Hydrogeologic analysis of the 'Yonge Street' aquifer, south-central Ontario: a multi-decadal pumping test

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ABSTRACT
The Yonge Street Aquifer (YSA) in the Greater Toronto Area is a prolific municipal supply aquifer that has been utilized since the mid-1900s. The aquifer occurs as a roughly north-south channelized sand and gravel feature at depths greater than 70 m, extending for a length exceeding 20 km and a width of at least 2km. The current municipal water supply system consists of nine wellfields installed between 1957 and 1991.

Based on high-quality seismic profile and continuously cored borehole data, a regional stratigraphy has been delineated consisting of the following major units: bedrock, Lower Sediments (Scarborough, Sunnybrook and Thorncliffe Formations), Newmarket Till, Oak Ridges Moraine and overlying surficial diamict/glaciolacustrine sediments. The YSA occurs within a Thorncliffe age channel. This paper focusses on an analysis of the groundwater level response to municipal groundwater pumping that confirms connection along the channel. Analyses suggest that the YSA is a semiconfined (leaky) strip aquifer with observed transmissivities between 1500 to 4500 m^2/d, in contrast to regional aquifer transmissivities that are less than 500 m^2/d. It is anticipated that this conceptual model can inform groundwater exploration and development for aquifers that exist within similar glaciated terrains.

RÉSUMÉ
L'aquifère Yonge Street au nord de Toronto est un aquifère municipal prolifique qui a été utilisé depuis les années 1940. L'aquifère est composé de sable et de gravier canal, 70m de profondeur, à 2 km de large et étend 20 km le long d'une trajectoire nord-sud. Le système municipal se compose de neuf champ de captage installés entre 1957 et 1991.

Avec les profils sismique de haute qualité et de données de forage en continu, une stratigraphie régionale a été délimitée, constituée des principales unités suivantes: soubassement, sédiments profonds (les formations Scarborough, Sunnybrook et Thorncliffe), Newmarket Till, Moraine Oak Ridges et les sédiments glaciolacustres. Deux générations de canaux incisés nord-sud à travers la stratigraphie régionale sont interprétées. Une analyse de la réponse au niveau de l'eau souterraine au pompage municipal confirme la connexion le long du canal. Les analyse suggèrent que l'aquifère Yonge Street est un aquifère à bande semi-confiné (qui fuit) avec des transmissivités observées entre 1500 à 4500 m²/j, contrairement aux transmissivités régionales de l'aquifère qui sont en général inférieures à 500 m²/j. Il est prévu que le modèle conceptuel présenté aidera à l'exploration et au développement des eaux souterraines pour les aquifères qui existent dans des terrains glaciés similaires

1 INTRODUCTION

The Yonge Street Aquifer (YSA) in the Greater Toronto Area is a prolific municipal supply aquifer that has been utilized since the mid-1900s. Prior to 1941 local supply in Aurora and Newmarket was obtained from shallow flowing wells and springs (Hainstock *et al*., 1948; 1952). The first deep wells were drilled into the Yonge Street aquifer between 1937 and 1941 and were located in Newmarket. Newmarket PW11 was the last remaining of these original wells and was taken out of commission in 1990. The current municipal supply system consists of nine wellfields installed between 1957 and 1991 in the communities of Aurora, Newmarket, Holland Landing and Queensville. The aquifer occurs as a roughly north-south channelized sand and gravel unit below Newmarket Till at depths greater than 70 m, extending for a length exceeding 20 km and a width of at least 2 km (Figure 1). Historical reporting suggested a possible link of the aquifer system to bedrock valleys where coarser-grained sediments occurred at elevations below 200 metres above sea level (m asl; International Water Supply, 1991).

Gerber *et al*. (2017) analysed new and existing geologic and hydrogeologic data to determine that the YSA is a channelized aquifer system within a channel-esker-fan sequence believed to be of late Thorncliffe Formation age (> 20 ka). The YSA is considered to be a semiconfined (leaky) strip aquifer with observed transmissivities between 1500 to 4500 m^2/d, in contrast to regional aquifer transmissivities that are less than 500 m^2/d. Younger Oak Ridges Moraine age (< 14 ka) channels occur within the area and may overlap with older channels.

Numerical models (steady state and transient) exist within the study area (Earthfx Inc, 2006; 2014). Early steady state models represent average municipal pumping conditions over a specified time period (i.e. Earthfx Inc., 2006; 1990 to 2002 average conditions). Subsequent steady state and transient modelling (Earthfx Inc., 2014) focussed on average conditions (2010 & 2011) and planned future conditions. Transient calibration focussed on shorter term pumping tests (e.g. 72 hours).

Hydraulic analyses of pumping tests commonly assume that an aquifer has a sheet geometry with extension in every direction (e.g. Kruseman and d Ridder, 2000). Less common but significant are aquifers with a strip dimension confined along the length such as a channel or buried valley aquifers bounded by lower permeability confining units (e.g. van der Kamp and Maathuis, 2012). Gerber *et al.* (2017) have highlighted such a strip aquifer setting for the YSA. An excellent example of strip aquifer drawdown analysis methodology is included in van der Kamp and Maathuis (2012) for a buried bedrock valley aquifer situated near Estevan, Saskatchewan. Drawdown for the Estevan Valley Aquifer was analysed assuming a strip aquifer using the type curves developed by Vandenberg (1977), and extended by others (e.g. Butler and Liu, 1991) for similar cases. The key characteristic of strip aquifers as outlined by van der Kamp and Maathuis (2012) is the increased magnitude of drawdown and drawdown effects at much greater distances than would occur within a sheet aquifer with similar hydrogeologic properties (transmissivity and storativity).

1.1 Objective

This paper focusses on an analysis of the response of piezometric levels to hydraulic stress for the entire period of municipal groundwater pumping initiated in the early 1940s. It builds upon earlier work by analysing hydraulic transients as a long-term (since 1941) pumping test. Insights gained here are intended to inform the next version (refinement) of the existing three-dimensional numerical flow model which will focus on analysing long term groundwater level trends induced by historical pumping rates, and also the refinement of the three-dimensional architecture of the channelized strip aquifer. The conceptual model is discussed with respect to how it can inform groundwater exploration and development programs for aquifers that exist within similar glaciated terrains.

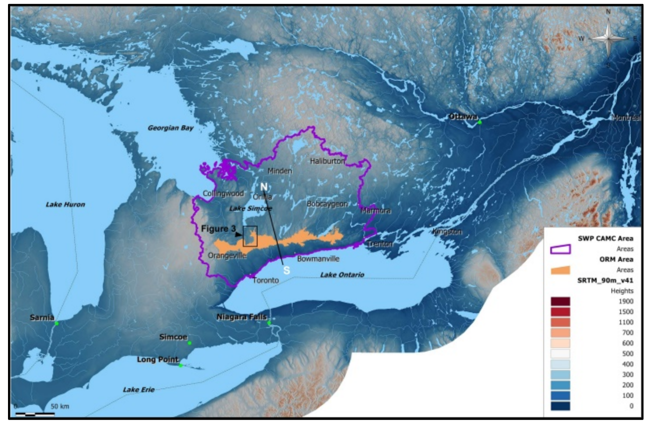

Figure 1: Study area within the Greater Toronto Area and the Oak Ridges Moraine Groundwater Program area (SWP CAMC Area). YSA is within the black box enlarged in Figure 3.

2 PHYSICAL SETTING

Two regionally significant features dominate the physical setting of the study area, a major north to south trending buried bedrock valley system and the west-east trending Oak Ridges Moraine (ORM). The Laurentian bedrock valley system occurs between Georgian Bay and Lake Ontario, bounded on the west by outcrops along the Niagara Escarpment and to the northeast by the Canadian Shield. The bedrock geology consists of Paleozoic carbonate rocks in the north and shale in the southern part of the study area (Johnson *et al*., 1992).

The bedrock valley system has been infilled over the last 135,000 years with Quaternary sediments that can exceed 200 m thickness consisting of alternating glacial (till and diamict) and interglacial (lacustrine and fluvial) sequences. The Oak Ridges Moraine formed approximately 13,000 years ago and consists of glaciofluvial-glaciolacustrine sediments bound by glacial ice in the north over the Canadian Shield and in the south in the ancestral Lake Ontario basin.

The interpreted Quaternary stratigraphy is illustrated on Figure 2. This interpretation is based on the work of Karrow (1967), Eyles (1987), Barnett *et al*. (1998) and Sharpe *et al*. (2004). Further details are included in Earthfx Inc. (2006; 2014). There are three major aquifer systems that occur within the Quaternary sequence. Deep aquifers are found beneath the Newmarket Till within deposits of the Scarborough and Thorncliffe Formations. A major shallow aquifer system occurs above the Newmarket Till within deposits of the Oak Ridges Moraine. Significant accumulations of gravel and sand are associated with tunnel channel erosion and infill activity. There are two interpreted time periods of channel activity within the study area, an older Thorncliffe channel period approximately 22,000 years ago and an ORM channel period approximately 13,500 years ago (Sharpe *et al*., 2011). The YSA occurs within a Thorncliffe channel of basal gravel overlain by sand and capped with silt and clay rhythmites (Gerber *et al*., 2017).

The ORM forms a groundwater divide in all three aquifer systems with flow to the north of the ORM converging on the Kawartha Lakes in the east, Lake Simcoe (Cook's Bay) and Georgian Bay in the west, with local deflections to rivers and streams. Flow south of the ORM is southward towards Lake Ontario with local deflections to rivers and streams. Groundwater discharge along the flanks of the ORM forms the headwaters of many study area streams.

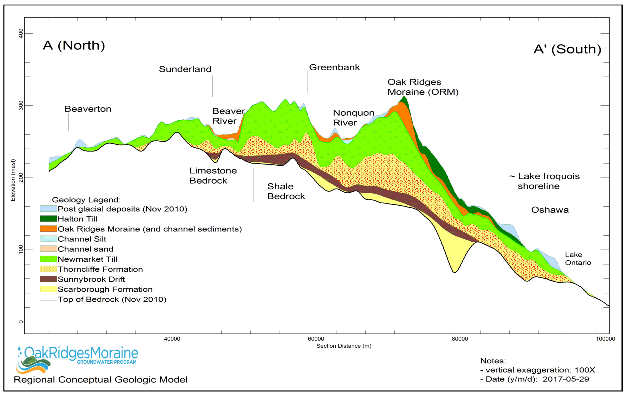

Figure 2: Regional north-south cross section through study area. Cross section location is shown on Figure 1.

3 METHODS

Various methods are being employed to analyse the three-dimensional architecture and hydraulic properties of the YSA study area. Here the observed and predicted groundwater level response at three select monitoring wells screened within the YSA (Figure 3) are linked to the historical municipal pumping that has occurred at the YSA wellfield locations. Well locations are shown on Figure 3 and the observed average annual pumping rates are summarized on Figure 4. Note that municipal pumping quantity data are sparse prior to 1970. Data used are from Hainstock *et al*., 1948; 1952). Estimated drawdown is calculated assuming a leaky aquifer without overlying aquitard storage. Ignoring aquitard storativity for this analysis is considered adequate given the time frame of the analysis (decades). Calculations were conducted utilizing the AQTESOLV software package (v4.5; Duffield, 2007) which incorporates boundaries using the method of image wells and also incorporates the presence of multiple pumping wells.

One limitation with the methodology employed is that the Hantush-Jacob method for a leaky aquifer without aquitard storage assumes that the water level at the top of the aquitard overlying the pumped aquifer remains constant, and that drawdown in the overlying shallower aquifer is zero. The study area suffers from limited observed shallow groundwater level observations of decadal length. Where data do exist, in some YSA monitoring locations there does not seem to be shallow groundwater level trends related to YSA pumping but in other locations (Aurora MW06, Queensville, Vandorf) there appear to be shallow aquifer drawdowns on the order of 1 to 4 m (Gerber *et al*., 2017). Another problem with analyzing drawdown in the YSA is the determination of pre-pumping (municipal) static water levels in the aquifer system given that most of the monitoring well observations started after the onset of municipal pumping. Another limiting factor is the difference in the conceptual model when compared to that modelled here (no-flow), in that the YSA channel is considered to be surrounded by variable but lower hydraulic conductivity material (both aquifers and aquitards), not no-flow or impermeable boundaries.

Given that gaps in the availability of detailed geologic and hydrogeologic information necessary to refine the conceptual and numerical models exist, a multi-method approach can help narrow possibilities when it comes time to refine the more sophisticated existing three-dimensional numerical models (Earthfx Inc., 2014; Golder Associates, 2015). Analysing the predicted effects of possible channel widths and hydraulic properties (transmissivity - T, storativity - S) by utilizing pumping test analysis methodology is believed to be a useful step to help refine existing numerical models.

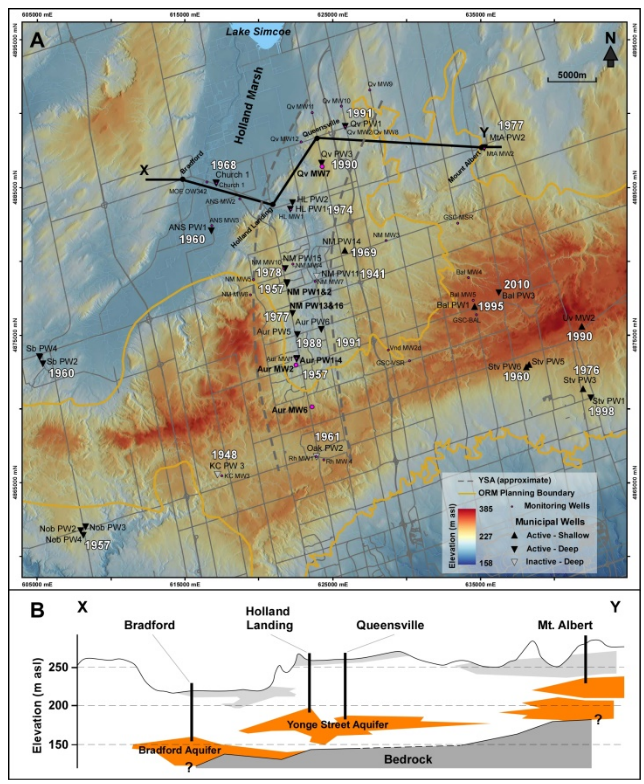

Figure 3: a) Municipal pumping and monitoring well locations, and b) historical west-east cross section from International Water Consultants (1991). Years in white indicate initiation of municipal groundwater pumping at the wellfield. Study sites discussed in results are highlighted by the purple dots labeled Qv MW7, Aur MW2 and Aur MW6.

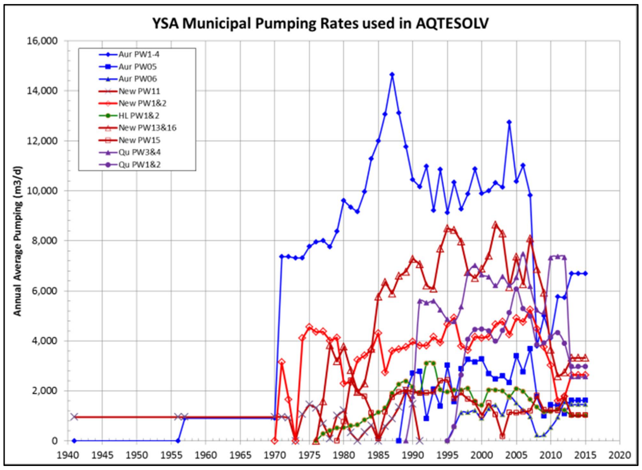

Figure 4: YSA municipal annual average pumping rates for various well fields.

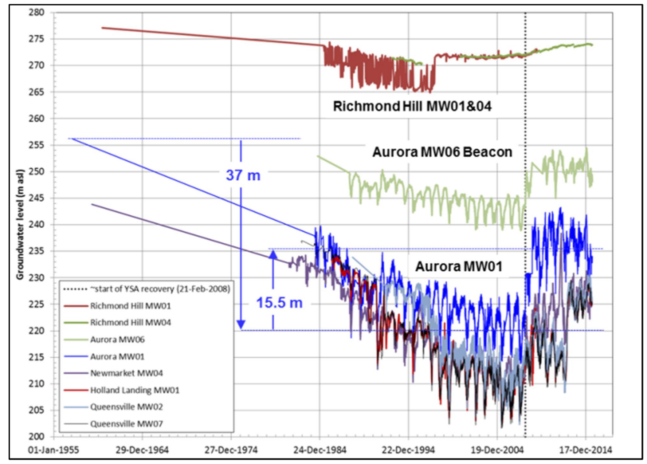

Figure 5: YSA groundwater level drawdown and recovery.

4 RESULTS & DISCUSSION

The response of three discreet wells is presented from three sectors of the YSA; Queensville, Aurora, and a monitoring well south of Aurora (Figure 3). The response of groundwater levels to municipal groundwater pumping along and transverse to the YSA will be controlled by many factors including the complex three-dimensional arrangement of variable hydraulic conductivity geologic materials as well as the magnitude of vertical groundwater flow through overlying aquitards that replenish the deep aquifer system. The observed groundwater levels for various monitoring wells along the YSA are shown on Figure 5. Note that there is a paucity of observed groundwater levels prior to 1980 when monitoring by the municipality was initiated. For the period 1960 to 1970, groundwater levels in the Aurora PW1-4 area declined by 7.6 m (Hydrology Consultants Limited, 1970), similar to the slope shown for the Aurora MW01 location (blue line) shown on Figure 5. The maximum groundwater level drawdown observed at some locations was between 35 to 40 m, this corresponding to the historical maximum municipal pumping that occurred during 2005 (43,873 m^3/d; Gerber *et al.,* 2017).

The first monitoring location where observed groundwater levels and predicted drawdown are analysed is Queensville MW07 (Figure 6), which is situated in the northern part of the YSA near the municipal groundwater pumping centre Queensville PW3 and 4. Groundwater level monitoring started in late 1982 and the steep decline in levels suggests that induced drawdown in this part of the YSA had started prior to monitoring The estimated pre-municipal pumping static groundwater level by International Water Consultants Ltd. (1977) and Vallery *et al*. (1982) at this location is 244 m asl. The latest three-dimensional groundwater flow model (Earthfx Inc., 2014: Golder Associates, 2015) predicts a pre-municipal static water level of approximately 242 m asl.

Analysis of historical groundwater levels and pumping tests for this location suggests a transmissivity range of approximately 2,200 to 3,250 m^2/d for the YSA, similar to that estimated below for the Aurora MW02 location. At Queensville, there are some significant deviations from the observed drawdown, particularly during the period 2010-2011 where observed drawdown is greater than predictions. Deviations of predicted groundwater levels from observed levels are possibly due to transmissivity differences along the length of the YSA. This analysis has assumed constant transmissivity values along the full length of the YSA, which is likely an oversimplification due to facies changes in the channel sediments. The estimated drawdown at this location assuming a sheet aquifer with transmissivity of 2,246 m^2/d would only be approximately 5 m, compared to the observed drawdown of about 35 m assuming a strip or channel aquifer. For this transmissivity, the estimated maximum drawdown at this location induced by municipal pumping from Holland Landing, Newmarket and Aurora is approximately 22 m. Approximately 13 m of drawdown is attributed to pumping from the local Queensville PW3 and 4 and PW1 and 2 wellfields.

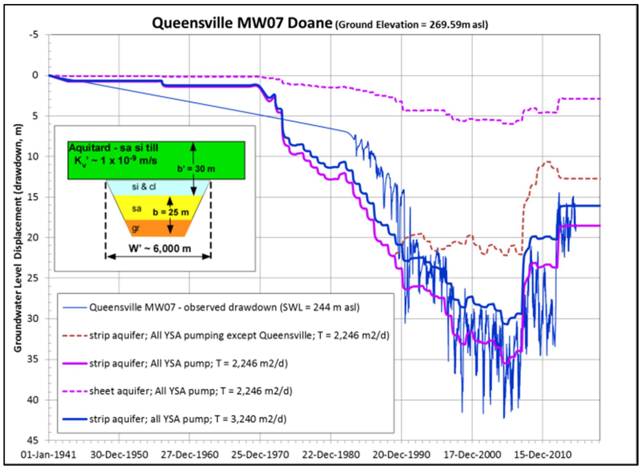

Figure 6: Monitoring well Queensville MW07 analysis.

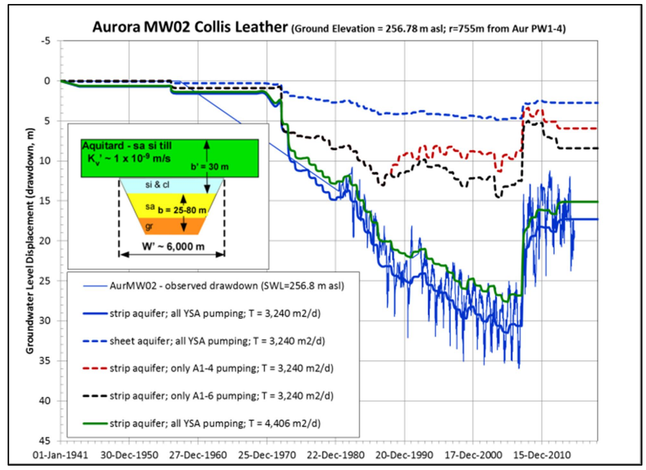

Figure 7: Monitoring well Aurora MW02 drawdown analysis. Location is 755 m south of the most southerly existing YSA wells at Aurora (Aurora PW1-4).

The next monitoring location analysed is Aurora MW02, situated 755 m south of pumping wells Aurora PW1-4 (Figure 3), near the south end of the YSA. Aurora PW1-4 is the only location with documented static water levels near the beginning of municipal pumping from the YSA. In 1957 as pumping at this location began, static water levels were 2.1 m above ground surface at Aurora PW1 (Hydrology Consultants Limited, 1977) corresponding to an elevation of 256.2 m asl. The non-pumping static water level for Aurora MW02 has been assumed as the ground surface elevation (see observed drawdown on Figure 7). The assumed strip aquifer channel configuration and hydraulic properties are summarized on Figure 7**Error! Reference source not found.**.

A transmissivity of 3,240 m^2/d closely approximates the observed drawdown for the parameters listed on Figure 7. The estimated maximum drawdown at MW02 located south of all pumping wells along the YSA is 31.5 m. The estimated maximum drawdown at this location as attributed to pumping at the closest pumping centre (Aurora PW1-4) is only approximately 11 m, illustrating the interaction and extent of drawdown induced by other pumping centres to the north along the YSA channel aquifer (strip aquifer). If analysed as a sheet aquifer (homogeneous and infinitely extensive), the estimated drawdown at this location would only be approximately 5 m taking into account the pumping at all YSA wellfields.

Monitoring location Aurora MW06 is situated near the southern end of the YSA at 3.5 km south of the most southerly existing YSA municipal wells at Aurora (Aurora PW1-4). There is a paucity of information regarding pre-municipal pumping groundwater levels for this area which is situated just north of an approximate groundwater divide that occurs beneath the crest of the Oak Ridges Moraine. Ministry of the Environment water well records for the period 1968 to 1976 suggest a static water level in the 262 to 268 m asl range. Observed drawdown for this range of pre-pumping static water levels is approximately 20 to 25 m which is less than observed drawdown of approximately 30 m at Aurora MW02 situated much closer (r = 755 m) to the Aurora PW1-4 municipal wells.

Predicted drawdown within the YSA at this location is similar to observed with a transmissivity value in the range of 3,240 to 4,400 m^2/d, assuming a pre-municipal pumping static water level estimate of 268 m asl. Predicted drawdowns for similar transmissivity values for a sheet aquifer are estimated at a maximum of approximately 7 m which is less than any of the estimated observed drawdown values. Beatty & Associates Limited (2000) have estimated the local transmissivity at this site to be 1150 m^2/d based on a 72-hour pumping test. The hydraulic conductivity is estimated to range from 1×10^{-3} to 3×10^{-3} m/s for an estimated aquifer thickness ranging from 4.4 to 13.3 m. The current interpretation of the Thorncliffe Formation sediment sand and gravel thickness (Thorncliffe channel) at this site is 35 m, or approximately three times the thickness inferred by Beatty. Correcting the transmissivity for the increased aquifer thickness leads to local estimates of T in the 3000 to 4000 m^2/d range, consistent with the estimates necessary to match the observed drawdown in Figure 8. Gerber *et al.* (2017) suggested that the YSA channel feature occurs from Queensville south to Aurora, with the channel feature transitioning into a broader fan feature south of Aurora. This was based on an analysis of groundwater levels both along and transverse to the YSA channel, and the

Thorncliffe Formation depositional model. The resolution of the analysis presented here does not seem to represent the effects of the channel to fan transition for the YSA at this location, although admittedly there is some uncertainty regarding pre-pumping static water levels and longitudinal transmissivity variation has not been incorporated.

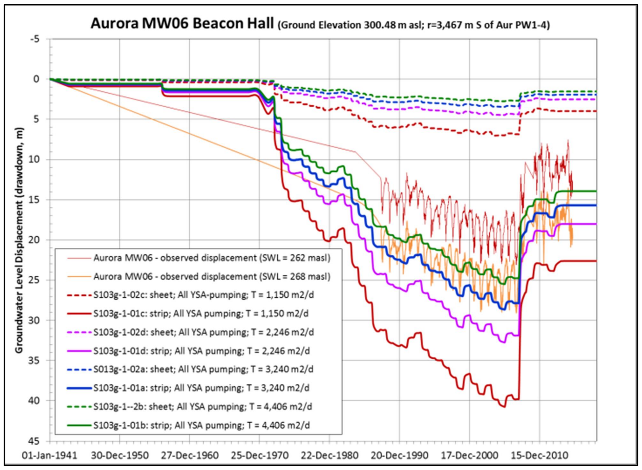

Figure 8: Monitoring well Aurora MW06 drawdown analysis. Location is 3.5 km south of the most southerly existing YSA wells at Aurora (Aurora PW1-4).

Error! Reference source not found. Figure 9 provides a comparison of the estimated YSA aquifer properties to the Estevan (bedrock) valley aquifer in Saskatchewan. Differences in the conceptual models include i) a lower vertical groundwater flux through the overlying till aquitard in Saskatchewan; and ii) the Estevan aquifer is contained within a shale bedrock valley with very low surrounding permeability. For the YSA, the channel aquifer is surrounded by a mix of lower permeability aquifer and aquitard units as shown on Figure 2 and Figure 10. The YSA has been modelled here with lateral ‘no-flow’ boundaries to analyse a key control on YSA drawdown which includes vertical flow through the overlying aquitard, and width and transmissivity of the channel fill.

The key component of the YSA is that it is recharged by vertical groundwater flow through the overlying aquitard comprised of Newmarket Till and/or channel fill capping layered silts and clays. A bulk vertical hydraulic conductivity for the aquitard ($K_v' = 1x10^{-9}$ m/s) is consistent with values used for regional numerical groundwater flow modelling (e.g. Earthfx Inc., 2006; 2014; Gerber and Howard, 2000). The observed thickness of sand and gravel within the YSA channel aquifer ranges from 20 to 80 m. Basal gravel occurs as 5-10 m thick units interbedded with sand to a maximum thickness of 40 m. An overlying sand facies is up to 41 m thick with 1 to 2 m thick sand beds. In the YSA area the overlying aquitard of channel fill silt and clay plus Newmarket Till is generally less than 30 m thick with local variation (Gerber *et al*., 2017). For this analysis the aquifer gravel and sand was given a thickness of 25 m and transmissivity (T) was varied to match observed drawdown values (1500 to 4500 m^2/d). A storativity (S) of $1x10^{-4}$ was used based on estimates obtained from many shorter-term (e.g. 48 to 72 hour) pumping tests summarized in Gerber *et al.* (2017).

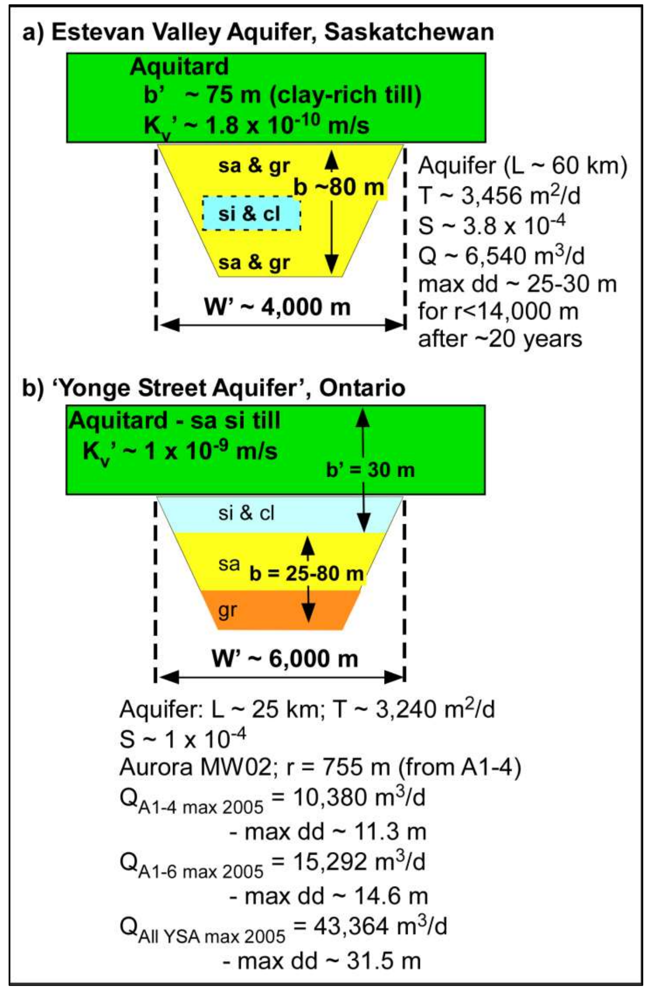

Figure 9: Comparison of a) Estevan (bedrock) Valley Aquifer estimated properties (van der Kamp and Maathuis, 2012) and b) possible conceptual model of the YSA channel aquifer (channel-esker-fan structure) at the Aurora MW02 location.

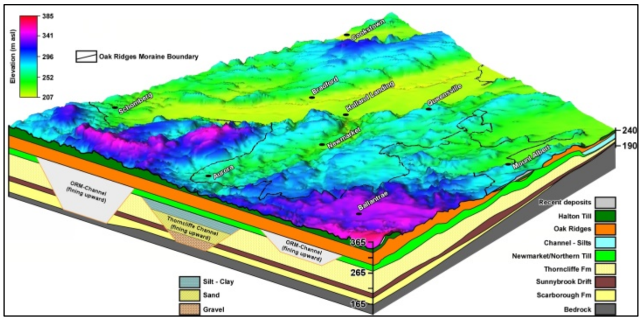

Figure 10: Conceptual model of the YSA as a Thorncliffe Channel.

5. SUMMARY AND CONCLUSION

An existing three-dimensional numerical groundwater flow model (Earthfx Inc., 2014; Golder Associates, 2015) was utilized for municipal water supply Source Water Protection efforts assuming initial conditions representative of 2010-2011, and analyzing various possible future scenarios of population and land use. Gerber *et al*. (2017) analysed continuous cored boreholes, seismic surveys and groundwater levels along and transverse to the YSA to conclude that the YSA represents a channel-esker-fan sequence from Queensville in the north to Aurora in the south. The channel sequence appears to broaden from confined proximal to less laterally confined distal sand dominated fan deposits south of Aurora. It was also suggested in Gerber *et al*. that there may be two generations of channel activity, Thorncliffe Formation age (>20ka) and Oak Ridges Moraine aged (<14 ka). Future enhancements to the three-dimensional model will include refinement of the three-dimensional channel rendering of both ages of channelized features that is made difficult by the presence of facies changes along and lateral to the channels, and also due to the lack of high quality borehole information in some areas. The entire historical sequence of municipal groundwater pumping and groundwater levels was not considered during the calibration effort for the existing numerical model. It is intended to refine the numerical model with updated conceptual understanding and consideration will be given to the entire pumping and monitoring data record during the recalibration effort. For example, in the existing numerical models, the YSA only includes ORM-channels, not Thorncliffe-channels; therefore, this is a significant refinement that needs to be completed without the benefit (currently) of further high-quality geologic information.

This paper presents an analysis of groundwater levels as they relate to municipal pumping at three select locations situated along the YSA. This paper has extended previous work by analysing groundwater levels within the context of a long-term pumping test initiated in 1941 via municipal water extraction. Taking into account a number of limitations, the analysis carried out here provides some key constraints on how the existing three-dimensional model of the area can be refined as it evolves through future work. Key information gleaned from this analysis includes: i) it appears that the YSA has a transmissivity of between 1,500 to 4,500 m^2/d; ii) channel widths less than 6 km lead to predicted drawdown greater than observed for the stated overlying aquitard properties; iii) a key feature of the YSA strip aquifer is that a width of 6 km and a length exceeding 25 km, along with a bulk K_v' of $1x10^{-9}$ m/s for the overlying aquitard, leads to vertical groundwater flow quantities that reflect the observed groundwater levels; and iv) channelized features must be incorporated into the conceptual geological and hydrogeological model of the area.

The methodology employed here has assumed a constant transmissivity along the entire length of the YSA depending on the groundwater level data available for the three monitoring locations analysed. This estimated transmissivity is slightly different at each of the locations analysed representing the expected variability of transmissivity along the YSA. The channels have been considered as no-flow boundaries here but in reality are bounded by lower permeability aquifer and aquitard units (Thorncliffe Formation Aquifer; Sunnybrook Drift aquitard; Scarborough Formation aquifer). Another limitation of this study is the paucity of reliable municipal groundwater pumping quantities prior to 1970 and the limited groundwater level information prior to 1980 when municipal monitoring efforts were initiated. The estimates presented here are all part of a multi-method analysis of geological and hydrogeological information that is being conducted to advance and refine the conceptual model of the deep aquifer system (situated beneath the Newmarket Till) present within south-central Ontario (Figure 10).

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