ground water

The Unusual and Large Drawdown Response of Buried-Valley Aquifers to Pumping

by Garth van der Kamp[1] and Harm Maathuis[2]

Abstract

The buried-valley aquifers that are common in the glacial deposits of the northern hemisphere are a typical case of the strip aquifers that occur in many parts of the world. Pumping from a narrow strip aquifer leads to much greater drawdown and much more distant drawdown effects then would occur in a sheet aquifer with a similar transmissivity and storage coefficient. Widely used theories for radial flow to wells, such as the Theis equation, are not appropriate for narrow strip aquifers. Previously published theory for flow to wells in semiconfined strip aquifers is reviewed and a practical format of the type curves for pumping-test analysis is described. The drawdown response of strip aquifers to pumping tests is distinctive, especially for observation wells near the pumped well. A case study is presented, based on extensive pumping test experience for the Estevan Valley Aquifer in southern Saskatchewan, Canada. Evaluation of groundwater resources in such buried-valley aquifers needs to take into account the unusually large drawdowns in response to pumping.

Introduction

Long and narrow strip aquifers in the form of buried-valley deposits confined by low-permeability aquitards are common in the glaciated terrain of northern North America and north-western Europe (Andersen and Haman 1970; Kehew and Boettger 1986; Shaver and Pusc 1992; Parks and Bentley 1996; Maathuis and Thorleifson 2000; Desbarats et al. 2001; Sandersen and Jorgensen 2003; Russell et al. 2004; BurVal Working Group 2006; Seifert et al. 2008; Ahmad et al. 2009). These aquifers occur as long and narrow, highly transmissive, sand and gravel units that are incised into much less permeable clay-rich formations or into the less permeable bedrock. The aquifers may be highly productive sources of groundwater, but their distinctive hydraulics can also lead to unexpectedly large drawdown of the groundwater levels over large distances. Hence it is important to have appropriate conceptual and theoretical models that provide understanding of how such strip aquifers function, and that can be used in analyzing pumping test data and predicting the impacts of pumping.

Most theoretical models for groundwater flow to a well are based on the assumption that the aquifers occur as sheets, extensive in every direction, and that the flow is radially symmetric (Kruseman and de Ridder 1990). The models can be extended to simple types of aquifer boundaries by means of the image well method. However, the radial flow models are not useful for long narrow aquifers, such as occur within valley deposits, in which the flow is strongly influenced by boundaries on either side and where the flow is not radially symmetric except very near the pumping well.

The purpose of this paper is to describe the large drawdowns caused by pumping that are encountered for narrow buried-valley aquifers and to present a simple conceptual and quantitative model for anticipating, predicting and analyzing such drawdown behavior, based on previously published theoretical analyses. Practical strip-aquifer type curves are described, an example of a

[1]Corresponding author: National Water Research Institute, 11 Innovation Boulevard, Saskatoon, Saskatchewan, Canada S7N 3H5; garth.vanderkamp@ec.gc.ca

[2]Cameco Corporation, 1131 Avenue W South, Saskatoon, Saskatchewan, Canada S7M 4E8; harm_maathuis@cameco.com

Received January 2011, accepted April 2011.

doi: 10.1111/j.1745-6584.2011.00833.x

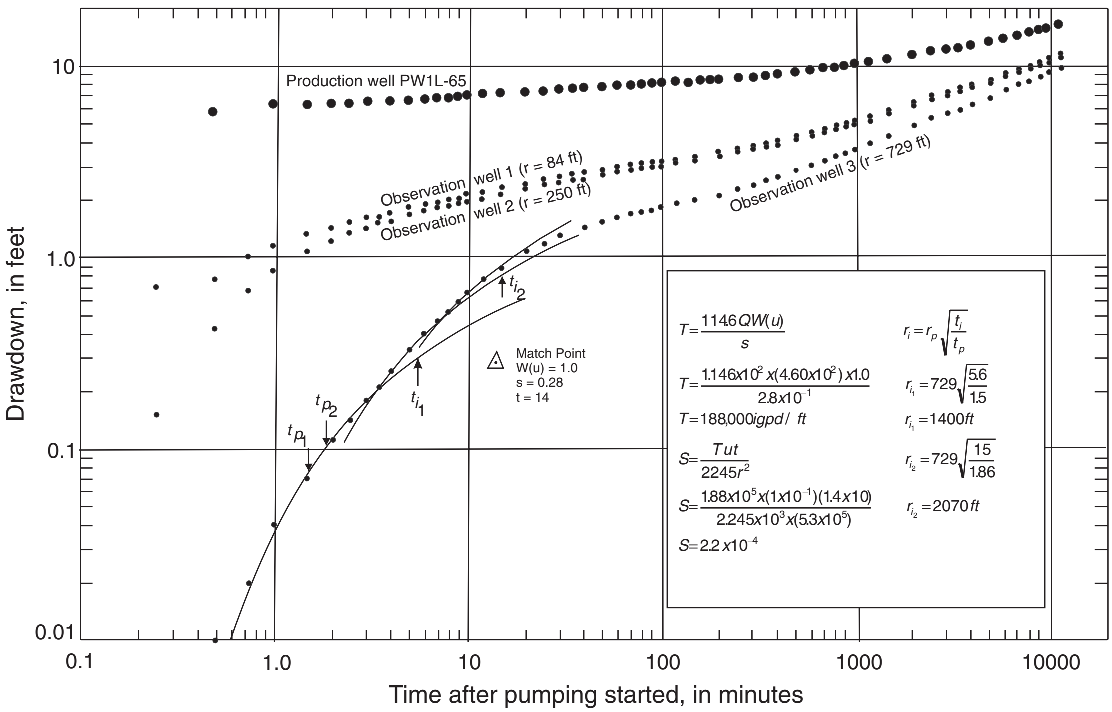


Figure 1. Data and type curve analysis for an 8-day pumping test of the Estevan Valley Aquifer (adapted from Walton 1965).

field application is given, and attention is drawn to the distinctive drawdown behavior of observation wells near the pumped well in strip aquifers.

Type-Curves for a Strip Aquifer

The shortcomings of using radial flow models to analyze drawdown data for strip aquifers is illustrated in Figure 1, which is a reproduction of the data and analysis for an 8-day pumping test carried out for a buried-valley aquifer near Estevan in Southern Saskatchewan, Canada (Walton 1965, 1970). An analysis with two image wells to take boundaries into account could use only the first 20 min of the data, and analysis of the full 11,500 min of data would have required many more image wells. Thus the desirability of a more general mathematical approach is indicated. The response to pumping of this aquifer will be further described in this paper.

Vandenberg (1976, 1977) developed type curves for the drawdown caused by pumping in semiconfined strip aquifers. Motz (1991) and Zhang (1992) carried out theoretical analyses of one-dimensional transient flow in a leaky aquifer in response to water level changes in rivers or canals. These analyses are mathematically equivalent to Vandenberg's results (Gill 1992). Related results were presented by Butler and Liu (1991) for the special case of a confined linear aquifer embedded in a matrix with different permeability.

Except for the assumption of one-dimensional flow rather than radial flow, the analyses by Vandenberg (1977), Motz (1991), and Zhang (1992) are based on assumptions about the aquifer-aquitard system and its properties that are identical to the assumptions for the well-known theory of radial flow in a semiconfined aquifer as first developed by Hantush and Jacob (1955). These assumptions include:

1. The aquifer is uniform and infinitely long in both directions from the pumped well and the underlying and adjoining formations are impermeable.
2. The overlying aquitard has a zero elastic storage coefficient, so that all the storage is in the aquifer itself. Drawdown at the top of the aquitard is assumed to be zero, implying that the storage (or specific yield) at the top of the aquitard is very large.

Details of the mathematical derivations are not presented here since they are available in the aforementioned papers by Vandenberg, Motz, Zhang, and Gill.

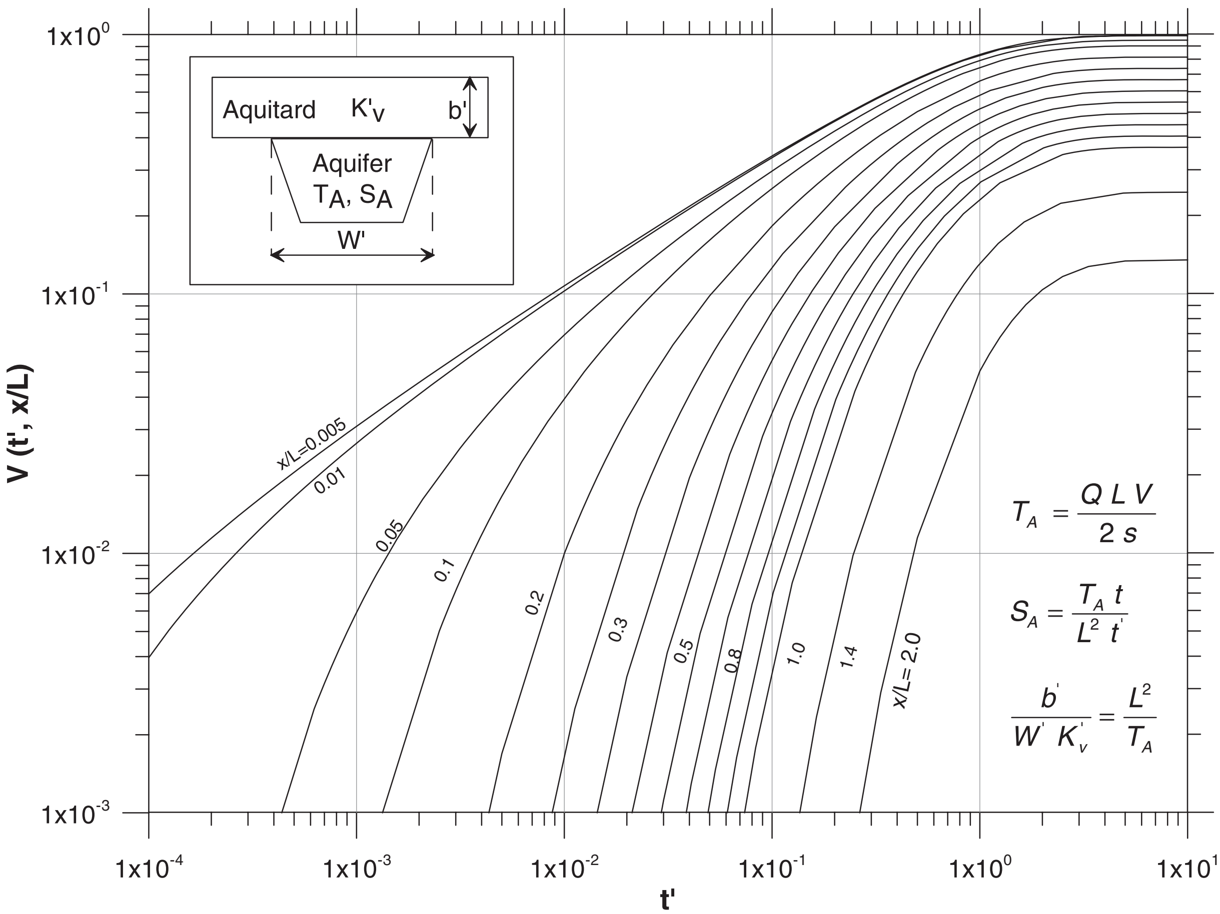
The original equations derived by Vandenberg (1977) are:

$$s = \left(\frac{Qx}{2TW'}\right) F\left(u, \frac{x}{L}\right) \qquad (1)$$

where:

$$u = \left(\frac{x^2 S}{4Tt}\right) \text{ and } F\left(u, \frac{x}{L}\right) = \left(1/2\pi^{\frac{1}{2}}\right) \int_u^\infty y^{\frac{-3}{2}} \exp\left(-y - \frac{x^2}{4L^2 y}\right) \mathrm{d}y \qquad (2)$$

in which s = drawdown, Q = pumping rate (constant), x = distance between the pumped well and the observation well measured along the aquifer, T = transmissivity, W' = strip aquifer width, L = leakage length = $(Tb'/K'_v)^{\frac{1}{2}}$,



$$T_A = \frac{Q\,L\,V}{2\,s}$$

$$S_A = \frac{T_A}{L^2}\frac{t}{t'}$$

$$\frac{b'}{W'\,K'_v} = \frac{L^2}{T_A}$$

Figure 2. Type curves for semiconfined strip aquifers (adapted from Zhang 1992).

$S =$ storage coefficient, $t =$ time since pumping started, $b' =$ thickness of the confining aquitard and $K'_v =$ vertical hydraulic conductivity of the aquitard. The leakage length L is the same as the leakage length for sheet aquifers, commonly denoted as L (Kruseman and de Ridder 1990) or as B (Hantush and Jacob 1955). Values for $F(u, x/L)$ have been provided by Vandenberg (1977) and Kruseman and de Ridder (1990).

These equations are based on the assumption that the flow in the aquifer is one-dimensional, in other words the pumped well is represented mathematically as a face of constant discharge across the full width and depth of the aquifer. In practice the flow converges radially to the pumping well which is essentially a vertical line sink. Vandenberg (1977) showed that for observation wells further than one aquifer width distant from the pumping well the one-dimensional flow equations provide a good approximation of the drawdown. At smaller distances from the pumping well there is additional drawdown caused by the radial flow component. In this paper a slightly modified version of the type curves presented by Zhang (1992) is used, conforming to the commonly used "log-log" format for presenting drawdown data (Figure 1). Other mathematically equivalent forms of the type curves were described by Vandenberg (1977) and Motz (1991). The type curves (Figure 2) represent plots of dimensionless drawdown V as a function of dimensionless time t' and dimensionless distance x/L, which can be written in the form:

$$V(t', x/L) = \left(\frac{2T_A}{QL}\right) s(x, t) \tag{3}$$

$$t' = \left(\frac{tT_A}{S_A L^2}\right) = t/(Sb'/K'_v) \tag{4}$$

V and t' are related to Vandenberg's $F(u, x/L)$ and u by $V = (x/L)F$ and $t' = (x^2/L^2)(1/4u)$. Values of V and t' have been tabulated and are available from the authors on request.

The type curve parameters are expressed in terms of T_A, the cross sectional conductance or transmissive capacity of the aquifer; S_A, the cross-sectional storativity of the aquifer; and L, the leakage factor, defined by:

$$T_A = TW' \tag{5}$$

$$S_A = SW' \tag{6}$$

$$L = \left(\frac{T_A b'}{W' K'_v}\right)^{\frac{1}{2}} \tag{7}$$

where T and S are the average values of transmissivity and storage coefficient of the aquifer, averaged over,

W', the width of the top of the aquifer (see Figure 2), b' is the thickness of the overlying aquitard, and K'_V is the vertical hydraulic conductivity of the aquitard. The width of the top of the aquifer, W', is used because it reflects the inflow from the overlying aquitard. These modified type curves are identical to the type curves presented by Zhang (1992, Figure 8, type A curves) with the proviso that here the cross-sectional conductance T_A and storativity S_A are used rather than T and S.

As suggested by Vandenberg (1977) use of the cross-sectional parameters T_A and S_A is appropriate for a narrow strip aquifer because the primary interest is usually with the total water transmitting and water storing capacity of the aquifer. For instance, the total rate of flow of water along the aquifer is simply the product of T_A and the hydraulic gradient along the aquifer. The use of these cross-sectional parameters avoids the need to determine the distributions of permeability and storage coefficient in the usually highly heterogeneous aquifers. However, the type curves can also be analyzed in terms of the parameters TW', S/T, and L, as indicated by Equations 1 and 2. Calculation of representative values of S and T for the entire cross-section of the aquifer then requires an independent determination of the aquifer width.

The analytical solution shows that the behavior of an ideal leaky strip aquifer is governed by the three aquifer parameters T_A, S_A, and L. These parameters can be determined by fitting measured drawdowns, plotted as a function of time, to the type curves. The procedure is the similar to the type curve fitting procedure used in the analysis of pumping test results for radial flow in sheet aquifers (Kruseman and de Ridder 1990). Ideally data from more than one observation well should be plotted together and then matched simultaneously to the type curves, with values of x/L for each of the wells being proportional to the distance x for the various observation wells. The value of L is calculated from the type curve values of x/L for the observation wells at known distances x from the pumping well. T_A and S_A are then determined from the match point values of V, t', s, and t by means of Equations 3 and 4 which can be written:

$$T_A = \left(\frac{QLV_{\text{mp}}}{2s_{\text{mp}}}\right) \tag{8}$$

$$S_A = \left(\frac{t_{\text{mp}}T_A}{t'_{\text{mp}}L^2}\right) \tag{9}$$

V_{mp}, s_{mp}, t_{mp}, and t'_{mp} are the values of V, s, t, and t' corresponding to the match point. An example is given in the following section of this paper.

Case Study: Analysis of Pumping-Test Data for Estevan Valley Aquifer

The Estevan Valley Aquifer in southern Saskatchewan (Figure 3) is an extensive buried-valley aquifer system that has been evaluated for its groundwater resource potential in the process of several successive studies. The main features of the aquifer have been described in reports and papers (Meneley et al. 1957; Walton 1970, pp. 73–81; Beckie Hydrogeologists Ltd. 1984; van der Kamp 1985; Maathuis and van der Kamp 2003). The aquifer consists of sand and gravel within several intersecting buried channels, confined by 50 to 100 m of clay-rich till. The main buried-channel aquifer units are 1000 to 4000 m wide. The aquifer is up to 80 m thick and at most locations in the channels consists of

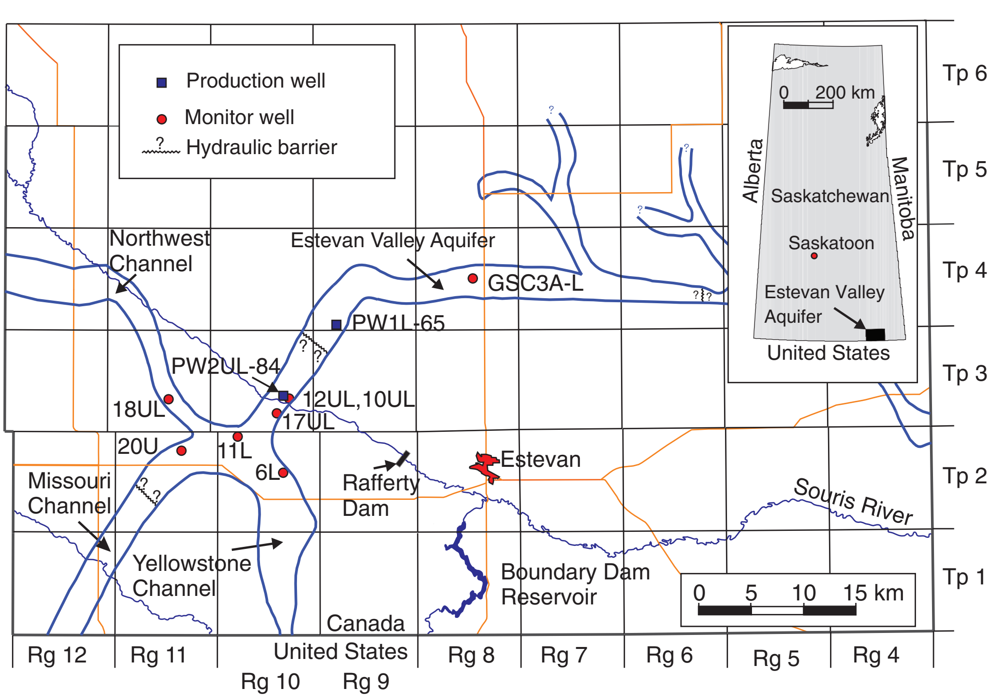


Figure 3. Plan view of the Estevan Valley Aquifer in southern Saskatchewan.

a lower and upper sand and gravel zone, separated by a clay and silt layer. The channels have been traced by means of geologic and geophysical logs for farm and oil wells and extensive test drilling over distances of up to 60 km. However, the static water levels and the pumping test data indicate that there are several transverse barriers across the aquifer channels that partially or completely eliminate hydraulic connection between different aquifer segments (Figure 3), similar to the barriers that have been described by Shaver and Pusc (1992) for buried-valley aquifers in North Dakota, USA. The well identifications shown in Figure 3 include "U," "L," or "UL" to indicate whether they are screened in the upper, lower, or both zones of the aquifer. The top of the buried valley aquifer lies well below the bottom of the Souris River valley and no effects of interaction with the overlying river could be detected in the hydraulic head data for the aquifer.

An 8-day pumping test, with a pumping rate of 0.035 m^3/s was carried out in 1965 (Walton 1965) at PW1L-65 (Figure 3), with three observation wells at distances of 26, 76, and 222 m (84, 250, and 729 feet) that were decommissioned after the test. All wells were screened in the lower zone of the aquifer. Only the first 20 min of the drawdown data were used for analysis on the basis of the Theis confined-aquifer type curves, which gave $T = 0.032$ m^2/s (188,000 Igpd/ft) near the well and $S = 2.2 \times 10^{-4}$ (Figure 1). After the first 10 min of pumping the observed drawdown increasingly exceeded the drawdown that would be expected for radial flow in a sheet aquifer, reflecting the influence of the channel boundaries. At the end of the test a drawdown of 0.20 m (0.59 feet) was measured for well GSC3A-L, 13,400 m east of the pumping well site (Figure 3), indicating that the drawdown effects could be far-reaching if pumping were continued for a longer time.

In 1984, a 29-day pumping test was conducted on pumping well PW2UL-84 screened in the upper and lower permeable zones of the Estevan Valley aquifer, at a point about 8600 m distant from the site of the 1965 test (Figure 3). The pumping rate was 0.0757 m^3/s (van der Kamp 1985). Drawdown was measured in numerous observation wells at distances between 30.5 and 13,000 m from the pumping well, including well PW1L-65 that was pumped in 1965. The recovery after pumping was very slow and the residual drawdowns were measured for ten months after pumping ceased (Figure 4). The measured drawdowns in the observation wells follow a regular pattern of smaller drawdown with increasing distance, except for the drawdown in well PW1L-65 where the drawdown was much smaller. This smaller drawdown indicates the existence of a partial hydraulic barrier between the pumped well and PW1L-65, a hypothesis that was corroborated by a discontinuity in the static hydraulic gradient between the wells prior to pumping.

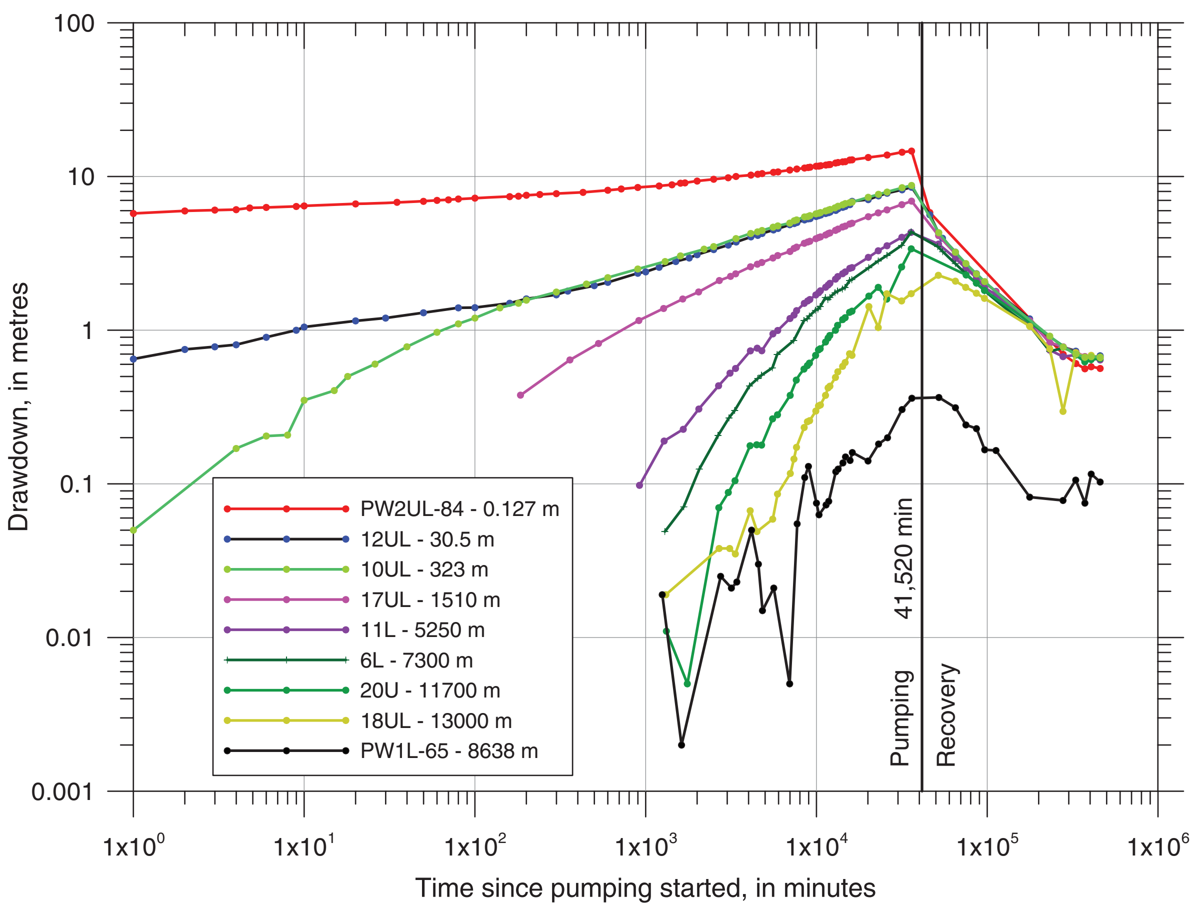


Figure 4. Drawdown data for the pumping and recovery phases of the 1984-85 pumping test on well PW2UL-84.

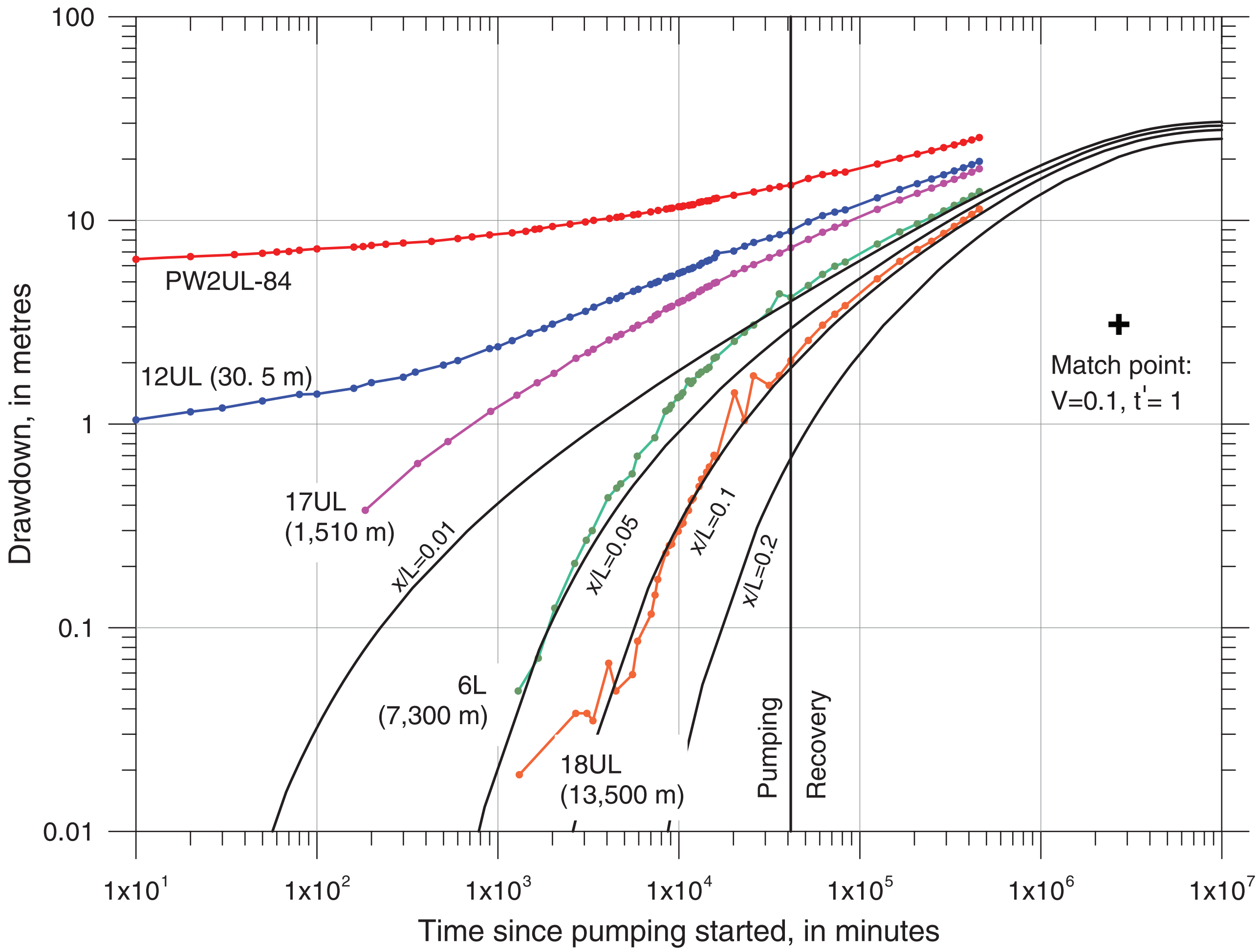


Figure 5. Extrapolated drawdown data for wells PW2UL-84, 12UL 17U, 6L, and 18UL compared with strip aquifer type curves matched to the data for 18UL. The match point is indicated for $x/L = 0.1, x = 13{,}500$ m (observation well 18UL).

The residual drawdowns were used to calculate the drawdowns that would have occurred had pumping continued, using the extrapolation method of van der Kamp (1989), thus extending he effective length of the test to almost 1 year. The extrapolation method is very general in its applicability, but it does accumulate the uncertainty in the residual drawdown during recovery because of uncertainty of the background "static water level," so that the possible error in the extrapolated drawdowns toward the end of the 11-month period is about ±0.5 m. The late-time drawdown data for selected observation wells, including the extrapolated drawdown based on the recovery data, are plotted in Figure 5 as a log-log plot to facilitate matching to the type curves. As for the 1965 test on well PW1L-65 (Figure 1), the log-log plots of the drawdown curves for observation wells near the pumped well exhibited a "straight-line" behavior. The late-time drawdowns are likely to be influenced by transverse hydraulic barriers across the aquifer channels, the existence of which can be inferred from discontinuities in the hydraulic gradient along the various portions of the channels (Figure 3). Such barriers would be expected to lead to greater late-time drawdown then would be the case if the channels were continuous to very large distances (i.e., distances much greater than L).

To obtain aquifer parameters and an estimate of long-term yield for the aquifer, a type-curve match was made using the drawdown data for the far away well 18UL ($x = 13{,}000$ m, greater than $W' = 4000$ m) because it is the only distant observation well screened in both the top and bottom zones of the aquifer, corresponding to the pumped well. The drawdown curve for 18UL most closely matched the type curve for $x/L = 0.1$ (Figure 5). The match point is shown, with values of $V_{\mathrm{mp}} = 0.1$, $s_{\mathrm{mp}} = 3.1$ m, $t_{\mathrm{mp}} = 2.7 \times 10^6$ min and $t'_{\mathrm{mp}} = 1.0$, resulting in values for the aquifer system properties of: $L = 130$ km, $T_A = 160$ m^3/s, and $S_A = 1.5$ m.

If the effective width of the aquifer, W', is taken to be 4000 m, these values give transmissivity and storage coefficient for the aquifer of 0.04 m^2/s and 3.8×10^{-4}. Assuming an effective thickness of the aquitard of 75 m the vertical hydraulic conductivity of the aquitard K'_v is then 1.8×10^{-10} m/s. The T and S values are comparable to the results of the 1965 pumping test which assessed only the lower zone of the aquifer. The K'_v value of the glacial till aquitard corresponds to similar values obtained at other sites in Saskatchewan (Keller et al. 1989; Shaw and Hendry 1998).

With $x/L = 0.1$ for well 18UL-84 at $x = 13{,}000$ m, the drawdown data for well 6L-82, at $x = 7300$ m would ideally match the type curve for $x/L = 0.05$. However, the drawdown data for well 6L-82 lie slightly above the $x/L = 0.05$ type curve. Considering the complexity of the aquifer geometry and taking into account that 6L is screened only in the upper aquifer zone, this lack of precise correspondence with the drawdown data for 18UL is not surprising. The drawdown curves show no obvious sign of a "leveling off" (indicating an approach to equilibrium) even for $t = 4.6 \times 10^5$ min, or almost 11 months (Figure 5), but the matched type curves suggest that full equilibrium would be approached after about 1×10^7 min, or about 20 years.

Within a few thousand meters of the pumped well the observed drawdowns (Figure 5) are influenced by radially convergent flow to the pumping well, causing the drawdown data at late time for well 12UL, 30.5 m from the pumped well, to lie above the type curve for $x/L = 0.01$ by about 6 m. The drawdown in the pumped well (diameter 0.254 m) was increased by about 11 m through a combination of radial flow and well losses.

Discussion

For late-time conditions ($t' > 3$, Figure 2), when steady-state conditions have been reached, the drawdown, s_0, in the aquifer at distances greater than one aquifer width from the pumping well is given by (Vandenberg 1977):

$$s_0 = \left(\frac{QL}{2T_A}\right) e^{(-x/L)} \tag{10}$$

Equation 10 shows that the steady-state drawdowns decrease exponentially with distance away from the well, so that at $x = L, 2L$, and $3L$ the drawdowns are 0.37, 0.13, and 0.05 of the drawdown near the well (neglecting radial flow). The parameter L thus gives a useful measure of the extent of the drawdown "cone" when steady-state conditions are approached. For deep buried-valley aquifers, L values can be as large as 10 to 100 km or more and well interference can be significant even for production wells (or well fields) spaced tens of kilometers apart.

The peculiar properties of semiconfined strip aquifers as compared to semiconfined sheet aquifers are illustrated with the theoretical drawdown results given in Table 1 which summarizes the steady state drawdowns as a function of distance from the pumping well for a 1000 m wide strip aquifer and for a sheet aquifer with the same values of T and L. The steady-state drawdown in a semiconfined sheet aquifer is given by (Kruseman and de Ridder 1990):

$$s = \frac{Q}{2\pi T} K_0\left(\frac{r}{L}\right) \tag{11}$$

Table 1
Theoretical Values of Steady-State Drawdown in a Semiconfined Strip Aquifer and a Semiconfined Sheet Aquifer with the Same Hydraulic Properties ($T = 0.03$ m²/s, $L = 35{,}000$ m) and for the Same Pumping Rate (0.040 m³/s)

	Drawdown (m)	
Distance x or r (m)	Strip aquifer	Sheet aquifer
0.127	>23.3	2.68
30	>23.3	1.52
500	>23.01	0.93
1000	22.7	0.78
7000	19.1	0.37
35,000	8.58	0.09
70,000	3.16	0.02

Note: The width of the strip aquifer is assumed to be 1000 m and the diameter of the pumping well is 0.254 m.

where r is the radial distance form the pumping well and K_0 is the modified second kind Bessel function of order zero.

These calculations show that the drawdowns caused by pumping from a strip aquifer can be at least an order of magnitude greater than for a sheet aquifer with the same hydraulic properties, especially at distances far from the pumped well. Clearly expectations about the hydraulic response to pumping for strip aquifers can be highly erroneous if they are based on experience with sheet aquifers.

The much larger drawdowns and much larger extent of the drawdown "cone" for strip aquifers have important implications for the design of pumping tests. Observation well distances of a few hundred meters, such as are typically used for sheet aquifers, can provide reasonable results for transmissivity and storage coefficient near the pumped well, but will not give useful results for the response of the strip aquifer at large distances from the pumped well. The response of the Estevan Valley Aquifer is a case in point. During the 1965 pumping test (Figure 1) with duration of 8 days, the focus was on the nearby observation wells up to 222 m distant, which provided useful data for only the first 20 min of the test. The 1984 to 1985 test (Figure 4) showed that after 8 days of pumping significant drawdowns extended out to at least 13,000 m. Observation well spacing for narrow strip aquifers should be much larger than the aquifer width and much greater than for sheet aquifers with similar hydraulic properties.

The transmissivity in the vicinity of the pumping well is an important parameter for well field design because it has a major bearing on the drawdown of the water level in the well. This transmissivity can be determined from the early-time drawdown data for nearby observation wells ($x \ll W'$) as was done for the 1965 test (Figure 1) or by means of a distance-drawdown analysis for radial flow if data from more than one nearby observation well are available. For wide buried-valley aquifers, with width approaching or exceeding the leakage length L, the drawdown caused by pumping may be dominated by radial flow. For such cases sheet-aquifer type curves may be applicable, making use of image well methods.

When hydrogeologic data are sparse, it may not always be obvious that a particular aquifer will behave like a strip aquifer. "Straight-line" segments of the drawdown curves on log-log plots may be an indication that one is dealing with a strip aquifer or with an aquifer that has strip-like properties. The theoretical slope of the straight-line segment on a log-log plot would be 1/2 for observation wells near the pumped well in ideal strip aquifers, but radial flow drawdown will result in higher drawdown then predicted by the strip-aquifer type curves and straight-line behavior with a slope less than 1/2. Slopes somewhat less than 1/2 are commonly reported, in part because most reported pumping tests for buried-valley aquifers only had observation wells located near the pumped well, as is routine for sheet aquifers. For example, Andersen and Haman (1970, Figure 6); Shaver and Pusc (1992, Figure 6) and Parks and Bentley (1996, Figures 6 and 9) each presented pumping test results that have typical "straight-line" strip aquifer behavior. The drawdown data for the Estevan Valley Aquifer (Figures 1 and 5) also illustrate such behavior.

Transverse low-permeability barriers are commonly encountered within buried-valley aquifers associated with glacial deposits (Shaver and Pusc 1992), but their origin is not well understood (Russell et al. 2004). Barriers of this type may not be identifiable on the basis of sparse geologic data, but a characteristic indication of their presence is the occurrence of "steps" in the hydraulic head profile along the aquifer. With respect to the drawdown caused by pumping, the possible presence of barriers means the aquifer should not be assumed to be of infinite extent. This restriction is particularly telling for buried strip aquifers in view of the large extent of the drawdown "cone." The presence of barriers, even at large distances from the pumped well may lead to additional drawdown at the well. Evaluations of flow in buried-valley aquifers typically need to take account of hydrogeological complications such as partially permeable transverse barriers within the aquifer, significant flow exchange with adjacent aquifers and complex buried-valley geometry. The type curves for an ideal leaky strip aquifer appear to be remarkably robust for simulating observations, judging by the example of the nonideal Estevan Aquifer. Nevertheless, their applicability is limited and more detailed numerical methods should be used as appropriate.

Conclusions

The type curves for semiconfined strip aquifers can be usefully employed in the understanding, prediction and analysis of drawdown caused by pumping from such aquifers. For narrow strip aquifers evaluations of groundwater resource availability based on the assumption of radial flow to the pumping well in a sheet aquifer can lead to underestimation of drawdowns and overestimation of the sustainable yields by as much as an order of magnitude.

The type curves for a strip aquifer are not applicable near the pumped well, but provide a useful theoretical model for drawdown far away from the pumping well caused by long-term pumping. Design of pumping tests for buried-valley aquifers should include placement of observation wells at distances from the pumped well greater than the width of the aquifers, and typically much further away then would be indicated by normal practice for sheet aquifers.

Log-log plots of drawdowns measured near the pumped well have a characteristic "straight-line" pattern which can serve as an indicator that a particular aquifer is behaving as a strip aquifer.

Many real-world strip aquifers, such as the buried-valley aquifers that are common in glacial deposits, have complex structures that challenge delineation by means such as test drilling or geophysical methods. Hence a pragmatic approach to dealing with groundwater flow in such aquifers is indicated, dealing with the aquifers as complex systems whose responses to pumping can only be determined and predicted by actual testing of the entire system. For important and complex cases numerical methods may be appropriate. However the strip-aquifer type curves allow useful estimates of how buried-valley aquifers respond to pumping.

Acknowledgments

An earlier version of this paper was published in conference proceedings (van der Kamp and Maathuis 2002). Many investigators have contributed to the information reviewed and summarized in this paper, among whom W.A. Meneley, W.C. Walton, and V.G. Beckie deserve particular mention. Most of the work on which this paper is based was carried out while the authors were employed by the Saskatchewan Research Council and with the financial support of the Saskatchewan Power Corporation and the Saskatchewan Watershed Authority.

References

Ahmad, J., D.R. Schmitt, C.D. Rokosh, and J.G. Pawlowicz. 2009. High-resolution seismic and resistivity profiling of a buried Quaternary subglacial valley: Northern Alberta, Canada. *GSA Bulletin* 121, no. 11/12: 1570–1583.

Andersen, L.J., and Z. Haman. 1970. Pumping tests and hydrogeological investigations of an artesian aquifer nears Horsens, Denmark. *Nordic Hydrology* 2: 69–110.

Beckie Hydrogeologists Ltd. 1984. *Estevan Valley Aquifer System Exploration and Pump Test Program, Souris River Site*. Regina: Beckie Hydrogeologists Ltd., 53 pp.

BurVal Working Group. 2006. *Groundwater Resources in Buried Valleys—A Challenge for Geosciences*. Hannover, Germany: Leibniz Institute for Applied Geosciences (GGA-Institut).

Butler, J.J., and W.Z. Liu. 1991. Pumping tests in non-uniform aquifers—the linear strip case. *Journal of Hydrology* 128: 69–99.

Desbarats, A.J., M.J. Hinton, C.E. Logan, and D.R. Sharpe. 2001. Geostatistical mapping of leakance in a regional aquitard, Oak Ridges Moraine area, Ontario, Canada. *Hydrogeology Journal* 9: 79–96.

Gill, M.A. 1992. Drawdowns for constant-discharge one-dimensional leaky aquifer—discussion. *ASCE Journal of Irrigation and Drainage Engineering* 118, no. 2: 332–333.

Hantush, M.S., and C.E. Jacob. 1955. Non-steady flow in an infinite leaky aquifer. *Transactions, American Geophysical Union* 36, no. 1: 95–100.

Kehew, A.E., and W.M. Boettger. 1986. Depositional environments of the buried-valley aquifers in North Dakota. *Ground Water* 24, no. 6: 728–734.

Keller, C.K., G. van der Kamp, and J.A. Cherry. 1989. A multiscale study of the permeability of a thick clayey till. *Water Resources Research* 25, no. 11: 2299–2317.

Kruseman, G.P., and N.A. de Ridder. 1990. *Analysis and Evaluation of Pumping Test Data*, 2nd ed. Wageningen, The Netherlands: International Institute for Land Reclamation and Improvement.

Maathuis, H., and G. van der Kamp. 2003. Groundwater resource evaluations of the Estevan Valley aquifer in southeastern Saskatchewan: a 40-year historical perspective. *Proceedings (CD) of the 56th Canadian Geotechnical and 4th Joint IAH-CNC and CGS Conferences*, Winnipeg, MB, September 29—October 1, 4 p.

Maathuis, H., and L.H. Thorleifson. 2000. *Potential Impact of Climate Change on Prairie Groundwater Supplies: Review of Current Knowledge.* Saskatoon: Saskatchewan Research Council, Publication No.11304-2E00.

Meneley, W.A., E.A. Christiansen, and W.O. Kupsch. 1957. Preglacial Missouri river in Saskatchewan. *The Journal of Geology* 65, no. 4: 441–447.

Motz, L.H. 1991. Aquifer parameters from constant discharge nonsteady-leaky type curves. *Ground Water* 29, no. 2: 181–185.

Parks, K.P., and L.R. Bentley. 1996. Derivative-assisted evaluation of well yields in a heterogeneous aquifer. *Canadian Geotechnical Journal* 33, no. 3: 458–469.

Russell, H.A.J., D.R. Sharpe, G. van der Kamp, and M.J. Hinton. 2004. A review of the architecture, sedimentology and hydrogeology of buried valley aquifers in Canada. *Proceedings of the 57th Canadian Geotechnical conference and the 5th Joint IAH-CNC/CGS Groundwater Conference*, Quebec, October 24–27, 2B26-2B33.

Sandersen, P.B.E., and F. Jorgensen. 2003. 229–248.

Seifert, D., T.O. Sonnenborg, P. Scharling, and K. Hinsby. 2008. Use of alternative conceptual models to assess the impact of a buried valley aquifer on groundwater vulnerability. *Hydrogeology Journal* 16, 659–674.

Shaver, R.B., and S.W. Pusc. 1992. Hydraulic barriers in Pleistocene buried-valley aquifers. *Ground Water* 30, no. 1: 21–28.

Shaw, J., and M.J. Hendry. 1998. Hydrogeology of a thick clay till and Cretaceous clay sequence, Saskatchewan, Canada. *Canadian Geotechnical Journal* 35, 1041–1052.

Vandenberg, A. 1977. Type curves for analysis of pump tests in leaky strip aquifers. *Journal of Hydrology* 33, 15–26.

Vandenberg, A. 1976. Tables and type curves for analysis of pump tests in leaky parallel-channel aquifers. *Environment Canada, Inland Waters Directorate, Technical Bulletin* 96, 28.

van der Kamp, G. 1989. Calculation of constant-rate drawdowns from stepped-rate pumping tests. *Ground Water* 27, no. 2: 175–183.

van der Kamp, G. 1985. *Yield Estimates for the Estevan Valley Aquifer System using a Finite-Element Model*. Saskatchewan Research Council Publication No. R-844-4-C-85.

van der Kamp, G., and H. Maathuis. 2002. The peculiar groundwater hydraulics of buried-channel aquifers. *Proceedings of the 55th Canadian Geotechnical and 3rd Joint IAH-CNC and CGS Conferences*, Niagara Falls, Ontario, October 20–23.

Walton, W.C. 1970. *Groundwater Resource Evaluation.* Toronto: McGraw-Hill Book Company.

Walton, W.C. 1965. *Potential yield of a sand and gravel aquifer in a buried valley near Estevan, Saskatchewan—results of aquifer and well production tests and evaluation of groundwater potential*. Report prepared for the Saskatchewan Research Council.

Zhang, W.Z. 1992. Transient groundwater flow in an aquifer-aquitard system in response to water level changes in rivers or canals. *Journal of Hydrology* 133: 233–257.