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by

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Introduction

In Alberta, it has been customary to describe the hydrogeological performance of geologic layers with a procedure which is said to reflect the response of the aquifer to pumping: the so-called safe yield for 20 years of continuous pumping (Q20 or Q_{20}). In the past there have been doubts expressed about the procedure used and its physical validity. WDA was asked to apply this method in determining the available groundwater supply in a rural area of Southern Alberta. When examining the history of the 20-year safe yield and its physical meaning it became evident why this parameter often has little relation to the actual behaviour of the aquifer if pumped for 20 years. Below we present the results of our investigation and show alternatives to the present use of the 20-year safe yield.

20-year safe yield (Q20) of wells

The 20-year safe yield (Q20) for a well is defined as the rate at which a well can be pumped continuously for a period of 20 years so that the pumping water level does not fall below the top of the aquifer. In practice the available drawdown is sometimes taken as the difference between non-pumping water level and the top of the screen.

This is not the place to describe in all detail the basic hydraulics and the mathematical derivations and assumptions which led to the simplified calculation of transmissivity, apparent transmissivity, the safe rate of pumping, the 20-year safe yield Q20, and the apparent Q20 as widely used in Alberta. Nevertheless, WDA has been asked by The Prairie Farm Rehabilitation Administration (PFRA) to explain, why, in our opinion, the use of the Q20 concept does not add to hydrogeological knowledge to the degree to justify its general use, and in particular its use based only on two water level measurements, the so-called 'apparent Q20'.

In Alberta, the public data base maintained by 'The Groundwater Centre' (TGWC) offers in its well data sets over 77,000 calculated 'apparent transmissivities' and 'apparent Q20' (based upon two water level measurements two hours apart) while it offers only about 100 Q20 values presumably based on long term pump tests (TGWC, 2003).

While data supplied by TGWC list ‘apparent Q20’ it has become the custom in Alberta to refer to the ‘apparent Q20’ simply as Q20, thus creating a false sense of confidence in the value. We should keep in mind that nearly all reported transmissivity and Q20 values in Alberta are actually ‘apparent transmissivities’ and ‘apparent Q20’ values based on 2 hour pumping tests with two water level readings, the static non-pumping water level before pumping and the water level at the end of pumping. This procedure already violates a basic condition of the use of Jacob’s simplified solution method to calculate the transmissivity of an aquifer, namely the long duration of the pumping test (see below for more detail). Hence, simply because this condition does not apply to the determination of ‘apparent transmissivity’ and ‘apparent Q20’, calculation of these parameters is in our opinion not a useful exercise.

Farvolden (1959) introduced the concept of the safe pumping rate of a well for 20 years in Alberta. The report remained unpublished and is not easily available. Hence, the practical literature normally refers to Farvolden (1961) as the source of the Q20-concept. In reality Farvolden (1961) does not apply the safe yield concept in the calculations of the report and does not refer to the Q20 concept at all. The concept was then used by Tóth (1966), who called it a safe yield Q_{s20}. It was then adopted by the Alberta Research Council in the preparation of the hydrogeological maps of Alberta (Tokarsky, 1971; Ozoray and Barnes, 1977, Stevenson and Borneuf, 1977, etc.).

Farvolden (1959, p.7) required, for the calculation of a safe pumping rate, a pump test of 1000 minutes length with readings taken “*every minute from 1 to 10 minutes, every 5 minutes from 10 to 30 minutes, every 10 minutes from 30 to 100 minutes and every 50 minutes from 100 to 1000 minutes*”. From the straight drawdown curve (on semi-logarithmic paper with the time axis in $\log_{10}$-scale and the drawdown in linear scale) Farvolden (1959, p. 8) calculates the transmissivity following Jacobs simplified method of solution (Cooper and Jacob, 1946; Jacob, 1950). Todd (1959, p.94) points out that Jacobs’s method can be applied for small values of *u* (a variable in the non-steady state Theis equation for calculation of permeability in confined aquifers; see Kruseman and de Ridder, 1976, p.52). Small *u* occur if *r* (the diameter of the cone of drawdown) is small and the value of *t* (time of pumping) is large. The equation to derive the apparent transmissivity and safe yield can then be described as:

$$T = (264*Q)/\Delta s \qquad [\text{igpd/ft}] \qquad \text{(in imperial units)}$$
$$T = (0.183*Q)/\Delta s \qquad [m^3/\text{day}/m = m^2/\text{day}], \qquad \text{(in metric units)}$$

where Q is the pumping rate of the well and Δs is the drawdown of the well.

Subsequently the straight-line drawdown curve was extrapolated by calculation to 8 log cycles (10 million minutes = 19 years). The 20-year safe rate Q was then calculated:

$$Q = (T*H*0.7) / 2110 \; [\text{igpd}] \qquad \text{(in imperial units)}$$
$$Q = (T*H*0.7)/14.71 \; [m^3/\text{day}] \qquad \text{(in metric units)}$$

where T is the transmissibility (transmissivity), H is the available head (difference between static non-pumping water level and the top of aquifer), and 0.7 is a safety factor reducing the Q value to 70%. In later works Farvolden's (1959) safe rate Q for 20 years was renamed by others to 20-year safe yield Q20. Farvolden (1995) regretted his 1959 introduction of the 20-year safe pump rate, due to inadequate physics involved and the way people had been applying the concept without regard to it's limitations, in particular the requirement of a measured straight semi-log-line for 1000 minutes of drawdown. To our knowledge, Farvolden never published the concept of safe yield and never seems to have applied it himself.

Farvolden (1961) also introduced the calculation of what he called the 'apparent transmissivity' based on two water levels only, the static 'non-pumping water level' [NPWL] and the water level at the end of the test [pumping water level; PWL]. "*The validity of this method of determining transmissibility* [this author: transmissivity] *is open to serious doubt because a number of factors that may have significant influence on the results are not considered. The answers obtained from such a calculation are therefore termed 'apparent transmissivity' in this paper"* (Farvolden, 1961, p. 9).

Farvolden's (1961) comments likely refer to the physics of groundwater flow as it affects the transmissivity calculation based on only two points. Farvolden (1961) does not refer to the mathematical ambiguity a two-point calculation of 'apparent transmissivity' introduces into the result as there exists mathematically no unique solution for the determination of Δs, the drawdown over one log-cycle. In Figure 1 we show how the assumed starting value of the diagram affects the outcome of the determination of Δs because there exists no zero time point on the horizontal logarithmic time axis. Now it is up to our inclination to choose the logarithmic starting point (t_s) at 1 minute, 0.1 minute,

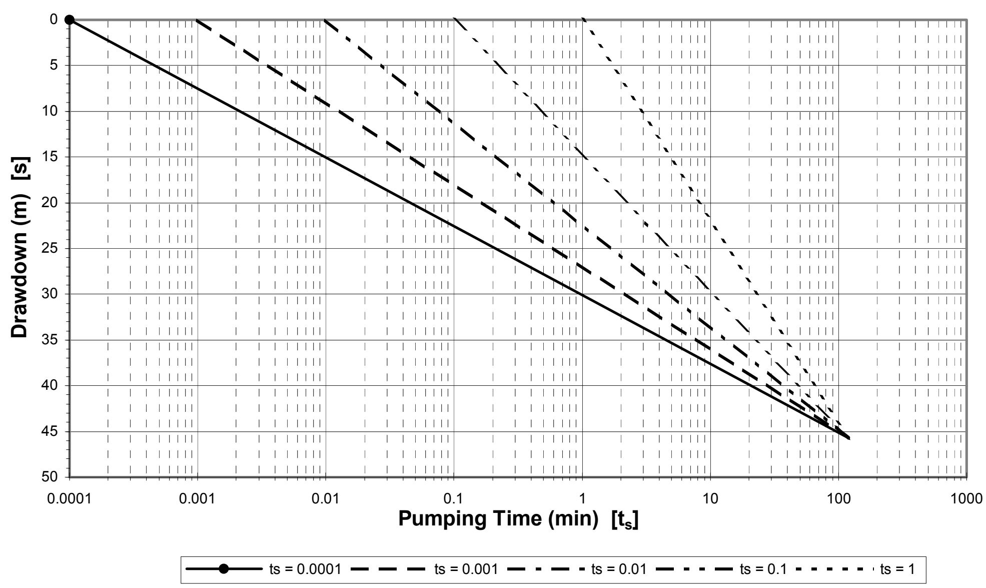

Figure 1: Mathematical ambiguity in calculating the drawdown curve of well 1401908.16NW.01 in dependence of assumed starting time t_s. (compare table 1)

0.01 minute, or 0.001 minutes, etc.. Unfortunately, that choice immediately and significantly affects the result of our calculation. Table 1 shows that the selection of the drawdown starting point on the time axis can mathematically change the end result by 100 % or more.

T apparent = 0.18 Q/Δs

Pump Rate Q = 111.3 m^3/day

Starting Value	Δs [m]	T apparent [m^2/day]	% [%]
t_s = 1 (60 s)	22	0.91	100
t_s = 0.1 (6 s)	14.8	1.35	148
t_s = 0.01 (0.6s)	11.3	1.77	195
t_s = 0.001 (0.06s)	9	2.23	245
t_s = 0.0001 (0.006s)	7.5	2.67	293

Q_{20} apparent = 0.68 (T apparent)(H)(0.7)

T apparent = as calculated above

H = 94.18m (top of aquifer) - 24.38m (NPWL)

= 69.8m

Starting Value	T apparent [m^2/day]	Q_{20} apparent [m^3/day]	% [%]
t_s = 1 (60 s)	0.91	30.23	100
t_s = 0.1 (6 s)	1.35	44.85	148
t_s = 0.01 (0.6s)	1.77	58.81	195
t_s = 0.001 (0.06s)	2.23	74.09	245
t_s = 0.0001 (0.006s)	2.67	88.71	293

Values determined by TGWC [2003]

T apparent = 2.7 m^2/day

Q_{20} apparent = 70.75 m^3/day

Table 1:
Calculation of apparent transmissivity and Q20 for well W401908.16NW.01

Alberta Well ID: 185639
TGWC-ID: M35377.114025

Date of Pump Test:	13/06/1977
Avg. Pump Rate:	77.28 l/min 111.3 m^3/day
Drawdown:	45.72m
(Pumping duration not listed; 120 min assumed)	
NPWL:	24.38m

As pointed out before, there exist, in Alberta, over 77,000 determinations of 'apparent transmissivities' and 'apparent Q20' based on two water level measurements and only 100 determinations presumably based on long term pumping tests (TGWC, 2003; a requested clarification about the exact procedure was not available). The mathematical ambiguity of the existing 'apparent Q20' could have been eliminated had there been 3 measurements taken: one for the static, 'non-pumping water level', the second one, say, about 10 minutes into the pump test, and one at the end of the pump test.

This procedure, based on three short-term water level measurements usually within less than two hours, would still be very inadequate to project the behaviour of a well 20 years into the future, but at least the mathematical ambiguity would have been removed.

Bibby (1979, p.4) is of the opinion that in the typically-heterogeneous layer systems in Alberta "*the only meaningful parameter that can be used is the drawdown curve itself*." From long term pumping tests he noticed that, "*on a semi-logarithmic plot the straight-line portion observed in the shorter test continues for some time, eventually deviates from being straight, becomes successively steeper in a transition zone, and finally forms a straight line again (Fig.5*; this author: in Bibby, 1979*). This final straight line is always steeper than the initial one."* Bibby (1979, Fig 5) showed the final straight line to appear after about 1000 minutes (16.67 hours) of pumping. It would be ideal to continue pumping for altogether 10,000 minutes (7 days) until the next log cycle has been reached. That, however, may be impractical. Therefore we settle for a pumping duration of about 4,320 minutes (72 hours) such that the straight line could then be extrapolated to 10,000 minutes within that log-cycle. Bibby (1979, p.7) referred to a transmissivity, calculated from the first straight line, as 'local transmissivity' and to the one calculated from the second straight line as 'regional transmissivity'.

Bibby (1979, p.4) makes abundantly clear that the data obtained have no physical meaning. He states: "*Usually data are analyzed by fitting either Jacob straight lines or Theis non-leaky type curves to the segments of the plotted drawdown curves . The associated formulas are then used to obtain values of transmissivities and coefficient (for Theis), while acknowledging that the assumptions on which the formulas are based are not met. Used this way, these methods are strictly formulas, since there is no physical justification for their use. The transmissivity and storage values obtained are simply numbers, having no more meaning than the slope of the drawdown curve from which they are derived.*" That would then also have to be applied to the Q20-value as it is derived using the same procedure.

After questioning the value of the so-called transmissivities Bibby (1979, p. 9) discusses the procedure of prediction of the 20-year safe yield. *"Significantly, the method of predicting 20-year sustainable yields, as distinct from that used to calculate local and regional transmissivities, does not depend on Jacob's equation The sole assumption made is that if the drawdown curve is presumed known for 20-years for any constant pumping rate, then the 20-year sustainable yield can be obtained by a* <u>*linear*</u> *shift of this curve. For the specific purpose of predicting* $Q_{20,}$ *the calculation of transmissivity is a redundant step. This again indicates that the drawdown curve is the essence of well hydraulics in highly heterogeneous systems".*

Bibby (1979, p.9) states: *"Predictions of 20-year sustainable yields apply only to the well on which the test was conducted and cannot be applied to other points in the neighbourhood because, even if the regional transmissivity value were the same, local transmissivity values are too variable (having a log-normal distribution). The highly irregular cone of depression also prevents the prediction of drawdown at points in the aquifer away from the pumping well."*

Bibby's (1979) article made three things clear, (1) the one-hole well pumping test does not allow to determine real transmissivities in Alberta due to the heterogeneous nature of the 'aquifers', (2) drawing maps of Q_{20} values serves no purpose as the local transmissivity determines the behaviour of any new well drilled, and (3) there is no need to actually calculate a transmissivity for the determination of Q_{20}.

Determination of the slope is all that is needed for the linear shift of the curve in determining Q_{20}. We have shown above how the calculation of the slope is ambiguous and arbitrary if only two water levels are used as is the case in nearly all of Alberta's Q_{20} calculations. Hence the present use of Q20 in Alberta is arbitrary and needs to be changed if the real behaviour of groundwater in the tested aquifers should be reflected. This can probably be achieved by an extension of the pumping duration to at least 72 hours, as is now required by Alberta Environment (2002), and then evaluating of regularly recorded drawdown data and pumping rates following Bibby's (1979) proposals and/or use 'specific capacities' to describe the performance of wells as was proposed by Domenico and Schwartz (1990, p. 169-171).

Specific Capacity of wells

"Specific capacity of a well is the yield of a well per unit of drawdown, usually expressed as gallons of water per minute per foot (gpm/ft) of drawdown or cubic meters per day per m (m^3/day/m), after a given time has elapsed, usually 24 hours. Dividing the yield of a well by the drawdown, when each is measured at the same time, gives the specific capacity" (Driscoll, 1986, p. 207). Specific capacity generally varies with duration of pumping – as pumping time increases, specific capacity decreases. Driscoll (1986, p. 536) recommends pump tests with a minimum of 72 hours pumping and recovery up to 90% of drawdown for unconfined and a minimum of 24 hours pumping for confined aquifers and recovery again up to 90% of drawdown. For a step-draw-down test 24 hours is usually sufficient for either type of aquifer (Driscoll, 1986, p. 536).

Farvolden (1959, p.7) already recommended the use of specific capacity in case '*that the recharge balances the discharge*' of the well. That would be the case in many farmers wells in the province of Alberta, in particular as the wells are not pumped continuously but intermittently for altogether probably not more than one hour a day. Outside of Alberta, use of specific capacity is considered the way to describe the productivity of a well (Freeze and Cherry, 1979, p. 313). Domenico and Schwartz (1990, p.168) consider the 'specific capacity' as the accepted standard when comparing the strength of one well versus another.

Both, Freeze and Cherry (1979) and Domenico and Schwartz (1990) ignore the *safe yield Q20* concept and do not consider it at all when dealing with well productivity.

Domenico and Schwartz (1990, p.169) recommend the calculation of the specific yield using the following equation derived from Theis (1935)

$$Q/s = T/(264 \log (Tt/1.87r^2_w S) - 65.5), \quad \text{(in US units)}$$
$$Q/s = 15.27\, T/(4.03 \log (4Tt/r^2_w S) - 1), \quad \text{(in metric units)}$$

where t is the pumping period in days [days], r_w is the effective radius of the well in ft [m], T is the transmissivity in gallons per day per foot [m^3/day/m], S the dimensionless coefficient of storativity, and Q/s is the specific capacity in gallons per minute per foot [l/min/m].

This method is not suited for the data presently at hand in Alberta. This or similar methods may be considered if long time pumping tests with proper recording of water levels and flow rates become available.

Presently, in Alberta only the above method by Driscoll (1986) can be applied. The method is not restricted to three or more water level measurements and can therefore be used with the two-water-level-measurement recordings of pumping tests widely available in Alberta. There are, however, definite drawbacks to recording only two water level measurements during such pumping tests. If no record of the drawdown behaviour is kept during pumping then there is hardly any way to determine whether the after pumping water level measured is representative for the drawdown achieved or already disturbed by rapid rise of the water level after the end of pumping. Therefore, again, any evaluation of two-water-level-measurements is tentative and associated with great uncertainty.

The use of specific capacities is directly linked to the performance wells and hence cannot easily be regionalized for the typically-heterogeneous aquifers in Alberta. Use of specific capacity eliminates the mathematics of logarithms and therefore leads to more reliable numbers. A limitation is that specific capacities change with the length of the pumping. Hence records need to be kept about the water level and pumping rates need to be taken frequently to determine the changes within the specific capacity over the duration of pumping. This is not a burden in times of electronic data recorders. When comparing the performance of wells only specific capacities of same pumping duration should be compared.

For each particular pumping rate the specific capacity is directly dependant on the measured drawdown. In fact if, with increasing time of pumping, the changes in the water level approach zero and stay stable, then the accompanying water level indicates a stable water level for the applied pumping rate. In other words, we would have found a pumping rate which is supported by the hydraulics in the area of the well and the actual recharge having occurred previously in the area. Therefore, in this respect the specific capacity is also superior to the Q20, because the use of Q20 assumes that the groundwater pumped comes out of storage (storativity) and **no recharge** takes place for twenty years in support of the well's performance. This, of course, is an unfounded assumption not based in reality.

Conclusions

Pumping test data in Alberta have been evaluated for 'apparent transmissivity' (two-water-level measurements following the procedure by Farvolden (1961). We have shown that this procedure is mathematically ambiguous and can thereby introduce errors exceeding 100%. In determining a Q20 value it is not necessary to calculate an 'apparent transmissivity' because the calculation consists of a linear transfer of a curve only. This curve has no physical meaning and thus neither does the Q20 value. A Q20 value is only calculated and valid for a particular well and cannot be transferred to other wells in the area. Hence maps of Q20 values do not contain information useful for the construction of a particular well at a site chosen. The performance of this well depends on local conditions that simply cannot be predicted with Q 20 values.

The use of 'apparent Q20' values is based on two water level measurements: one at an undisclosed time before pumping, the second at or after the end of pumping. The problem with the first measurement is that a zero time cannot be easily determined due to the mathematics of logarithms, and the second measurement may be inadequate if hand-held measurements are done. The use of apparent Q20 in Alberta does not add to hydrogeological knowledge and should be discontinued. Nearly all of the Q20 values used in Alberta are 'apparent Q20' (TGWC, 2003). The 'apparent Q20' value is only a number which may mislead by providing a false sense of security.

Use of a Q20 value based on long duration pumping (Bibby, 1979) would give valuable performance data of individual wells but, in Alberta with its heterogeneous aquifers, cannot easily be transferred by maps or the like into regionally applicable information.

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