GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

Pumping Test in a Confined Aquifer: How to Detect a Poorly Sealed Monitoring Well

Robert P. Chapuis[a], Djaouida Chenaf[b]
[a] *Dept CGM, École Polytechnqiue, Montreal (QC), Canada*
[b] *Dept of Civil Engng, RMC, Kingston (ON), Canada*

ABSTRACT
When a well is monitoring a confined aquifer, its riser pipe must be perfectly sealed against the borehole wall. A poor seal produces a hydraulic short-circuit and preferential seepage in it. Then, the static water level in the monitoring well is not the aquifer piezometric level, which is unknown. During a pumping test, a poorly sealed monitoring well yields incorrect drawdown and recovery data. This paper explains how to detect short-circuiting and obtain the correct drawdown data, using the example of a test near Moncton, NB. The usual methods for interpreting the drawdown and recovery data ignored the possible short-circuiting: they yielded close values for transmissivity *T*, but storativity *S* values differing by 500%. The proposed method found that because of short-circuiting the static water level in the riser pipe was 124 cm below the aquifer piezometric level. Then, drawdown and recovery data were corrected and reanalyzed, which yielded new and close values for T and S, thus supporting the diagnosis of hydraulic short-circuiting.

RÉSUMÉ
Un puits qui surveille une nappe captive doit avoir son tuyau parfaitement scellé contre la paroi du forage. Un mauvais scellement cause un court-circuit hydraulique avec écoulement préférentiel. Ainsi, le niveau d'eau statique dans le tuyau n'est pas le niveau piézométrique de l'aquifère, qui est inconnu. Pendant un essai de pompage, un puits de surveillance mal scellé produit des valeurs de rabattement, en pompage et remontée, qui sont incorrectes. Cet article explique comment détecter un court-circuit hydraulique et obtenir les bonnes valeurs du rabattement, avec l'exemple d'un essai près de Moncton, NB. Les méthodes usuelles d'interprétation du pompage et de la remontée ont ignoré la possibilité d'un court-circuit : elles ont fourni des valeurs voisines pour la transmissivité *T*, mais des valeurs différant de 500% pour le coefficient d'emmagasinement *S*. La méthode proposée a démontré qu'à cause d'un court-circuit, le niveau d'eau statique du tuyau était 124 cm plus bas que le niveau piézométrique de l'aquifère. Par la suite, les données de rabattement en pompage et remontée ont été corrigées puis à nouveau analysées, ce qui a donné de nouvelles valeurs pour *T* et *S*, cette fois cohérentes entre elles, ce qui a confirmé le diagnostic de court-circuit hydraulique.

1 INTRODUCTION

Consider a monitoring well (MW) in a confined aquifer. The annular space between the riser pipe and the borehole wall must be sealed, everywhere between the pumped aquifer and the surface. Along a vertical line the hydraulic heads are different in aquifers and aquitards. If the MW is poorly sealed, a hydraulic short-circuit (HSC) is formed along the MW pipe, which modifies the hydraulic head close to the MW screen. The static water level (SWL) in the pipe is not equal to the piezometric level (PL) in the monitored aquifer. This HSC problem was studied by Chapuis (1988), Chapuis and Sabourin (1989), Avci (1992), and Brikowski (1993) among others. As a result, any drawdown during a pumping test is erroneous (Chapuis and Chenaf 1998). Similar problems occur with MWs having several screens to pump several small aquifers, and also open holes in fractured rock: below a static water level, complex upward and downward water movements take place in the riser pipe or the open hole (Chapuis 2006). The influence of drilling and sealing methods on the seal quality are not discussed here.

When there is a HSC, polluted surface water may seep along the defect and reach the confined aquifer used for water supply (Meiri 1989; Silliman and Higgins 1990; Nordbotten et al. 2004; Santi et al. 2006). The water analyses may lead to incorrectly conclude that the aquifer is polluted. For example, polluted water seeps along a poor seal at a rate of 5 cm^3/min: thus, each day, 7.2 L of polluted water reaches the MW filter pack and screen. If the MW water is sampled three months later, there will be 650 L (0.65 m^3) of polluted water close to the screen and filter pack. It is unlikely that all polluted water will be removed by purging or pumping until reaching stable physical and chemical conditions. The aquifer will be viewed as polluted, which is right, but how? The answer is: it is locally polluted by the poor seal along the MW.

Hydraulic short-circuits can be detected using indirect methods such as ultrasonic testing methods (Yesiller et al. 1997; Christman et al. 2002), or direct methods such as injection of a radioactive tracer (Dunnivant et al. 1997). All methods have limits (Chapuis 1998). Direct methods, which quantify the piezometric error and leakage rate, are preferable. Such a direct method, combining pumping test and tracer test, was designed and successfully tested (Chesnaux et al. 2006; Chesnaux and Chapuis 2007).

This paper describes another direct method for detecting a HSC, using the drawdown data of a pumping test at constant rate, Q_w, in a fully confined aquifer. This method gives the piezometric error – defined as the difference between the PL in natural conditions, and the SWL in the MW pipe – and then more correct values for the transmissivity *T* and the storativity *S* of the tested confined aquifer.

2 STEADY-STATE CONDITIONS

The steady-state solution for a hydraulically short-circuited MW (Chapuis and Sabourin 1989) is used here as a starting point to obtain the transient solution for a short-circuited pumping test in a confined aquifer. The hydraulic parameters (Fig. 1) have indexes 1 to 4, which refer to the upper aquifer (1), the poor seal in the aquitard (2), the lower confined aquifer (3) and the aquitard (4).

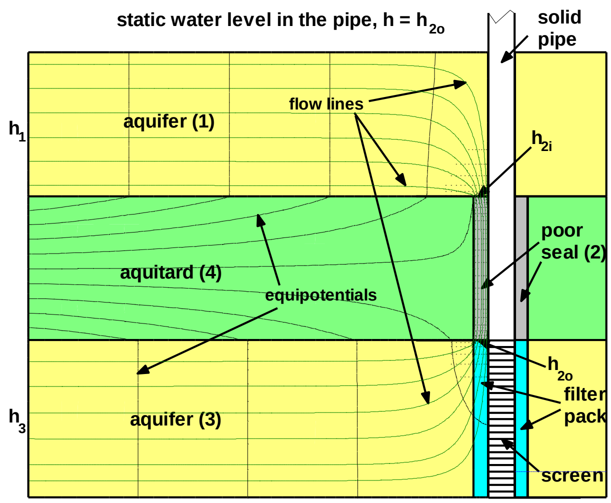

Figure 1. Schematic illustration of preferential seepage (hydraulic short-circuit) along a monitoring well (MW).

Before drilling, steady-state conditions are assumed. The hydraulic head h takes the local following values, in the vicinity of the MW to be installed: h_1 in the upper aquifer and h_3 in the lower aquifer (case $h_3 < h_1$ in Fig. 1). A MW is installed in the lower aquifer and poorly sealed. Through the poor seal, water leaks at a small flow rate, q, the hydraulic head varying from h_{2i} (inlet) to h_{2o} (outlet). Since the hydraulic head loss within the well solid pipe is negligible, the static water level in the pipe is h_{2o}. The piezometric error is thus defined as $h_3 – h_{2o} = H_0$.

For a leak at steady-state, the flow rate q_1 coming from the upper aquifer is equal to the flow rate q_2 flowing in the seal defect which, in turn, is equal to the flow rate q_3 injected into the lower aquifer. The aquitard drainage contribution to the leak is very small and thus neglected. Three expressions can be derived for the flow rate q. The properties of harmonic functions can be used for an injection zone either discharging or pumping at the boundary of an aquifer in steady state, which is a special type of constant-head permeability test (e.g., Hvorslev 1951):

$$q_1 = q = 2K_1 D_2 (h_1 - h_{2i}) \,, \qquad [1]$$

$$q_3 = q = 2K_3 D_2 (h_{2o} - h_3) \,. \qquad [2]$$

where K_1 and K_3 are the hydraulic conductivities of the upper and lower aquifers, whereas K_2 is the equivalent hydraulic conductivity and D_2 the equivalent diameter of the poorly sealed zone. The flow rate through this zone of length b_2 is given by Darcy's law as:

$$q_2 = q = \frac{\pi D_2^2}{4} K_2 \frac{h_{2i} - h_{2o}}{b_2} \,. \qquad [3]$$

To simplify the resolution, we define the a_j parameters:

$$a_1 = 2K_1 D_2 \,, \qquad [4]$$

$$a_2 = \frac{\pi K_2 D_2^2}{4 b_2} \,, \qquad [5]$$

$$a_3 = 2K_3 D_2 \,. \qquad [6]$$

The 3 Eqs (4-5-6) with 3 unknowns (h_{2i}, h_{2o} and q) yield:

$$q = (h_1 - h_3) / \sum a_i^{-1} \,, \qquad [7]$$

$$h_{2i} = \frac{a_1(a_2 + a_3) h_1 + a_2 a_3 h_3}{a_1 a_2 + a_2 a_3 + a_3 a_1} \,, \qquad [8]$$

$$h_{2o} = \frac{a_1 a_2 h_1 + a_3(a_1 + a_2) h_3}{a_1 a_2 + a_2 a_3 + a_3 a_1} \,. \qquad [9]$$

where the static water level in the MW riser pipe is h_{2o}:

$$h_{2o} = \frac{\alpha h_1 + \beta h_3}{\alpha + \beta} \text{ with } \alpha = a_1 a_2 \text{ and } \beta = a_2 a_3 + a_3 a_1 \,. \qquad [10]$$

These equations were verified using finite element (Chapuis and Sabourin 1989). Usually, h_{2o} is closer to h_3 than to h_1: it means that $\alpha / (\alpha + \beta)$ is small, and $\beta / (\alpha + \beta)$ is close to 1. The hydraulic heads h_1 and h_3 are still active at the radius of influence of the leaking zone, which is a small distance lower than a few meters (Guyonnet et al. 1993).

The leakage rate, q, is usually in the 1–10 cm^3/min range, which makes 1.4 to 14.4 L/day, and about 1 m^3 after three months, which may be the interval at which the MW is sampled. Before sampling, the screen is surrounded by polluted water. During water sampling, the pumped volume is usually much smaller than the surrounding polluted volume and polluted water never ceases to reach the screen area. In addition, during sampling, the local hydraulic head h2o is reduced, which increases the leakage rate and brings more polluted water. As a result, the groundwater is viewed as polluted, whereas it should be viewed as locally polluted by a faulty installation.

3. EQUATIONS DURING PUMPING

3.1. Perfect Monitoring Well

The well is pumped at a constant rate Q_w starting at time t = 0. The usual conservation equation for an isotropic saturated confined aquifer, of transmissivity T and storativity S, in polar coordinates (r, θ) is:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t} \,. \qquad [11]$$

If s is the MW drawdown at time t and distance r from the pumping well, the classical solution of Theis (1935) is:

$$s(r,t)=\frac{Q_w}{4\pi T}\int_u^\infty \frac{e^{-x}}{x}dx=\frac{Q}{4\pi T}\mathrm{W}(u)\text{ with } u=\frac{r^2S}{4Tt}, \quad [12]$$

where W(u) is the exponential integral function Ei(u), which is defined by a converging series:

$$\mathrm{Ei}(u)=-\gamma-\ln(u)+\frac{u}{1\cdot 1!}-\frac{u^2}{2\cdot 2!}+\frac{u^3}{3\cdot 3!}-\frac{u^4}{4\cdot 4!}\cdots, \quad [13]$$

γ = 0.577 2… being the Euler's constant.

The third and following terms in Eq 13 become negligible when t increases and thus u decreases (Cooper and Jacob 1946). Then, Equation 12 can be simplified as

$$s=\frac{Q_w}{4\pi T}\left[\ln\left(\frac{1}{u}\right)-\ln(1.781)\right]=\frac{Q_w}{4\pi T}\ln\left(\frac{2.25Tt}{r^2S}\right). \quad [14]$$

In a graph of s versus log (t), Equation 14 becomes

$$s=\Delta s\log\left(\frac{t}{t_0}\right),\ \Delta s=\frac{2.30Q_w}{4\pi T},\ t_0=\frac{r^2S}{2.25T}, \quad [15]$$

Which is a straight line of slope Δs and intercept (t_0, s = 0).

3.2. Poorly Sealed Monitoring Well

Before pumping, initial conditions are given by Eqs 1–10. For transient pumping conditions, the short-circuit solution becomes more complicated than that for steady-state because h_3 now varies with time, especially within the influence zone of small radius δr around the small leak. The short-circuit solution is obtained using the superposition principle. During pumping, if r is the radial distance of the MW to the pumping well, h_3 starts to vary first at (r–δr) but not yet at r and at (r+δr): thus the faulty MW initially reacts less than a perfectly sealed MW would have reacted, its drawdown $s_{2o}=s_{3f}$ (index f for faulty MW) being smaller than s_3 as given by Eq 12. The solution at early pumping time is not studied here. We consider only times long enough for the Cooper-Jacob approximation to be valid everywhere outside the small leak influence zone. According to Eq 15, the increase δs_3 in drawdown s_3 at any point at the boundary of the influence zone, between times, t_{j-1} and t_j, is

$$\delta s_3=s_3(t_j,r)-s_3(t_{j-1},r)=$$
$$\Delta s_3\log\left(\frac{t_j}{t_0}\right)-\Delta s_3\log\left(\frac{t_{j-1}}{t_0}\right)=\Delta s_3\log\left(\frac{t_j}{t_{j-1}}\right) \quad [16]$$

As a result, outside the radius of influence around the small leak, the hydraulic head is changed by the same constant value δs_3. Thus, the decrease in h_{2o} (or the increase in drawdown $\delta s_{2o}=\delta s_{3f}=-\delta h_{2o}$) can be obtained using the superposition principle as:

$$\delta s_3=-\left[h_{2o}(t_j,r)-h_{2o}(t_{j-1},r)\right]=$$
$$\frac{\beta}{\alpha+\beta}\delta s_3=\frac{\beta}{\alpha+\beta}\Delta s_3\log\left(\frac{t_j}{t_{j-1}}\right)=\Delta s_{3f}\log\left(\frac{t_j}{t_{j-1}}\right) \quad [17]$$

When the Cooper-Jacob approximation is valid, the drawdown s_{3f} at the faulty MW increases at a rate proportional to that of a perfectly sealed MW (Fig. 2). Thus, the faulty MW drawdown data (s_{3f}) still yield a straight line when plotted as s_{3f} versus log (t) (Fig. 2). The slope Δs_{3f} yields a transmissivity value T_{3f} slightly higher than the real value T_3 of the aquifer. The intercept t_{0f} gives a storativity value S_{3f} that may strongly differs from the real value S_3, because the difference between S_{3f} and S_3 also depends upon the unknown piezometric error H_0 before pumping (Fig. 2). The H_0 value could be precisely extracted from the initial portion of the drawdown curve of a faulty MW. However, the extracted solution for T_3 and S_3 would be unreliable due to many reasons why field data deviate from theory at early stage of a pumping test (e.g., Chapuis 1999). Here, the recovery data of the faulty MW are used to extract the H_0–value as shown below.

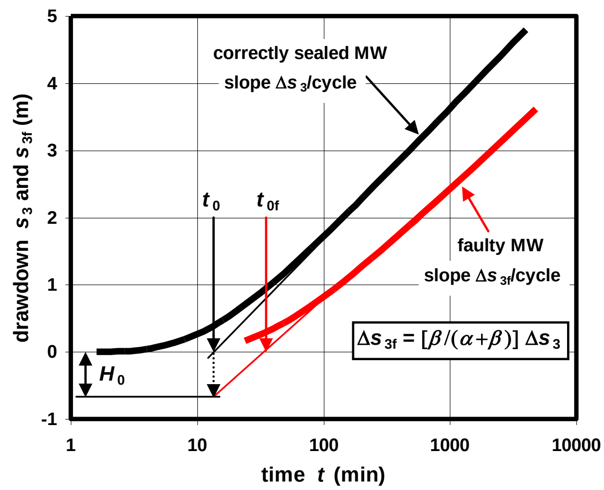

Figure 2. Graphs of s_3 and s_{3f} versus log (t) for correctly sealed and faulty monitoring wells.

4. EQUATIONS DURING RECOVERY

4.1. Perfect Monitoring Well

The recovery equations are obtained by superposing two solutions. When the pump is shut down, a new time t' starts for the recovery period. The residual drawdown s' is the same as if pumping had continued at the same constant rate Q_w and, the rate -Q_w were injected into the well from the time the pump was shut down. Theis (1935) has shown that:

$$s'=\frac{Q_w}{4\pi T}\left[\mathrm{W}(u)-\mathrm{W}(u')\right],\ u=\frac{r^2S}{4Tt},\ u'=\frac{r^2S}{4Tt'}. \quad [18]$$

In Eq 18, S has been assumed to be the same for pumping and recovery. If the times t and t' are large enough (u and u' are small enough), the well functions W(u) and W(u') can be replaced by their respective approximations (Cooper and Jacob 1946), which yield:

$$s'=\frac{Q_w}{4\pi T}\ln\left(\frac{t}{t'}\right). \quad [19]$$

When the s' data are plotted versus log (t/t'), Eq 19 gives the T value from the slope of the straight-line portion.

However, as S does not appear in Eq 19, it cannot be obtained from this graph. The S value can be obtained as follows (Chapuis 1992). The pumping period drawdown projected to time t' is called s_p (USDI 1977). This projected drawdown s_p is defined as:

$$s_p = \frac{Q_w}{4\pi T} \ln\left(\frac{t}{t_0}\right), \qquad [20]$$

and is obtained at any time t' by extrapolating the straight line semi-log plot, or using Eq 20 (Fig. 2). Then $(s_p–s')$ is:

$$s_p - s' = \frac{Q_w}{4\pi T} \log\left(\frac{t'}{t_0}\right). \qquad [21]$$

Equation 21 gives a straight-line relationship between $(s_p–s')$ and log t', with a slope $\Delta(s_p–s')$ over one time log cycle and a time intercept t_0 when extrapolating to $(s_p–s') = 0$. It is equivalent to the Cooper-Jacob equation for the pumping period drawdown, and valid for similar conditions on u' and t'. Consequently, the experimental values of $(s_p–s')$ plotted versus log t' (Fig. 3), provide T by:

$$T = \frac{2.30\, Q_w}{4\pi \Delta(s_p - s')}, \qquad [22]$$

and then, S by:

$$S = \frac{2.25\, T t_0'}{r^2}. \qquad [23]$$

The resulting recovery plot (Fig. 3) is similar to that for drawdown, and the equations for T and S are similar.

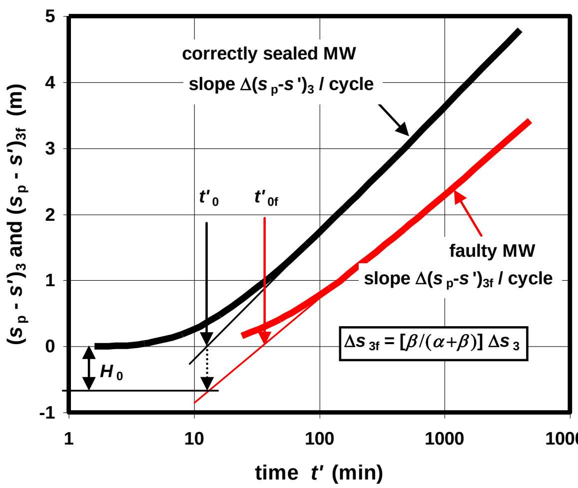

Figure 3. Graph of $(s_p–s')_3$ and $(s_p–s')_{3f}$ versus log t' for correctly sealed and faulty MWs.

4.2. Poorly Sealed Monitoring Well

The short-circuit solution for transient recovery is obtained with the superposition principle. When recovery starts, h_3 varies at $(r–\delta r)$ but not yet at r and at $(r+\delta r)$: thus, the faulty MW initially reacts less than a perfectly sealed MW would have reacted. The complete solution to the mathematical problem at early times is not examined here. Again, solutions are developed for the times after which the conditions for the Cooper-Jacob approximation are met everywhere around the influence zone of the small leak. Consider an increase $\delta s'_3$ at any point at the boundary of the small leak influence zone, between successive times, t'_{j-1} and t'_j. According to Eq 21:

$$\delta s_3' = \Delta s_3 \left[\log\left(\frac{t_j'}{t_j}\right) - \log\left(\frac{t_{j-1}'}{t_{j-1}}\right) \right]. \qquad [24])$$

Therefore, all conditions $h'_3(r, \theta, t)$ around the small leak are changed by the same constant value $\delta s'_3$. As a result, using the superposition principle and Eq 10, the change in h_{2o} (or residual drawdown $\delta s'_{2o} = \delta s'_{3f} = – \delta h_{2o}$) is:

$$\delta s_{3f}' = \delta s_{2o}' = h_{2o}'(t_j, r) - h_{2o}'(t_{j-1}, r) = \frac{\beta}{\alpha+\beta} \delta s_3'. \qquad [25]$$

Once the Cooper-Jacob conditions are met, the residual drawdown s'_{3f} in the faulty MW decreases at a rate which is proportional to the rate a perfectly sealed well would have decreased (Fig. 3). This means that the recovery data at the faulty MW yield straight lines in the semi-log plot. The graph of Eq 21 for recovery (Fig. 3) has the same drawback as the graph of Eq 18 for pumping (Fig. 2). It provides an apparent storativity S'_{3f}:

$$S_{3f}' = \frac{2.25 T t_{of}'}{r^2}, \qquad [26]$$

which differs from S_3. The difference depends upon the piezometric error H_0 before pumping (Fig. 3). If H_0 is known, then the intercept occurs at $t = t'_0$ and the real value of S can be calculated. Mathematically, the H_0 value is not easy to extract from the early portion of the recovery curve of a faulty MW.

On Fig. 3, the straight line has a slope $\Delta s'_{3f}$ such as:

$$\Delta s_{3f}' = \frac{\beta}{\alpha+\beta} \Delta s_3' = \frac{\beta}{\alpha+\beta} \frac{2.30 Q}{4\pi T_3}. \qquad [27]$$

In Eq 27, T_3 is the true aquifer transmissivity. Thus, the recovery data of a faulty MW yield T_{3f}, slightly larger than T_3, by the same ratio as for the drawdown curve (Eq 17):

$$T_{3f} = \frac{\alpha+\beta}{\beta} T_3 \succ T_3 \qquad [28]$$

The results of Eq 16 are plotted in Fig. 4. Extrapolating the straight line to the t/t' axis gives an intercept $(t'/t)_{0f}$, which is not equal to one as in theory for a perfect MW. However, extending this line to the s' axis gives H_0 (Fig. 4), the sought piezometric error. Therefore, Figure 5 yields the error H_0.

For long recovery times, the residual drawdown data ($s'_{3f} = s'_{2o}$) of the faulty MW deviate from the straight line (Fig. 4): they come back to zero, the hydraulic head returning to its initial value h_{2o}, which differs from h_3 by the error H_0. This field data shift at the end of the recovery curve (Fig. 4) does not appear if the recovery time is not long enough. When this late shift appears, it may be also be interpreted as resulting from a natural hydraulic head variation in the tested aquifer, or from different S values during pumping and recovery (Jacob 1963). The possibility of a poorly sealed

MW is a third option to be investigated, especially if the methods of Theis and Cooper-Jacob for the pumping phase yield different sets of values for T and S. The error H_0 has not the same influence in log-log and semi-log plots, which modify the extracted T and S, especially S.

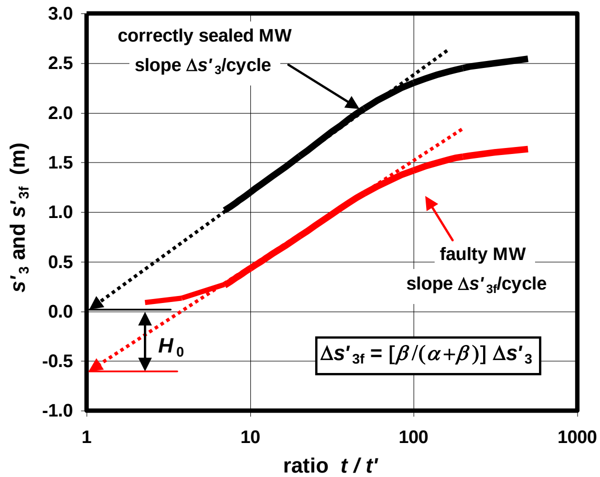

Figure 4. Graphs of s'_3 and s'_{3f} versus log t/t' for correctly sealed and faulty MWs.

If the assumption of a short-circuit influence is correct, the drawdown and recovery data must be corrected to give new plots, which should yield almost identical sets of (T, S) values. Having $S' < S$ occurs only if the aquifer is normally consolidated (geotechnical meaning relative to the effective stress levels) and has a settlement (during pumping) at least 10% higher that the recovery rebound: such a case is rare in nature. According to the authors' experience, the case of a poorly sealed MW is much more frequent.

The data of a pumping test performed near Moncton (New Brunswick) are analyzed below to illustrate how to use the proposed detection method for short-circuiting, and how to solve inconsistencies between different (T, S) sets as obtained by usual methods for pumping and recovery when the short-circuiting is ignored.

5. THE MONCTON PUMPING TEST

In a study of the Moncton area (New-Brunswick), Carr (1968) reported the data of a pumping test in a well 76 m deep (BH1, 250 ft). Here, we examine the drawdown and recovery data of a monitoring well located at 12.8 m (42 ft) from the pumping well. Since the data versus t and t' were not tabulated, the graphs 1A and 1B in Carr (1968) were digitalized to get the numerical values (Table 1).

5.1. Usual Interpretation for T and S

The confined aquifer was pumped at Q_w = 31 gpm = 8.47 x 10^{-2} m^3/s. For this paper, four methods were used to interpret the data of Table 1 for unsteady state conditions:

(1) the method of Theis (1935) for drawdown (Figure 5) provided T and S values;

(2) the method of Cooper–Jacob (1946) for drawdown (Figure 6) provided T and S values;

(3) the usual graph for recovery (Fig. 7), s' versus log (t/t'), gave T whereas the USDI equation (USDI 1981) or the method of Jacob (1963) gave S;

(4) the method of Chapuis (1992) for recovery, (s_p–s') versus log t', gave both T and S (Fig. 8).

Pumping phase			Recovery phase				
t min	r^2/t m2/min	s (m)	t' min	s' m	t / t' ---	s_p m	s_p - s' m
0		0.00	6	4.88	152.67	5.03	0.16
2	81.94	0.35	8	4.88	114.75	5.04	0.16
4	40.97	0.70	10	4.63	92.00	5.04	0.40
6	27.31	0.98	15	4.45	61.67	5.04	0.59
8	20.49	1.16	20	4.30	46.50	5.05	0.75
10	16.39	1.37	25	4.24	37.40	5.05	0.81
14.5	11.30	1.68	30	4.08	31.33	5.05	0.97
19	8.63	1.89	40	3.90	23.75	5.06	1.16
24	6.83	2.10	50	3.72	19.20	5.07	1.35
29	5.65	2.26	60	3.60	16.17	5.08	1.48
40	4.10	2.50	70	3.44	14.00	5.09	1.64
50	3.28	2.68	80	3.32	12.38	5.10	1.77
60	2.73	2.83	90	3.20	11.11	5.10	1.90
70	2.34	2.99	100	3.11	10.10	5.11	2.00
80	2.05	3.08	120	3.05	8.58	5.13	2.08
90	1.82	3.14	180	2.74	6.06	5.17	2.43
100	1.64	3.23	210	2.65	5.33	5.20	2.54
150	1.09	3.60	300	2.29	4.03	5.26	2.97
175	0.94	3.66					
200	0.82	3.75					
240	0.68	3.96					
350	0.47	4.27					
500	0.33	4.57					
910	0.18	5.00					

Table 1. Drawdown s (m) and recovery s' (m) at MW for the pump test in BH1 (Carr 1968). The tabulated values were obtained by digitizing the Figures in Carr (1968, p.10).

As a result, four sets of (T, S) values were obtained. The T values were close. However, the S values differed by a factor 518% (Table 2). Therefore, the usual interpretation methods, when the HSC was ignored, did not yield close values for S. In practice, this problem is frequent.

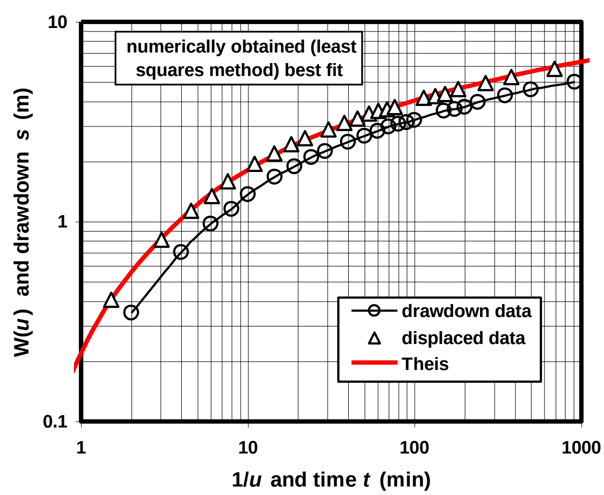

Figure 5: Method of Theis (1935) for MW drawdown data.

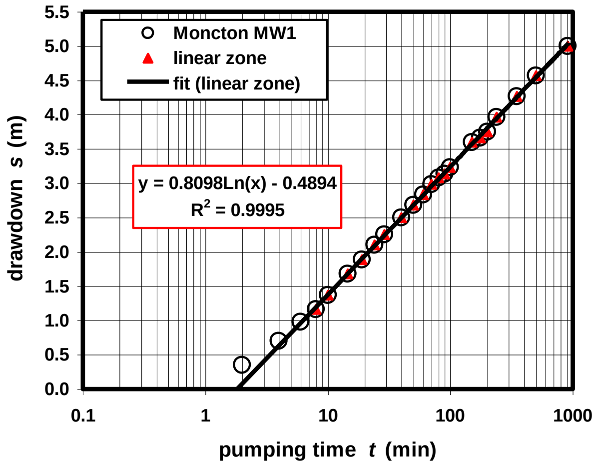

Figure 6. Method of Cooper–Jacob (1946) for MW drawdown data.

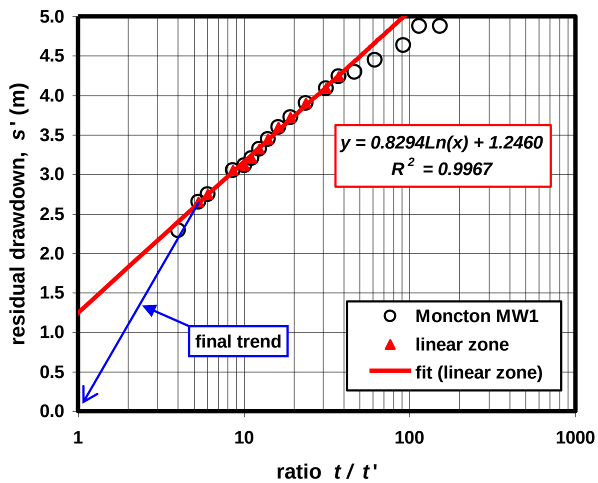

Figure 7. Graph of s' versus log (t/t') for MW recovery data.

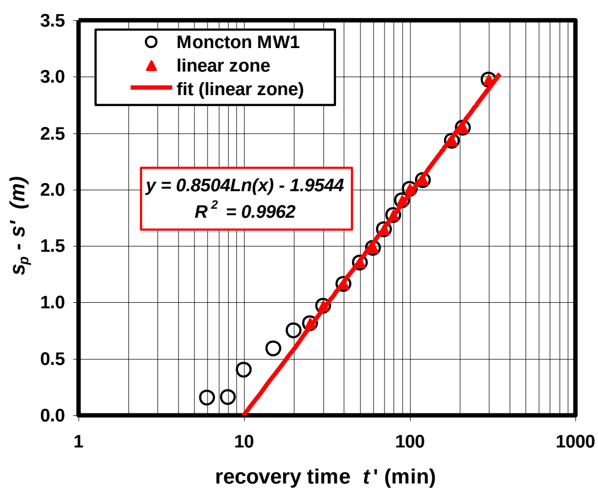

Figure 8. Graph of (s_p–s') vs. log t' for MW recovery data.

Table 2. Usual interpretations of pumping and recovery phases for the monitoring well.

Phase	Method	T (m^2/min)	S (—)
Pumping	log s vs. log t	1.30 x 10^{-2}	4.18 x 10^{-4}
	s vs. log t	1.38 x 10^{-2}	3.47 x 10^{-4}
Recovery	s' vs. log (t/t')	1.35 x 10^{-2}	n/a
	(s_p–s') vs. log t'	1.32 x 10^{-2}	1.80 x 10^{-3}
Mean		1.34 x 10^{-2}	8.55 x 10^{-4}
Variation	max / min	1.06	5.18

5.2. Detection of a HSC with the Recovery Curve

As shown before, a poor seal can be detected in the plot of s' versus log (t/t'). In Figure 7, the data form a straight line for a long time ratio. However, the extended straight line does not pass through the origin [$s' = 0$; $t/t' = 1$, or log (t/t') = 0] as it should in theory. At the end of the recovery, the data deviate from the previous straight line: it seems that they would finally reach the origin of axes.

This straight line not passing through origin may indicate that the monitoring well is short-circuited. The piezometric error H_0 is defined as the difference between the SWL and the PL close to the intake zone. In Figure 7, it is obtained by extrapolating the straight portion down to the s' axis, which yields H_0 = - 124.6 cm. This means that all drawdown and recovery data are probably wrong by this systematic error H_0. To confirm whether there is a HSC, new sets of values (T, S) must be calculated using new graphs with corrected drawdown and residual drawdown data.

5.3. Re-interpretation for T and S

The corrected s and s' data are used to re-analyze the pumping and recovery phases. The new plot for the Theis method appears in Figure 9. There is no need to re-draw the semi-log graphs (Figs 3 and 4) in which the H_0 value may be added as indicated. New S values are calculated using t_0^* (Fig. 3) and t'^*_0 (Fig. 4) instead of t_0 and t'_0 for the usual methods, which do not consider the hydraulic short-circuit effects. The new values of T and S, after correction, are now very close (Table 3).

Table 3. Re–analysis of pumping and recovery phases for the monitoring well, after correction of the piezometric error H_0 = 1.246 m as detected by the graph of s' vs. log (t/t').

Phase	Method	T (m^2/min)	S (—)
Pumping	log s vs. log t	1.39 x 10^{-2}	1.78 x 10^{-3}
	s vs. log t	1.39 x 10^{-2}	1.59 x 10^{-3}
Recovery	s' vs. log (t/t')	1.35 x 10^{-2}	n/a
	(s_p–s') vs. log t'	1.32 x 10^{-2}	1.81 x 10^{-3}
Mean		1.36 x 10^{-2}	1.73 x 10^{-3}
Variation	max / min	1.05	1.14

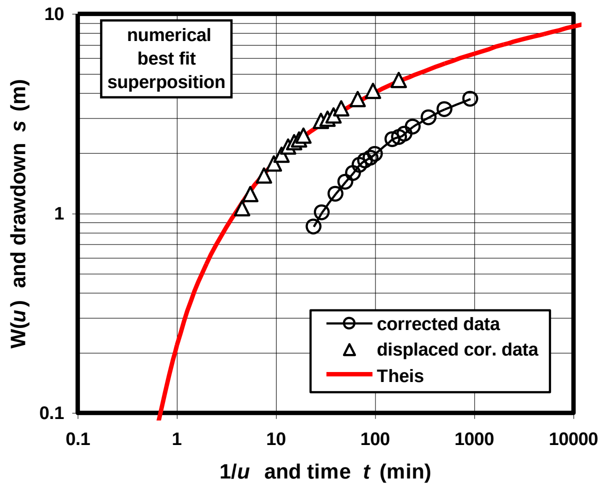

Figure 9. Method of Theis (1935) for corrected drawdown data of the monitoring well (MW).

The usual recovery curve of s' versus log (t/t') is used only to obtain H_0 (Fig. 6). It is not used here to assess new values of T and S. The recovery curve of Figure 8 is used to obtain new T and S values, which are compared with the new T and S values obtained during the pumping phase.

After correction of the piezometric error H_0 caused by a hydraulic short-circuit, all interpretation methods yield T = 1.36 x 10^{-2} m^2/s (error margin of 3%) and S = 1.73 x 10^{-3} (error margin of 7%). It is reminded here, as shown in the first part of the paper, that the corrected drawdown and residual drawdown data yield a T value slightly smaller than the real one, and an S value equal to the real one.

6. DISCUSSION AND CONCLUSION

A hydraulic short-circuit along a monitoring well corresponds to water movement in pervious zones along a poorly sealed monitoring well casing. This parasitic flow can explain the discrepancy between the T and S values when several methods are used to interpret pumping and revocery conditions of a pumping test. A hydraulic short-circuiting between different aquifers should not be confused with a leakage problem through the pipe wall or a fitting (EPA 1990; van der Kamp and Keller 1993), which can be easily detected by performing packer tests in the well casing.

By connecting two or more aquifer layers, a hydraulic short-circuit produces a small water leak: it gives a static water level in the monitoring well pipe, which is not the piezometric level for the monitored aquifer. Previous papers have shown that this error can be detected by a variable-head permeability test or by combining a pumping test and a tracer test. It is shown here that the usual recovery curve of a confined aquifer test can be used to detect the hydraulic short-circuit and obtain the value of the piezometric error. In the Moncton pumping test example, the drawdown and recovery graphs provided different T and S values. After correction for the piezometric error, they yielded very close T and S values, thus validating the diagnosis of a hydraulic short-circuit.

ACKNOWLEDGEMENTS

Poorly sealed wells represent over 65% of wells installed in North America since the late 1970s, according to Nielsen and Schalla (2005). This is therefore an important problem. Sadly, this paper was produced without research funds. The authors thank their universities for letting professors investigate and solve important problems even if public authorities do not seem interested, and let private industry compete for the lowest bid to install wells and monitoring wells, without enforcing, in the contract, technically sound and clear rules for installation.

REFERENCES

Avci, C.B. 1992. Flow occurrence between confined aquifers through improperly plugged boreholes. *Journal of Hydrology* **139**(1-4): 97–114.

Brikowski T. 1993. Flow between aquifers through filled cylindrical conduits: analytical solution and application to underground nuclear testing sites. *Journal of Hydrology* **146**: 115–130.

Carr P.A. 1968. *Hydrogeology of the Moncton Map–Area, New Brunswick*. Scientific Series No.1, Inland Waters Branch, Dept of Energy, Mines & Resources, Canada.

Chapuis R.P. 1988. Determining whether wells and piezometers give water levels or piezometric levels. *ASTM STP 963*, ASTM International, West Conshohocken, PA, pp. 162–171.

Chapuis R.P. 1992. Discussion of “Estimation of storativity from recovery data,” by P.N. Ballukraya and K.K. Sharma (1991). *Ground Water* **30**(2): 269–272.

Chapuis R.P. 1998. Discussion on ultrasonic method for evaluation of annular seals for wells and instrumented holes: Discussion. *Geotechnical Testing Journal* **21**(4): 370–371.

Chapuis R.P. 1999. Guide des essais de pompage et leurs interprétations. Ministère du Développement durable, de l’Environnement et des Parcs. ISBN 978-2-550-50664-5 (version PDF, 2007).

Chapuis R.P. 2006. Interpreting variable-head tests performed in open holes or monitoring wells with several screens. *Geotechnical Testing Journal* **29**(6): 467–473.

Chapuis R.P., and Chenaf D. 1998. Detecting a hydraulic short-circuit along a monitoring well with the recovery curve of a pumping test in a confined aquifer: Method and example. *Canadian Geotechnical Journal* **35**(5): 790–800.

Chapuis R.P., and Sabourin L. 1989. Effects of installation of piezometers and wells on ground water characteristics and measurements. *Canadian Geotechnical Journal* **26**(4): 604–613.

Chesnaux R., and Chapuis R.P. 2007. Detecting and quantifying leakage through defective borehole seals: A new methodology and laboratory verification. *Geotechnical Testing Journal* **30**(1): 17–24.

Chesnaux R., Chapuis R.P. and Molson J.W. 2006. A new method to characterize hydraulic short-circuits in defective borehole seals. *Ground Water* **44**(5): 676–681.

Christman M.C., Benson C.H., and Edil T.B. 2002. Geophysical study of annular well seals. *Ground Water Monitoring and Remediation* **22**(3): 104–112.

Cooper H.H., and Jacob C.E. 1946. A generalized graphical method for evaluating formation constants and summarizing well field history. *Trans. of American Geophysical Union* **27**: 526–534.

Dunnivant, F.M., I. Porro, C. Bishop, J. Hubbel, J.R. Giles, and M.E. Newman. 1997. Verifying the integrity of annular and back-filled seals for vadose zone monitoring wells. *Ground Water* **35**(1): 140–148.

EPA, 1990. Injection well mechanical integrity. Report EPA/625/9–89/007, Robert S. Kerr Environmental Research Laboratory, Ada, OK.

Guyonnet D., Mishra S., and McCord J. 1993. Evaluating the volume of porous medium investigated during slug tests. *Ground Water* **31**(4): 627–633.

Hvorslev M.J. 1951. Time lag and soil permeability in ground–water observations. Bull. No. 36, Waterways Experimental Station, Corps of Eng., U.S. Army.

Jacob C.E. 1963. The recovery method for determining the coefficient of transmissibility. U.S.G.S. Water Supply Paper 15361, pp. 281–292. Washington, D.C.

Meiri D. 1989. A tracer test for detecting cross–contamination along a monitoring well column. *Ground Water Monitoring Review* **9**(2): 78–81.

Nielsen D.M., and Schalla R., 2005. Design and installation of ground-water monitoring wells. *Chapter 10, Practical Handbook of Environmental Site Characterization and Groundwater Monitoring* 2nd ed. CRC Taylor & Francis.

Nordbotten J.M., Celia M.A., and Bachu S. 2004. Analytical solutions for leakage rates through abandoned wells. *Water Resources Research* **40**(4): Art. No. W04204.

Santi P.M., McCray J.E., and Martens J.L. 2006. Investigating cross-contamination of aquifers. *Hydrogeology Journal* **14**(1–2): 51–68.

Silliman S., and Higgins D. 1990. An analytical solution for steady-state flow between aquifers through an open well. *Ground Water* **28**(2): 184–190.

Theis C.V. 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage. *Trans. of American Geophysical Union* **16**: 519–524.

USDI 1977. *Groundwater Manual*. U.S. Department of the Interior. Bureau of Reclamation. Supt. of Documents, U.S. Govt. Printing Office, Washington, D.C.

van der Kamp, G., and C.K. Keller. 1993. Casing leakage in monitoring wells: Detection, confirmation and prevention. *Ground Water Monitoring and Remediation* **13**(4): 136–141.

Yesiller N., Edil T.B., and Benson C.H. 1997. Ultrasonic method for evaluation of annular seals for wells and instrumented holes. *Geotechnical Testing Journal* **20**(1): 17–28.