Characterization of the Paskapoo for sustainable groundwater development: a modeling approach

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ABSTRACT
The Paskapoo Formation is an important source of water in southwest Alberta. Irricana and Acme operated municipal groundwater systems in the Paskapoo but have since converted to surface water due to monitoring at Irricana that showed steady decline of water levels over 17 years. Such cases highlight the complexity facing development of groundwater in the region but present an opportunity to assess the system's response to long-term stress. The municipal case histories, recent hydrostratigraphic work, and results of preliminary modeling provide new information relevant to aquifer characterization, estimation of long-term yields, and sustainable groundwater development in the Paskapoo aquifer system.

RÉSUMÉ
La formation Paskapoo est une importante source d'approvisionnement en eau pour le sud de l'Alberta. Suite à une étude de suivi du niveau d'eau sur une période de 17 ans au site d'Irricana démontrant un déclin constant du niveau d'eau, les municipalités d'Irricana et d'Acme ont converti l'approvisionnement de leurs systèmes municipaux de l'eau souterraine provenant de la formation de Paskapoo vers un approvisionnement en eau de surface. Ces études de cas soulignent les difficultés liées au développement de la ressource en eau souterraine dans la région et permettent également d'évaluer le comportement de l'aquifère lorsque soumis à un stress sur une longue période. Les exemples municipaux, les récents travaux d'interprétation en hydrostratigraphie ainsi que les résultats préliminaires de modélisation sont autant de sources d'information pouvant servir aux travaux de caractérisation de l'aquifère, d'estimation des débits à long terme et de développement durable de la ressource en eau souterraine.

1 INTRODUCTION

The Paskapoo Formation aquifer system supplies water for rural, municipal, agricultural, and industrial purposes over an area of ~65,000 km^2 in southwest Alberta. Shale dominant overbank sediments deposited in a subsiding foreland basin encase fluvial sandstone units producing heterogeneity (non-ideal aquifer conditions) at several scales. Regionally the formation has a sandstone/shale ratio of 2:3 (Grasby et al. 2008: in review) while locally 1900 km^2 of the Paskapoo around Acme and Irricana has a ratio of 1:3 (Fig. 1). The non-ideal conditions, lower sandstone content, and a vertical flow component are investigated as possible factors that make it difficult to estimate long-term sustainable yields in the area.

Acme and Irricana operated multiple wells completed in the Paskapoo to support populations that increased from 341 to 648 in Acme and from 214 to 1104 in Irricana between 1975 and 2005 (Alberta Municipal Affairs 2007) (Fig. 1). In Alberta long-term groundwater use of this type is licensed and a maximum sustainable production rate must be estimated. The Q_{20} equation:

$$Q_{20} = [4 \pi T (H_A / 8) / 2.30] S_f = 0.683 T H_A S_f \quad [1]$$

(Maathuis and van der Kamp 2006) provides a theoretical discharge rate that will draw down H_A (available drawdown or difference between static water level and aquifer top) after 20 years of continuous pumping. T is transmissivity estimated from pumping test results. The safety factor ($0<S_f<1$) is included to account for heterogeneity, well loss, and to ensure water levels do not drop below the aquifer top (Maathuis and van der Kamp 2006). Since the calculation does not include recharge, and in most cases pumping is not continuous, the Q_{20} is considered a relatively conservative estimate for sustainable yield.

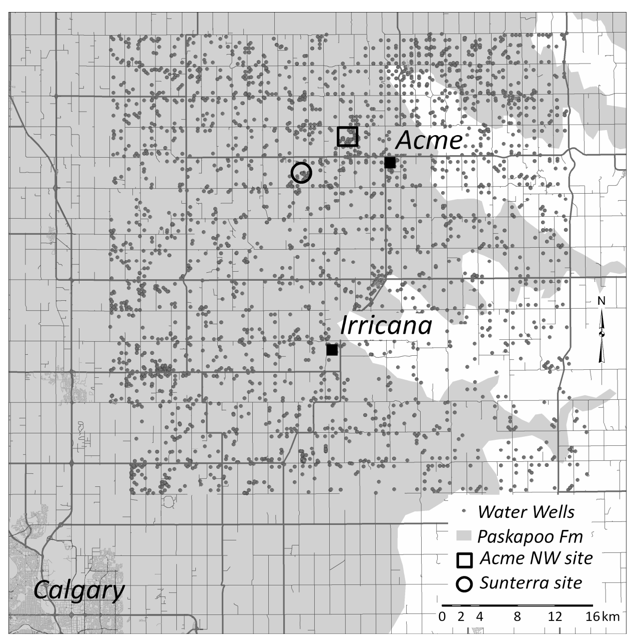

Figure 1. The selected groundwater wells completed within the Paskapoo Fm. cover 1900 km^2.

The Q_{20} is based on the Jacob straight-line method (Kruseman and Ridder 1990) which assumes homogeneous and isotropic conditions that do not exist in the Paskapoo (Nowak 2005), and the origin of the S_f that should account for heterogeneity is not well documented (Maathuis and van der Kamp 2006). Case histories for the two municipalities where Q_{20} values were used indicate sustainable yields are difficult to estimate consistently when homogeneity is assumed. Similar difficulty was encountered for pumping at a Sunterra Farms Ltd. site where sustainable yields were estimated using modeling that also assumed ideal aquifer conditions. Current modeling at the Sunterra site takes the previous work one step further to determine if vertical heterogeneity in the form of layered sandstone and shale units and flow across the shale aquitards need to be considered when evaluating pumping test results used to estimate Q_{20} values in the Paskapoo.

2 ACME CASE HISTORY

Prior to switching to surface water from the Kneehill Regional Services Commission pipeline in 2005, Acme developed and operated nine groundwater wells in two separate well fields. One well field was in the town site and the other 4.5 km to the NW (Fig. 2). Information and data were gathered for the five most recent wells drilled in the NW field. In 1976 two wells were completed in upper and lower sandstone units vertically separated by 11 m of shale. The wells are laterally 15 m apart and considered hydraulically connected (Hydrogeological Consultants Ltd. 1993). WSW No. 5 in the upper unit was completed at 899-893 m above sea level (m.a.s.l.) and maintained as a standby for peak demand periods. The Q_{20} (262 m^3/day) used to establish the annual licensed amount (9.6 x 10^4 m^3/yr) was based on the pumping test for WSW No. 4 in the lower unit completed at 871-882 m.a.s.l.

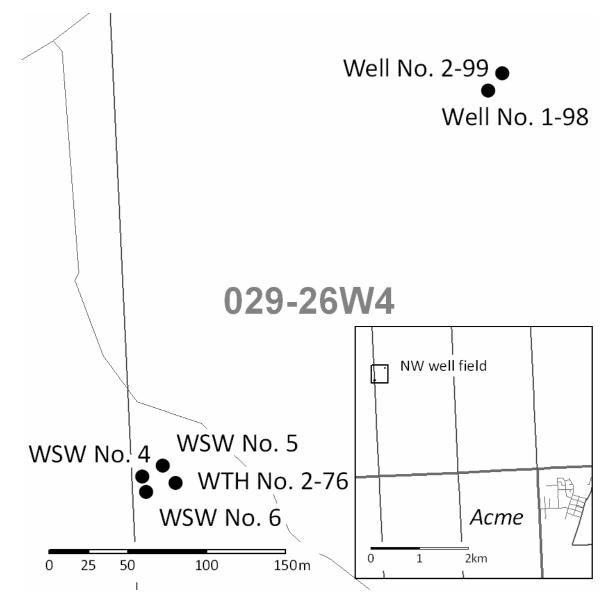

Figure 2. Wells in the NW field are 4.5 km from Acme (inset). The two primary production wells are 340 m apart.

Monthly production from the wells was maintained at less than half the licensed maximum rate (Eckfeldt 2008) until production was exceeded for four months in 1991 and for eight months in 1992 (Hydrogeological Consultants Ltd. 1993). Available data indicates total annual production from the field never exceeded the maximum licensed amount in any given year (Eckfeldt 2008), except 1992 when 10.5 x 10^4 m^3/yr was extracted (Hydrogeological Consultants Ltd. 1993).

In 1993 WSW No. 4 was abandoned due to deterioration of the well. The replacement, WSW No. 6, was located 10 m south of WSW No. 4 (Fig. 2) and completed in the same aquifer at 868-881 m.a.s.l. Depth to static water level in WSW No. 6 was 15.22 m below ground surface (m.b.g.s.), 13.63 m lower than the 1976 static level in WSW No. 4, 1.59 m.b.g.s. The loss of available head in the lower aquifer was a concern and by 1999 two additional wells were drilled 340 m to the NE of WSW No. 6. Well No. 2-99, completed at 840-856 m.a.s.l. augmented production and by 2002 was providing about one-third of the 9.6 x 10^4 m^3/yr licensed maximum for the well field. Despite the added production from a deep aquifer, water levels in WSW No. 6 dropped below the aquifer top for most of 2001 and part of 2002 indicating the original Q_{20} estimate did not provide a conservative estimate for a sustainable yield from the aquifer.

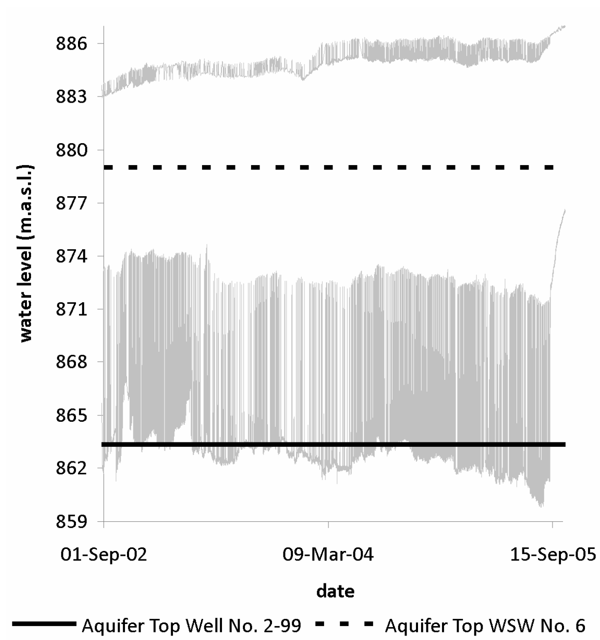

Figure 3. Water levels in Well No. 2-99 and WSW No. 6.

Data gaps between 1994 and 2002 do not allow for a proper comparison but data from WSW No. 6 indicate production was reduced to less than 1.05 x 10^4 m^3/yr during 2003/04. Water levels that were below the aquifer top in WSW No. 6 show a gradual recovery starting in 2002 and levels in Well No. 2-99 show a continuous decline below the aquifer top between 2002 and 2005 (Fig.3). The difference in water level response indicates the units are not in strong hydraulic connection while the interpretation of hydraulic connection between WSW No. 4 and 5 implies vertical leakage through 11 m of aquitard over a lateral distance of 15 m. It should be noted that WSW No. 5 was drilled to 871 m.a.s.l. and the open hole was used for aquifer testing prior to being backfilled to 889 m.a.s.l. The original report noted that "qualitative" aquifer tests were conducted in WSW No. 5 and WTH No. 2-76 at similar depths to WSW No. 4. Results indicated lower permeability in the region of these two wells than in the region of WSW No. 4 (Hydrogeological Consultants Ltd. 1976).

The upper aquifer at WSW No. 5 (899-893 m.a.s.l.), lower aquifer at WSW No. 4 and 6 (868-882 m.a.s.l.), and deep aquifer at Well No. 2-99 (840-856 m.a.s.l.) are of interest to modeling the system. According to the available information there are two factors that represent non-ideal conditions that can affect estimates for sustainable yields; 1) leakage between the upper and lower aquifer over a short distance, and 2) limited extent of homogeneity as indicated by the qualitative aquifer tests. The perceived weak hydraulic connection between Well No. 2-99 and WSW No. 6 over a 12 m vertical and 340 m horizontal separation can not be interpreted without detailed analysis of the production and water level data but a notable difference in water levels between the two wells indicates there is potential for downward directed flow in the region of the two wells (Fig. 3).

3 IRRICANA CASE HISTORY

The first three production wells in Irricana were completed in 1976 within 300 m of each other inside the town limits (Fig. 4).

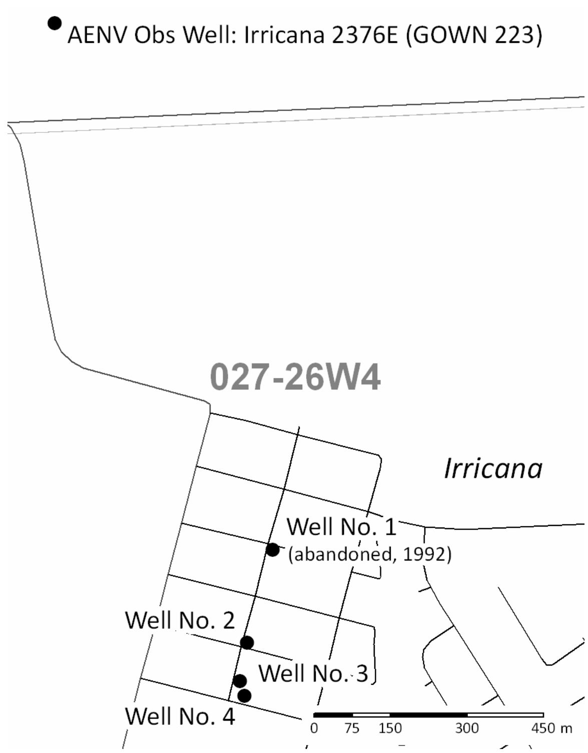

Figure 4. The AENV well is 1.3 km NW of Well No. 2.

The initial licensed production maximum was set at 1.23 x 10^5 m^3/yr in 1980, based primarily on production from Well No. 2 (4 x 10^4 m^3/yr) and Well No. 3 (8.2 x 10^4 m^3/yr). Well No. 4 was added in 1984 and eventually replaced Well No. 1, which was filled and capped by 1992. Well No. 4 augmented production from Well No. 3, which was expected to have a drop in production due to sand intrusion (Eckfeldt 2008). The licensed amount was adjusted to 1.2 x 10^5 m^3/yr in 1993, to reflect the changes, and remained there through to 2005 when access to the Kneehill Regional Services Commission pipeline was established.

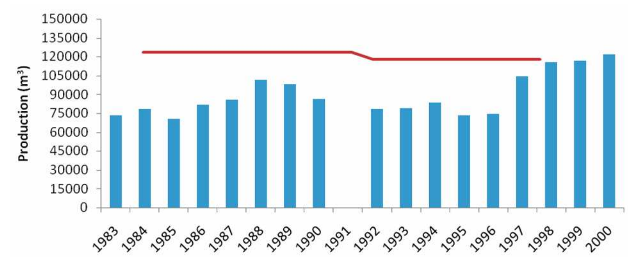

Figure 5. Production at Irricana only exceeded the licenced yield (horizontal line) in 2000.

The combined annual production for all wells in the field gradually increased from 7.43 x 10^4 m^3/yr to 1.22 x 10^5 m^3/yr. between 1983 and 2000, only exceeding the maximum licensed amount in 2000 (Fig. 5). Well No. 3 and 4 have completion intervals between 875-896 m.a.s.l. Well No. 2 does not have completion information but has a final drilling depth at 870 m.a.s.l. Water levels in the three main production wells declined between 1984 and 2001 in the range of 15-20 m and dipped below the aquifer top in Well No. 3. Reports that include the Q_{20} estimates were not found but microfiche records include projected drawdown for a neighbouring well 610 m away. After 20 years of continuous pumping at the rate established for Well No. 3, 2.4-3.2 m of drawdown was estimated (Eckfeldt 2008).

Alberta Environment (AENV) operates an observation well 1.3 km NW of the production wells (Fig. 4). The well is screened across 886-887 m.a.s.l. at the mid-point of completion intervals for Well No. 3 and 4 (877-895 m.a.s.l.) in the near horizontal Paskapoo Formation (Hamblin 2004). The AENV observation well recorded a 10 m drop over the 17 years of groundwater production at Irricana. The drop in water levels 1.3 km from the pumping wells in a completion zone of similar elevation is consistent with continuity or connectivity in a sandstone channel. However, the observed monitoring data is not consistent with the 2.4-3.2 m drawdown estimate based on 20 years of pumping in a homogeneous aquifer for a well at half the distance and implies the existence of non-ideal conditions. If continuity of the aquifer is along the length of a sandstone channel, the lateral extents can still influence drawdown and produce the greater than expected drop in water levels caused by long-term pumping in a setting similar to a strip aquifer (van der Kamp and Maathuis 2002).

4 PASKAPOO AQUIFER SYSTEM

From the eastern margin of the outcrop belt where Irricana and Acme are located, the Paskapoo formation has a regional sub-horizontal dip of <1° west into the Alberta Syncline. The width of sandstone channels is assumed to be consistent with observations at outcrop, on the order of tens to hundreds of metres (Hamblin 2004). Lithology data from water well drilling logs in the Groundwater Information Centre (GIC) records (Alberta Environment 2004) are used to estimate the thickness of sandstone and shale units in the local 1900 km^2 area (Fig. 1). Individual sandstone units range from 0.3-26.8 m in thickness with an average thickness of 3.7 m and shale units range from 0.3-73.2 m with an average of 7.3 m. Thick multi-storied sandstone units may represent overlapping depositional events while splay deposits may be associated with 1-3 m sandstone units that have local broad extent as opposed to the longitudinal and possibly sinuous geometry of channels (Hamblin 2004). Inter-layered sandstone/shale and shale/sandstone sequences (0.6-14.3 m and 0.3-68.6 m respectively) reported in the drilling logs may represent overbank and splay successions with units in the sequences likely <1-3 m thick. A detailed regional description of formation and aquifer properties is summarized in (Grasby et al. 2008: in review).

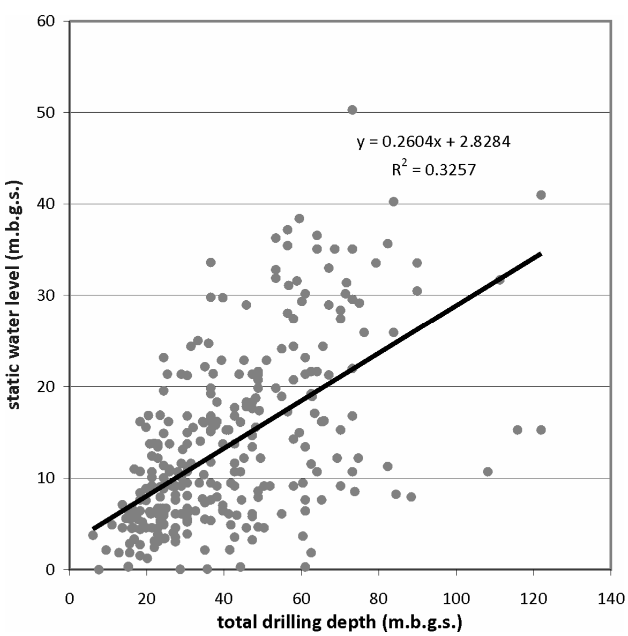

Figure 6. Depth to static water level increases with drilling depth in the 400 km^2 area around the Sunterra site.

A weak relationship between depth to static water level and increased total drilling depth (Fig. 6) may reflect the influence of a downward directed hydraulic gradient (Grasby et al. 2008: in review) to the underlying Belly River Fm. (Bachu and Michael 2003). Horizontal flow in the sandstone units is influenced by heterogeneity at different scales. Small scale changes were noted as fining sequences in petrographic analysis (Grasby et al. 2007), observations at outcrop noted fining and coarsening sequences (Hamblin 2007), and bedding planes at the larger scale can all produce preferential horizontal flow in sandstone units (Swanson et al. 2006).

Groundwater seeps that occur along sandstone/shale contacts at outcrop may be evidence of regional scale horizontal flow, while fractures noticed at outcrop and in shallow core may also promote vertical flow or enhance horizontal flow through sandstone and shale units. The heterogeneity at various scales and the possibility of a downward directed hydraulic gradient may be factors to consider when interpreting changes in water levels, continuity and connectivity between sandstone units, the effects of leaky aquitards, and the results of pumping tests used for estimating Q_{20} values.

5 A MODELING APPROACH

Modeling is currently in the data evaluation and hypothesis testing phase. Sufficient data were available to warrant preliminary modeling of a Sunterra Farms Ltd. site west of Acme (Fig. 1). Between May 1994 and December 1996, 16 wells were drilled in the NE quarter of section 18-029-26 W4. Primary production of the 1996 licensed amount (72,737 m^3/yr, ~200 m^3/day) was recommended for WSW No. 18, the last well completed in 1996. Of the previous 15 wells drilled in 1994/95, seven were maintained for monitoring and stand-by purposes (Fig. 7). The well cluster has completions at various depths and pumping test data is available for 7 wells providing good potential for modeling vertical heterogeneity and flow.

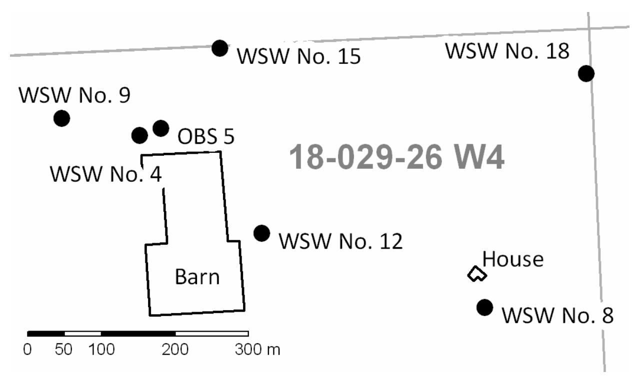

Figure 7. Sunterra site with 7 of the 16 wells plotted.

A site-specific conceptual model (Hydrogeological Consultants Ltd. 1998) that identified three aquifer units at increasing depth provided a starting point. Layers in the ModFlow (McDonald and Harbaugh 1988) model were assumed homogeneous but are assigned different parameters (Table 1). Parameters were adjusted to calibrate the model to the head at WSW No. 18, completed in Layer 7 at the centre of the model domain. The head at other wells completed in the aquifer layers were then checked for consistency with observed values.

Table 1. Model Layers and parameters for M2Ke-10.

Layer	Hydrostratigraphy	Bottom (m)	Sandstone/ Shale	K (m/s)	S_s (m^{-1})
1	Glacial	variable	N/A	2.18E-07	5.0E-05
2	Aquitard	938	0.6	1.64E-10	3.8E-07
3	Upper Aquifer	928	1.6	5.16E-05	4.1E-04
4	Aquitard	918	0.4	1.64E-10	3.8E-07
5	Middle Aquifer	909	1.4	4.32E-05	4.1E-04
6	Aquitard	907	0.4	1.64E-10	3.8E-07
7	Lower Aquifer	895	1.2	1.27E-04	4.1E-04
8	Aquitard	800	0.6	1.64E-10	3.8E-07

Layers (Table 1) in the 13 x 13 km model were determined using lithology data from GIC drilling logs. A sandstone/shale ratio >1 for intervals in a vertical well log designate a sandstone rich aquifer layer while a ratio <1 designates a shale dominant aquitard layer. Elevations of the aquifer layers roughly correspond to those identified by HCL (Hydrogeological Consultants Ltd. 1998). The apparent transmissivity (T_a) values (Hydrogeological Consultants Ltd. 2007) from pumping tests conducted in the upper and middle aquifer layers are converted to conductivity (K) and the geometric mean of the K values are used in the corresponding layers. The effective transmissivity T_e (Hydrogeological Consultants Ltd. 1998) calculated from the late time recovery data in a 1997 WSW No. 18 pumping test is used for the lower aquifer. Specific storage (S_s) for all aquifer layers is the value used in previous modeling at the site (Hydrogeological Consultants Ltd. 1998). Values of K that fall in a published range (Freeze and Cherry 1979) are used for glacial till in the top unconfined layer and the shale dominant aquitards. S_s for the glacial till is in the range of published values referenced by EnviroBase (Guiguer et al. 2003) and for the aquitards is arbitrarily based on low storativity (S) values from two pumping tests near Irricana (Nowak 2002).

Table 2. Top GHB settings and associated recharge.

GHB K (m/s)	M1Ke-9 (K = 1.6e-9) Recharge (mm/yr)	M2Ke-10 (K = 1.6e-10) Recharge (mm/yr)	M3Ke-11 (K = 1.6e-11) Recharge (mm/yr)
5.00E-11	2.14	4.02*	2.46
1.00E-10	3.91	4.83	3.35
1.05E-10	4.08*	6.92	3.44
1.50E-10	5.70	7.96	4.01*
2.00E-10	8.08	8.64	4.55
5.00E-10	25.43	10.46	5.75
1.00E-09	32.47	11.31	6.53

* recharge target for corresponding model

The ModFlow General Head Boundary (GHB) package (McDonald and Harbaugh 1988) allows head at the model limits to adjust with changing conditions in the model and flow to cross model boundaries. The flux and heads at the boundary are governed by a calculated conductance:

$$C = [(L W) K] / D \qquad [2]$$

that requires an average value of K between the model and an assigned head at a given distance D from the model (Waterloo Hydrogeologic Inc. 2006). LW is the area of the GHB grid cell at the model boundary. Values for K in the top GHB (Table 2) were adjusted to control vertical flow measured as recharge. K of 10^{-11} m/s was established to control discharge at the base. The perimeter of each layer is assigned GHB's using the K in each corresponding layer (Table 1) and controls horizontal flow across the sides of the model. Reference heads were selected for location 3 km distant from the model boundaries based on water levels in surrounding wells. The bottom reference head was assumed 710 m from the bottom boundary based on information in (Bachu and Michael 2003), and 1 m below surface elevation at the top based on the multiple wetlands that imply a shallow water table. The GHB is not an infinite source of water and grid cells can potentially go dry.

Table 3. Calibration results for 6 model runs.

Model		M1Ke-9		M2Ke-10		M3Ke-11	
K m/s, Q_R mm/yr		1.6e-9, 4.08		1.6e-10, 4.02		1.6e-11, 4.01	
Aquifer	Well	Head (m.a.s.l.)	residual (m)	Head (m.a.s.l.)	residual (m)	Head (m.a.s.l.)	residual (m)
Upper	OBS 5	920.1	-27.1	930.6	-16.7	938.7	-8.5
	No. 4	920.1	-26.1	930.6	-15.7	938.7	-7.6
	No. 9	920.2	-23.6	930.7	-13.1	938.7	-5.1
Middle	No. 8	918.9	-0.7	919.2	-0.4	921.4	1.8
Lower	No. 12	918.9	-0.8	917.0	-2.7	915.1	-4.6
	No. 15	919.0	2.0	917.0	0.0	915.2	-1.8
	No. 18	918.5	2.3	916.6	0.4	914.9	-1.4
RMS (m)			16.8		10.0		5.2
Absolute Residual Mean (m)			11.8		7.0		4.4

a)

Model		M4Ke-9		M5Ke-10		M6Ke-11	
K m/s, Q_R mm/yr		1.6e-9, 32.47		1.6e-10, 11.13		1.6e-11, 6.53	
Aquifer	Well	Head (m.a.s.l.)	residual (m)	Head (m.a.s.l.)	residual (m)	Head (m.a.s.l.)	residual (m)
Upper	OBS 5	937.4	-9.8	938.9	-8.4	939.8	-7.4
	No. 4	937.4	-8.9	938.9	-7.4	939.8	-6.4
	No. 9	937.5	-6.3	938.9	-4.9	939.9	-3.9
Middle	No. 8	928.3	8.7	921.8	2.2	922.3	2.7
Lower	No. 12	927.4	7.7	918.4	-1.3	915.5	-4.2
	No. 15	927.4	10.4	918.5	1.4	915.6	-1.5
	No. 18	926.7	10.5	918.1	1.8	915.3	-1.0
RMS (m)			9.0		4.8		4.5
Absolute Residual Mean (m)			8.9		3.9		3.9

b)

The GHB's allow vertical flow into the model and recharge (Q_R) is used to gauge consistency with the conceptual model. Results that are not consistent with the conceptual model occur when high K and Q_R values are used. If the average K_z controlled by aquitard K's in the models is too high, more recharge is required to prevent cells in the top layer from drying and increased flow through the base reduces the horizontal flow measured as flux at the model sides. It is noted by the steady state relationship:

$$d^2h / dx^2 = Q_R / K \qquad [3]$$

that different pairs of Q_R and K will produce the same head (h) distribution, i.e. non-unique results. Thus the constraint used to calibrate the steady state simulations is limited to the degree of confidence in the Q_R estimate and 3-4 mm/yr recharge (VanDijk 2005) was considered suitable for the parameter estimation in the area.

In early runs of the model it was recognized that K_z exerted the greatest influence on calibration results. The effects of using three different values of K in the aquitards with a recharge target of 4 mm/yr were evaluated (Table 3a). There is greater confidence in the estimated aquifer K-values and these remained the same in all simulations (Table 1). Results reported in the paper are from models that have vertical anisotropy of 1/100 in the aquifers but later testing showed that model results were insensitive to aquifer anisotropy.

The head at wells in the upper, middle, and lower aquifer show the response to changing K in the aquitards (Table 3a). In the models where Q_R is 4 mm/yr, M2Ke-10 produced the best results for the middle and lower aquifers and M3Ke-11 produced the best overall results for all three aquifers. Based on a qualitative evaluation of zone budgets, flow through the models is consistent with the conceptual model. Very little flow (0.09 mm/yr) leaves the bottom boundary and most of the added recharge is accounted for in the horizontal flow across the model sides.

Increased vertical flow in the M1Ke-9 simulation produced model calculated heads for the upper and middle aquifer units that are close to heads observed in the lower aquifer while heads in M3Ke-11 are separated across a wider range of elevations similar to observed values (Table 3a). The head field at the surface of these two models also provides a contrast for the effect of higher and lower K in the aquitards. Dry cells result over 70% of the area in M1Ke-9 and only 6% in M3Ke-11. The M3Ke-11 head field is consistent with the numerous wetlands in the area. Increasing recharge reduces the overall residual values in M5Ke-10 (Table 3b) but the lowest residuals for the middle and lower aquifers are in M2Ke-10 (Table 3a) where the water from 4 mm/yr recharge and flow controlled by K in the aquitards appear to allow enough vertical flow to calibrate the model to observed heads.

6 DISCUSSION

The model results provide some evidence for non-ideal, possibly leaky, aquifer conditions at the Sunterra site. If this is the case, use of analytical solutions or models that assume ideal conditions will not produce values representative of the system and consequently unreliable Q_{20} estimates. Diagnostic analysis of pumping test data from WSW No. 18 (eight day test, Nov. 1997) supports the model results. The drawdown curve for WSW No. 18 pumping well data produces a good straight-line semi-log plot and the diagnostic radial flow plot in AqteSolv® (Duffield 2007) shows evidence of ideal conditions. However, a derivative plot for WSW No. 18 (Fig 8) using the Huntash-Jacob leaky solution (Duffield 2007) indicates a downward trend in the late data considered diagnostic of leaky conditions. The report noted that pumping in the middle aquifer at WSW No. 8 occurred during the test and introduces uncertainty regarding the diagnostics (Hydrogeological Consultants Ltd. 1998). However, the main effect of reducing the head in the region of WSW No. 8, above the lower aquifer, would be to reduce the potential for leakage and the diagnostic plot is considered a reasonable indicator of the non-ideal conditions in the region of WSW No. 18.

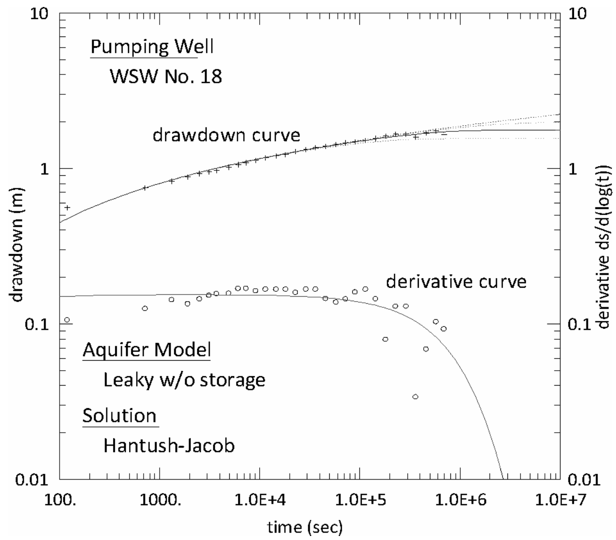

Figure 8. Log-log plot of WSW No. 18 data with derivative curve that indicates leaky conditions.

Aquifer testing at the Sunterra site in 1995, which included testing at six wells with observation wells used in three tests, was inconclusive (Hydrogeological Consultants Ltd. 1995). Modeling was used to help estimate long-term yields and monitoring of water levels was recommended. Modeling was also used after the aquifer testing at WSW No. 18 in 1997 and in both cases ideal homogeneous aquifer conditions were assumed for modeling the aquifer. The current modeling differs from the previous work by introducing heterogeneity that controls vertical flow through aquitard units.

The eight day pumping test at WSW No. 18 was also simulated in the layered model with WSW No. 8 and 15 used as observation wells. The largest model calculated drawdown at WSW No. 8 was 0.048 m in M4Ke-9 which is less than the 0.06 m observed in WSW No. 8 during a one day test at WSW No. 12 in 1995. WSW No. 12 and 18 are completed at similar elevations below WSW No. 8 and the distance of the observation well from the pumping well is similar for both tests (318 m and 344 m respectively). Considering the current conceptual model, the drawdown results at WSW No. 8 for the two tests are comparable and the modeled and observed results indicate some hydraulic connection between the middle and lower aquifers. The model calculated drawdown at WSW No. 15 is on the order of 0.14 m which is close to the observed drawdown on the order of 0.10 m and implies that lateral continuity between WSW No. 15 and 18 produces observed data similar to that modeled under leaky conditions.

7 CONCLUSIONS

The results for M2Ke-10 (Table 3a) indicate the model is capable of reproducing the observed vertical separation in head that implies downward directed flow in a vertically heterogeneous system. Low average K_z attributed to aquitard K is an important factor that controls the vertical differences as well as the availability of water where increased recharge in M4Ke-9 and M5Ke-10 improved calibration results. Use of the GHB to simulate recharge and flow through the system provides a degree of constraint on K_z. Despite 33 mm/yr recharge, 12.5 % of the surface area in M4Ke-9 has dry cells indicating K_z on the order of 10^{-9} m/s is too high for the upper layers. The 11.13mm/yr of recharge added to M5Ke-10 produces a plausible head field, improved calibration, and implies that K_z on the order of 10^{-10} m/s allows for the vertical flow needed to match observed heads. K_z on the order of 10^{-11} m/s appears to be necessary for the lower layers but is likely on the low end for the middle layers considering that even 10^{-9} m/s does not allow for the vertical flow apparent in the WSW No. 12 test.

Available data indicates water levels in WSW No. 18 have dropped approximately 6 m between 1996 and 2006. The average annual production over the same period is less than the annual licensed amount but double the drawdown originally estimated for a 20 year period (Hydrogeological Consultants Ltd. 1998) has occurred in 10 years. Water level measurements in July 2006 at WSW No. 18 recorded drawdown that reached the aquifer top. Similar problems have been observed at the Acme and Irricana sites where water levels also declined. In part, the rapid drawdown may be due to dimensions of the sandstone units associated with the 1:3 sand to shale ratio. Despite implied connectivity noted at Irricana and the Sunterra site, assumptions of homogeneity used to estimate Q_{20} values and construct models for estimating long-term pumping rates do not appear to work effectively in this part of the Paskapoo aquifer system. A greater understanding of the Paskapoo aquifer system must be developed to improve management of groundwater resources in the region and preliminary work indicates modeling can contribute.

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REFERENCES

Alberta Environment 2004. Alberta Groundwater Data, Final Edition, Groundwater Information Centre two CD set, West of 4M and West of 5/6M, Data Current April 2003. Alberta Government.

Alberta Municipal Affairs 2007. Alberta Population Profile. In http://www.altapop.ca/urban.htm, 2008/04. Alberta Government.

Bachu, S., and Michael, K. 2003. Possible controls of hydrogeological and stress regimes on the producibility of coalbed methane in Upper Cretaceous-Tertiary strata of the Alberta basin, Canada. American Association of Petroleum Geologists Bulletin, 87(11): 1729-1754.

Duffield, G.M. 2007. AQTESOLV for Windows Version 4.5 User's Guide. In On-line Manual. Hydrosolve, Inc., Reston, VA., USA.

Eckfeldt, M. 2008. Sustainable Groundwater in Alberta: Assessing the Effectiveness of the Q20 in Determining Safe Well Yields for Acme and Irricana. B.Sc., University of Calgary, Calgary, Alberta, Canada.

Freeze, R.A., and Cherry, J.A. 1979. Groundwater. Prentice Hall, Inc., Upper Saddle River, NJ, USA.

Grasby, S.E., Tan, W., Chen, Z., and Hamblin, A.P. 2007. Paskapoo groundwater study. Part I: Hydrogeological properties of the Paskapoo Formation determined from six continuous cores. In Open File 5392. Geological Survey of Canada, Natural Resources Canada, Calgary, p. 6.

Grasby, S.E., Chen, Z., Hamblin, A.P., Wozniak, P.R.J., and Sweet, A. 2008: in review. Regional Characterization of the Paskapoo Aquifer System, southern Alberta.

Guiguer, N., Horvath, M., Franca, M.P.R., Draeger, M., and Helmer, C. 2003. Enviro-Base 1.0. In Visual ModFlow Utility. Waterloo Hydrogeologic Inc., Waterloo, Ontario.

Hamblin, A.P. 2004. Paskapoo-Porcupine Hills Formations in western Alberta: Synthesis of regional geology and resource potential. In Open File 4679. Geological Survey of Canada, Natural Resources Canada, Calgary, p. 30.

Hamblin, A.P. 2007. Paskapoo Groundwater Study Part V: Detailed outcrop measured sections of the Scollard, Porcupine Hills and Paskapoo Formations in the Calgary region, Alberta. In Open File 5536. Geological Survey of Canada, Natural Resources Canada, Calgary, p. 17.

Hydrogeological Consultants Ltd. 1976. Village of Acme, Water Well No. 4 and Water Well No. 5. In unpublished contract report.

Hydrogeological Consultants Ltd. 1993. Village of Acme 1992 Water Supply Well (WSW No. 6) 35-29-26-W4M, Replacement for WSW No. 4. In unpublished contract report.

Hydrogeological Consultants Ltd. 1995. Pig Improvement (Canada) Ltd., Acme Area, NE 18-029-26 W4M, 1995 Groundwater Evaluation. In unpublished contract report.

Hydrogeological Consultants Ltd. 1998. Pig Improvement (Canada) Ltd., Acme Area, NE 18-029-26 W4M, Stanley Project - Water Supply Well Licencing. In unpublished contract report.

Hydrogeological Consultants Ltd. 2007. Groundwater Data Extraction; student.mdb. Hydrogeological Consultants Ltd.

Kruseman, G.P., and Ridder, N.A.d. 1990. Analysis and Evaluation of Pumping Test Data. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

Maathuis, H., and van der Kamp, G. 2006. The Q20 Concept: Sustainable Well Yield and Sustainable Aquifer Yield, Saskatchewan Research Council, Saskatoon Environment and Forestry Division, National Water Research Institute, Saskatoon, Canada.

McDonald, M.G., and Harbaugh, A.W. 1988. A Modular Three-Dimensional Finite-Difference Ground-water Flow Model. In Techniques of Water-Resources Investigations of the United Sates Geological Survey. U.S. Geological Survey, Reston, Virginia, USA. p. 588.

Nowak, B. 2002. Groundwater Supply Evaluation, Village of Irricana SW-21-27-26-W4M. In unpublished contract report. Groundwater Exploration & Research Ltd., p. 46.

Nowak, B. 2005. Groundwater Supply Evaluation, Sunterra Farms - Acme, AB., SW-22-29-26-W4M. In unpublished contract report. Groundwater Exploration & Research Ltd., p. 30.

Swanson, S.K., Bahr, J.M., Bradbury, K.R., and Anderson, K.M. 2006. Evidence for preferential flow through sandstone aquifers in Southern Wisconsin. Sedimentary Geology, 184(3-4): 331-342.

van der Kamp, G., and Maathuis, H. 2002. The Peculiar Groundwater Hydraulics of Buried-Channel Aquifers. Proceedings of the 55th Canadian Geotechnical and 3rd Joint IAH-CNC and CGS Groundwater Specialty Conferences: 695 - 698.

VanDijk, T. 2005. Depression-focused recharge and the impacts of land use on the hydrology of small depressions in Calgary, Alberta. Master of Science, University of Calgary, Calgary, Alberta, Canada.

Waterloo Hydrogeologic Inc. 2006. Visual MODFLOW Premium 4.2, User's Manual. Waterloo Hydrogeologic Inc., Waterloo, Ontario, Canada.