groundwater interactions, water quality and seawater encroachment. Estimates of well capacity are made based on drawdown measured in the production well.

The 100-day method is not restricted to wells that are pumped intermittently. The method allows for the continuous operation of the well beyond 100 days.

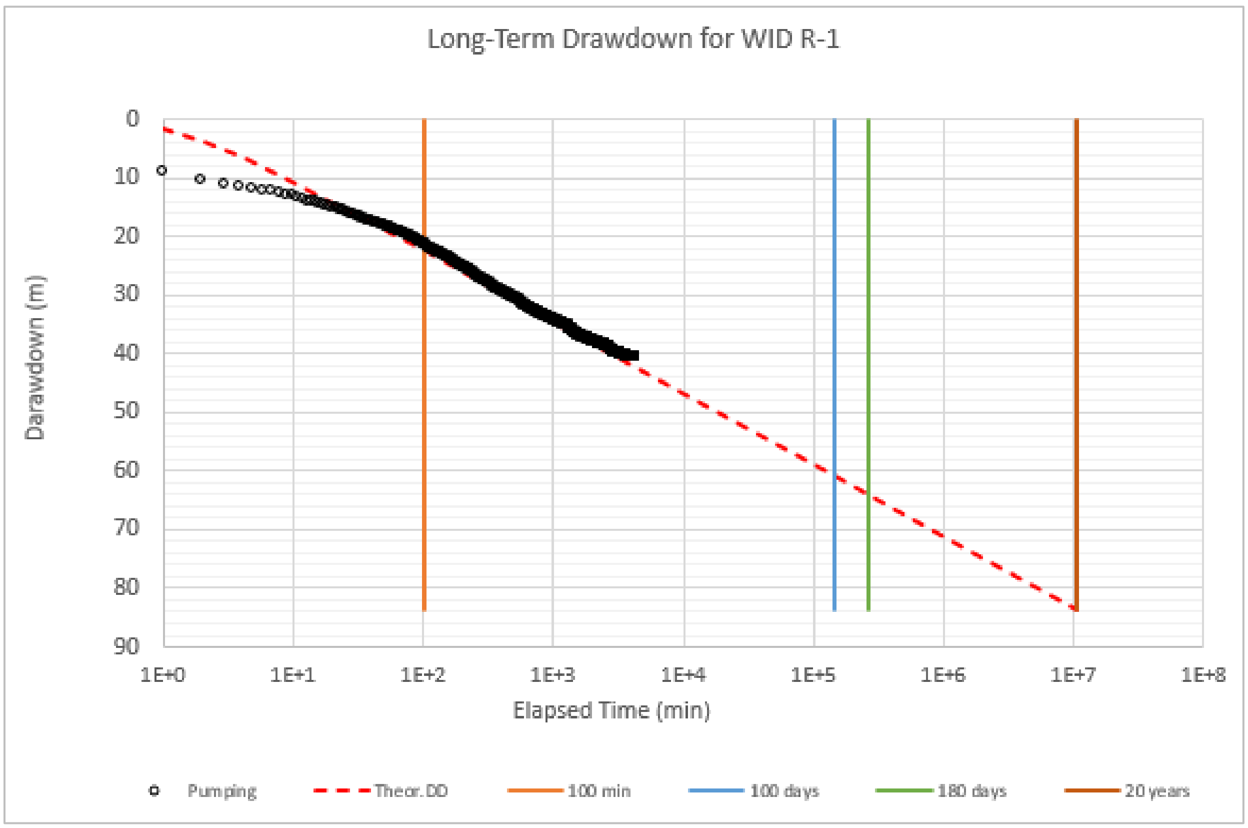

Figure 2. Time drawdown, semi-log graph, showing 100-minute, projected 100-day, 180-day and 20-year drawdowns using pumping well data from PHC (1994). PHC (1994) pumping and observation well hydrographs are presented in Appendix B.

2.2 Q_{20} Method

The modified Moell method (Maathuis and van der Kamp, 2006) is used to calculate the long-term yield of the well based on the theoretical drawdown after 20 years of continuous pumping from a fully confined aquifer. In many situations, Theis or Cooper & Jacob solutions provide reasonable matches with early time during a pumping test (i.e., the first 100 minute) where no boundaries or significant aquifer changes are encountered. A major assumption is that the extrapolation of the period of the pumping test, generally one to three days, to predict aquifer response at 20 years, is valid.

To improve the accuracy of the long-term well yield and aquifer parameter estimates, other solutions developed for various types of aquifer conditions may be more applicable than Theis or Copper-Jacob. Development of a comprehensive conceptual model of the local and regional groundwater system is critical to allow selection of an appropriate method of aquifer test interpretation (e.g., considering leaky aquifer solutions, boundaries). If there are enough data, numerical modeling may be considered.

The Q_{20} equation is essentially the same as that for the 100-day method, except that the SC equals the test pumping rate divided by the projected drawdown after 20 years modified by the well loss during the first 100 minutes of pumping. The projected drawdown after 20 years (s_{20yr}) therefore is (Equation 2).

$$s_{20yr} = [s_{100min}]_{actual} + [s_{20yr} - s_{100min}]_{theoretical} \tag{2}$$

Then the long-term well yield becomes (Equation 3):

$$Q_{20} = s_{available} \times S_f \times \frac{Q_t}{s_{20yr}} \tag{3}$$

Although the modified Moell method accounts for well loss in the first 100 minutes of the pumping test by adding the drawdown measured at 100 minutes (s_{100min} actual) to the 20-year theoretical drawdown, this may need to be adjusted if significant well loss occurs after 100 minutes (Maathuis and van der Kamp, 2006). This is done by obtaining actual drawdown and calculating a theoretical drawdown for a later time once well loss is no longer apparent. Well loss is constant only with a constant pumping rate; changes in the pumping rate results in increases in the well loss because of increased turbulent flow component.

The actual drawdown at 100 minutes should be measured during the constant-rate portion of an aquifer test. The aquifer must be allowed to recover after the completion of the step-rate test to the pre-pumping conditions prior to starting the constant-rate test if the true value of drawdown at 100 minutes is to be measured. If no recovery is allowed prior to the constant-rate test, the 100-minute drawdown will be exaggerated, and consequently, may lead to under-estimation of Q_{20}.

The theoretical drawdown at both 100 minutes and 20 years can be estimated using Theis or the Cooper-Jacob approximation of Theis' solution using the straight-line portion of the drawdown data in a semi-log plot, assuming that the Theis model is valid in a particular situation. If the Theis model is not applicable, then both the 100-minute and 20-year theoretical drawdowns must be determined by using another model. Other theoretical models may not plot as a straight-line on a semi-log plot; in these cases, the projected 100-minute and 20-year drawdown values must be calculated using the appropriate solution, which requires the determination of transmissivity.

If observation wells were monitored during the aquifer test, another method for calculating the theoretical drawdown at 100 minutes (s_{100min} theoretical) is by developing distance/drawdown graphs where the drawdown can be presented on an arithmetic scale (y-axis), and the distances of observation wells from the pumping well are presented on a log scale (x-axis). This is described further below for situations with one observation well and multiple observation wells.

If **one observation well** is monitored during aquifer testing, the drawdown/distance graph could be used to calculate s_{100min} theoretical. The straight-line representing drawdown should pass through the 100-minute measured drawdown in the single observation well at a drawdown per log cycle slope two times greater than drawdown per log cycle calculated from a time/drawdown graph used to calculate transmissivity (Driscoll, 1986). The line is then extended to the pumping well radius. This projected drawdown should represent the theoretical drawdown while ignoring well losses, (i.e., s_{100min} theoretical). Since this analysis uses only one measured value and relies on the drawdown calculated from the time-drawdown curve, the accuracy of s_{100min} theoretical calculated by this method is less reliable than that extrapolated from response in multiple observation wells.

If **multiple observation wells**, of differing distances from the production well, are monitored during aquifer testing, the straight line should be drawn through the drawdown data points measured at 100 minutes in each of the observation wells. The line is then extended to the pumping well radius; the projected drawdown represents s_{100min} theoretical drawdown while ignoring well losses (i.e., $s_{100\ minutes}$ theoretical).

3. DISCUSSION

This section provides information regarding prerequisites to using either method for evaluating long-term well yields and a discussion of each method in the context of its application and limitations, followed by general comments relevant to each method and some thoughts on sustainable yield of aquifers.

3.1 Prerequisites

Prerequisites to using these methods include:

- Pumping the well long enough to be able to assess the hydraulic response in the mid- to late-time frame (100-day method) or to apply the appropriate analytical method (Q_{20} method) and ascertain the long-term drawdown pattern (i.e., whether boundaries were encountered). The interference impact from other wells also needs to be considered. The available drawdown could be reduced or the pumping time could be extended by an order of magnitude (i.e., incorporating actual conditions) to account for interference impact. The analytical solutions underpinning both methods also assume a horizontal water table, emphasizing the requirement for conducting the pumping test during periods of no precipitation/recharge.
- Interpreting the pumping test data and well site hydrogeology to develop the conceptual model sufficiently such that the appropriate analytical model may be applied to generate the projected drawdown trend beyond the time frame of the pumping test (van der Kamp and Maathuis, 2006).

Prior to using either method, the analyst should verify the dataset is free of artefacts caused by human or equipment error or non-ideal conditions. For instance, boundary effects, significant variation in pumping rates, and leaky or semi-confined geology to name a few. Use of derivative analysis (see Appendix A) can help verify the adequacy of the data for further analysis.

3.2 One Hundred Day Method

The 100-day method was derived from the Theis and Cooper-Jacob solution to groundwater flow to a pumping well (Wei and Kohut, 1986) and is limited implicitly to that solution. It was originally designed to be a graphical solution to calculating long-term well yield. Because it uses an extrapolation of the actual drawdown data from the pumping test, monitored in the pumping well, it implicitly accounts for well loss.

This method was developed in B.C. where precipitation is expected to occur after a temporary period when groundwater recharge is minimal. The continuous pumping for 100-days gives a conservative result since supply wells are generally not pumped for 24 hours per day and 100 days continuously. However, with climate change, dry conditions are predicted to last longer in some areas and it may therefore be more appropriate to use an interval longer than 100 days (e.g., 180 days). Having recognized longer periods of drought, it is worth pointing out that the difference in drawdown between 100 and 180 days on a log-scale is not significant if the drawdown per log cycle is small (approximately 2%) but is more significant as the drawdown per log cycle increases (e.g., 10%). Alternatively, it may be of benefit to address this issue with an increase in safety factor (e.g., from 30% to 33% or 40%) which would result in a long-term yield reduction of 6 to 15% (Figure 3) independent of drawdown.

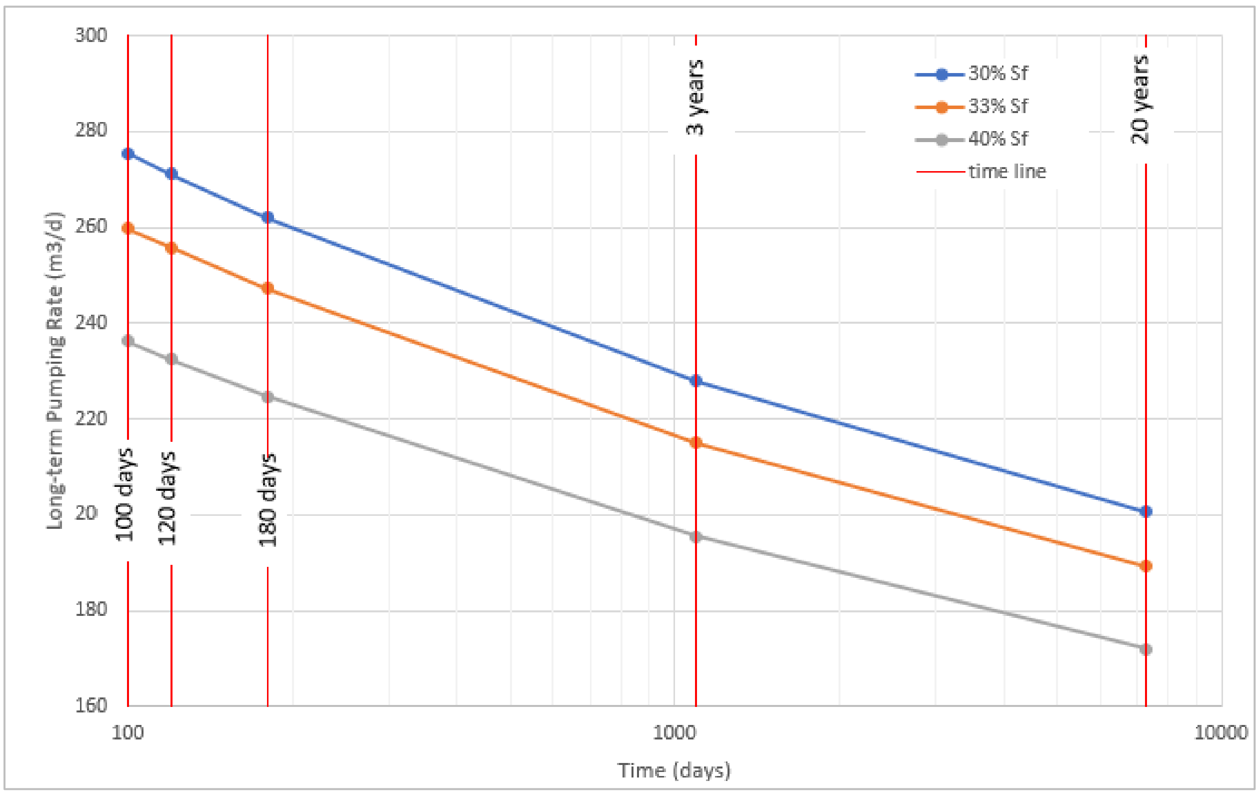

Figure 3. Effect of changing factor of safety on long-term pumping rate. Based on PHC (1994) data.

The 100-day method requires that late time data fall on a straight line (on a log-linear plot) which means that it cannot be applied if more than one boundary effect is noted in the data, nor if the data plot on a straight line on a linear-linear hydrograph or a downward curved line on a log-linear hydrograph. Thus, extrapolation of late time data can include the boundary effect as long as the late data fall on a straight line in a semi-log plot.

Wei and Kohut (1986) recommended a minimum 72-hour duration for a pumping test on a well completed in fractured bedrock because a 24-hour test was often not of sufficient duration to adequately assess aquifer conditions.

Transmissivity and storativity are not explicitly noted in Equation 1, however, they are implicit in the extrapolation of drawdown to 100-days on a semi-log plot in the Cooper-Jacob straight-line method.

3.3 Q_{20} Method

The Q_{20} method is more flexible in its choice of analytical solution; in addition, it accounts for long-term pumping over the projected life of the well. The Q_{20} method, developed for aquifers in the prairies where long periods of no precipitation or recharge are common, is more appropriate to use in drier climates and/or for deeper, confined aquifers. Although transmissivity and storativity are not explicitly present in equations 2 and 3, they are required for the extrapolation or calculation of drawdown after 20 years for any method other than straight-line extrapolation (Cooper-Jacob method).

The Q_{20} method solves for an ideal case with no well loss because it bases the determination of drawdown through an analytical solution developed for ideal conditions. Well loss is therefore accounted for explicitly through comparison of the actual and theoretical drawdowns after 100 minutes of pumping (equation 2).

Although not explicitly stated, 20 years was probably selected as an appropriate length of time for well operation because this is sufficiently far in the future to allow for more study of the aquifer system or it could be tied to groundwater licensing in Alberta, where most groundwater use permits have a 20-year renewal term (Geller, 2011).

In actual hydrogeologic conditions and groundwater use, the Q_{20} method is conservative because storage depletion is not the only source of water to aquifers that often receive natural or induced recharge at some point each year. In cases where aquifer depletion is possible, such as highly confined aquifers, aquifers in dry climates, or situations of known groundwater decline, the Q_{20} method may be realistic or even optimistic in terms of estimating long-term well yield (Geller, 2011).

Careful consideration for the use of the Q_{20} method in B.C. must be made because many aquifers in B.C. are situated in narrow mountain valleys and it is likely that boundary conditions (both negative – aquifer boundary and positive – stream recharge/leakage) will have been encountered long before 20 years have passed.

3.4 General Discussion of Methods

The 100-day method was developed based on the Theis solution assumptions using the Cooper-Jacob straight-line method to extrapolate drawdown to 100-days. The Q_{20} method can use the Theis solution or any other appropriate mathematical solution to the pumping test to predict drawdown to any time provided the solution adequately fits the well and aquifer characteristics and the conceptual model of the aquifer, and does not violate the inherent assumptions.

The Q_{20} method accounts for well loss in the first 100 minutes and any appropriate analytical solution can be applied whereas the 100-day method implicitly accounts for well loss and is restricted to the Theis analytical solution.

The Theis solution can be used in a wide variety of conditions even if the assumptions do not entirely hold, if the duration of the pumping test is long enough for the extent of the pumping influence to encompass a large enough volume of the aquifer to approximate a homogeneous, isotropic porous medium; as such it is not often necessary to resort to other analytical solutions.

Although the Q_{20} method assumes the groundwater resource becomes exhausted after 20 years (Maathuis and van der Kamp, 2006), the 100-day method assumes the calculated long-term well yield is sustainable over the long term, and that aquifer recharge occurs after 100 days. Thus, the 100-day method assumes that after a period of 100 days of groundwater withdrawals, either groundwater recharge would occur and/or pumping demand would be reduced during the off-season (e.g., winter in coastal regions, spring in interior regions).

Driscoll (1986) recommended that in cases where the late portion of the time-drawdown graph changes, becoming steeper or flatter, the long-term prediction should be done by extending the late portion of the graph to a desired time (e.g., 20 years). This method can be used to compare the final drawdown measured during a pumping test with the results obtained by application of the Modified Moell formula.

The mathematical formulae for prediction of aquifer behaviour that rely on ideal aquifer conditions assume that the calculated transmissivity and storativity values are valid only when using data obtained before encountering a boundary to the aquifer. Variation in the aquifer properties, hydraulic conductivity, aquifer thickness, recharge, etc., may therefore preclude further utilization of calculated aquifer parameters. Drawdown data obtained after encountering boundary effects cannot be used because physical characteristics of the aquifer differ further from the well. This applies to both methods.

Most pumping tests in B.C., and likely everywhere else, are conducted without monitoring data from an observation well, whether because of the added expense or inaccessibility issues. Data from an observation well is preferrable to pumping well data for at least two reasons: there is no well loss and other pumping-related effects to deal with and storativity can be determined.

3.5 Sustainable Aquifer Yield Perspective

During continued pumping, groundwater will initially be sourced from storage but eventually all groundwater pumped from the well will come from leakage. Leakage may be from an overlying aquifer, nearby surface water or seawater. This can eventually result in reduced groundwater discharge to a stream because of interception by the pumping well or reduced flow in a stream because of induced recharge to the aquifer from the stream.

Whereas well interference and seasonal variation in water levels should be considered as part of the safe available drawdown determination, neither method considers the influence of simultaneous pumping from multiple wells on the aquifer sustainable yield (Allen, 2014). Estimation of an aquifer's long-term sustainability must consider all groundwater use; the effects of pumping small amounts from individual wells are cumulative and create a composite drawdown cone of depression with a much larger range of influence (Allen, 2014).

Climate change predictions which are available through the Pacific Climate Impacts Consortium's Climate Explorer, area-specific Agricultural Water Demand models, and the province of B.C.'s Climate Change Strategy Regional Climate Change Summaries (https://www.pacificclimate.org/news-and-events/news/2013/regional-climate-summaries) should also be considered. The 100-day and Q_{20} methods are intended to assess the likelihood of supply and do not explicitly address climate change.

4. SUMMARY

Both methods are conservative for estimating long-term well yield in the sense that they consider neither recharge to the aquifer from precipitation nor leakage from overlying aquifers for the duration of the pumping interval (100 days or 20 years as appropriate).

Both methods are currently applicable in B.C. (Todd et al., 2020). However, the choice of method should be dictated by the conceptual model (i.e., aquifer characteristics) and both current and predicted future climatic conditions. If the methods are applied correctly, the 100-day estimated long-term well yield will always be greater than that of the Q_{20} method because the extrapolated drawdown after 20 years for the Q_{20} method is greater than that for the 100-day method.

Justification for the selection of a method for a specific site should be provided. Because these methods were developed for different conditions, they should not be used together for the purpose of more optimistically estimating well yield.

The following table compares the methods.

100-day Method	Q_{20} Modified Moell Method
Better for wells pumped on a seasonal basis e.g., irrigation wells	Better for municipal wells and other wells which are pumped year-round
Conditions with recharge (precipitation) after 100 or 180 days	Drier conditions (precipitation not guaranteed) or deeper, highly confined aquifers without annual recharge
As written is dependent on Theis ideal aquifer assumptions being valid	Can use any suitable analytical method
Implicitly assumes recharge occurs annually	Assumes exhaustion of supply after 20 years
Late-time drawdown trend must plot as straight line on semi-log plot prior to extension	Doesn't specify which portion of curve to use. Absence of boundaries and relatively flat derivative must be confirmed
Must be updated if pattern of decline in water levels changes	

Understanding of local hydrogeology is often limited, therefore, long-term monitoring, both prior-to and after the aquifer test, is invaluable for understanding and verifying long-term aquifer and well performance.

Further work could include a re-assessment of pumping tests done by utilities in the past, say 20 years ago, to confirm whether these methods have proved valid over time. Confirmation may be difficult given that recharge to the aquifers will have occurred during this time. As well, effects such as well fouling may mask results. In any case it would be useful to confirm any changes in use of the water supply.

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APPENDIX A: DISCUSSION OF TRANSMISSIVITY AND STORATIVITY

Transmissivity

In most cases, transmissivity is interpreted from the time-drawdown graphs of the pumping interval or from the time-residual drawdown (recovery) curves; or from both. Some practitioners calculate the average or geometric mean derived from various aquifer testing analyses. This is not reflective of best practices; these transmissivity estimates are representative of different volumes intersected during the pumping test (e.g., early time may be pre-boundary and late time may reflect post-boundary impacts) and should not be statistically combined.

The conceptual hydrogeologic model should guide the selection of the portion of the drawdown curve that is most likely to represent the assumed conditions for the analysis used. A derivative analysis (e.g., Renard et al. 2009; Spane and Wurstner, 1999) can help assess the applicable portion of the drawdown curve. A transmissivity value derived from a post-boundary segment of the time-drawdown data, has failed the assumptions of the analytical solutions that do not consider such boundaries. Therefore, the aquifer transmissivity obtained in this situation does not truly represent the actual conditions. This effective transmissivity, based on late-time data influenced by hydraulic boundaries, introduces safety factors in the long-term predictive analytical simulations to address the uncertainty. The effective transmissivity acknowledges that assumptions may not be valid because the curve matching technique used data that was influenced by a boundary condition. The use of the effective transmissivity is conservative when completing long-term (20-year) predictive simulations using analytical solutions that do not otherwise account for the boundaries.

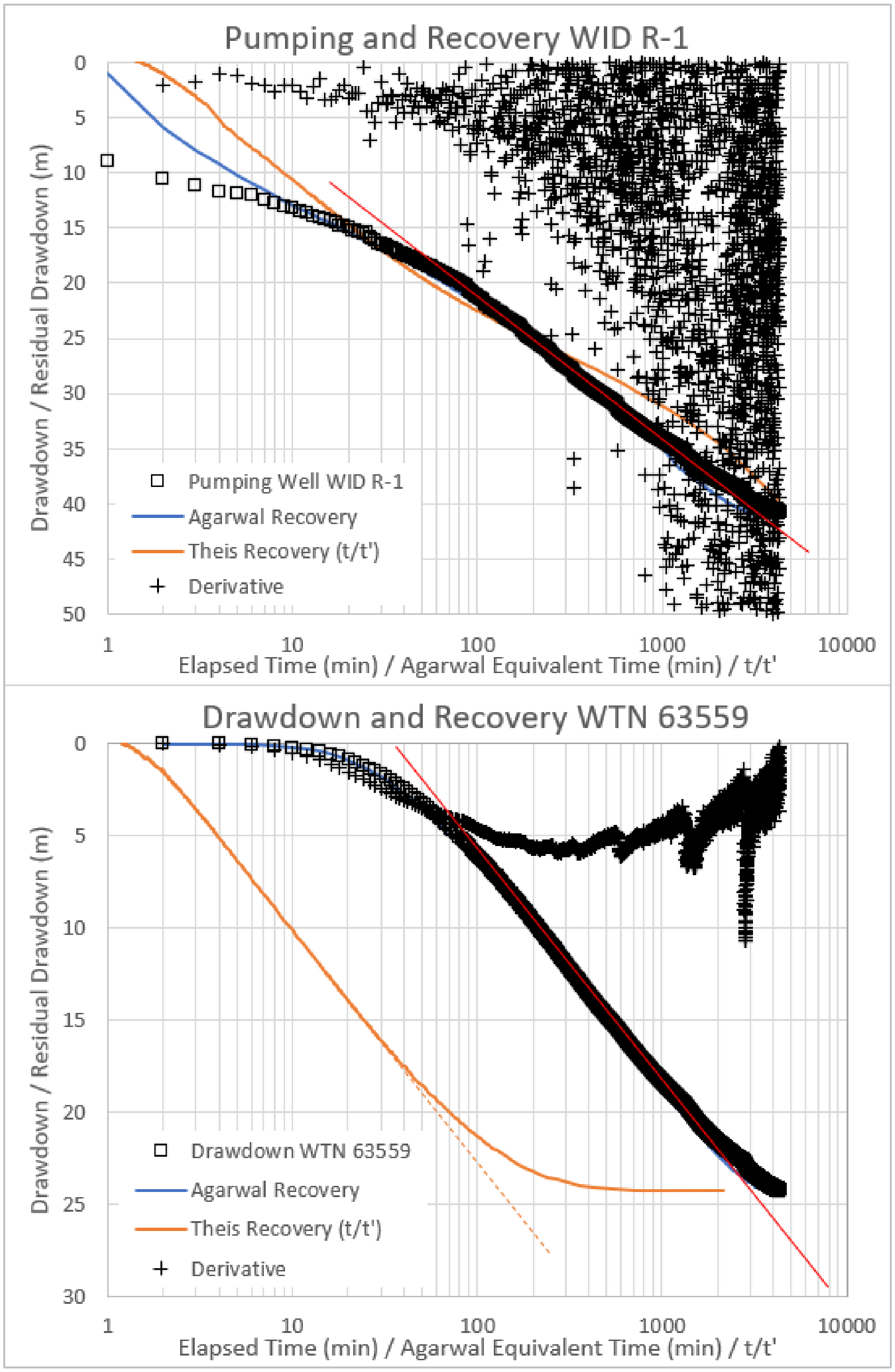
If well storage effects are relatively small and can, therefore, be neglected, the application of the Theis or Cooper-Jacob solutions may be appropriate to obtain transmissivity from the early-time data analysis. This analysis is effective if the cone of depression does not encounter substantial changes in the aquifer properties associated with a hydraulic boundary in the first 100 minutes of production. However, if casing storage is considerable and the specific capacity ($Q/\Delta s$) is low, a careful assessment is required to eliminate the casing storage effects (Driscoll, 1986, p.232). Transmissivity and storage thus determined, can be applied to appropriate analytical solutions to predict the theoretical drawdown at various times.

Storativity

The storativity value should be obtained from the data collected at the observation well, prior to the influence of a hydraulic boundary, because storativity derived from the Cooper-Jacob (1946) solution includes a t_0 term (the intercept of the straight line with the time axis) that is influenced by well skin or well bore storage in the pumping well and eliminates such a well from the calculation of storativity. To overcome this condition, an observation well located in the vicinity of the production well is required to establish the storativity value. Boundaries encountered at early times (i.e., within the first 100 minutes) that influence drawdown in the production and observation wells also render the storativity estimate invalid, because the boundary conditions alter the t_0 value.

If there is no observation well, an approximation value of storativity can be taken from the literature and knowledge of the aquifer characteristics (e.g., confined or unconfined). In such a case, however, the accuracy of storativity is less reliable, and a statistical approach may be considered. Calculating storativity from the pumping well data will result in erroneous values because of the effects of wellbore storage.

APPENDIX B: EXAMPLE PUMPING TEST DATA FROM PHC (1994)



Pumping test data from the pumping well in upper graph showing mismatch in pumping (squares) and recovery (orange line) data. Lower graph contains observation well data from the same pumping test, showing matched drawdown and recovery data as well as 'flat' area in derivative ('+'); period of radial flow valid for Cooper-Jacob. Source: PHC, 1994.