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ARTICLE

# Conceptual hydrogeological model of the Yonge Street Aquifer, south-central Ontario: a glaciofluvial channel–fan setting[1]

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**Abstract:** The Yonge Street Aquifer (YSA) in the Greater Toronto Area of south-central Ontario is a prolific municipal supply aquifer. It has been considered to be channelized sand and gravel linked to a bedrock valley. Despite considerable work, the fundamental conceptual model for the YSA is not well developed and documented. Based on high-quality data, a revised conceptual model of the aquifer is presented. Seismic profiles define the geometry of the regional stratigraphy with four distinct units: bedrock, Lower sediments, Newmarket Till, and Oak Ridges Moraine (ORM) sediment. Seismic data reveal two generations of roughly north–south channels: older sub-Newmarket Till channels within Lower sediments (termed Thorncliffe channel) and ORM-related channels (termed ORM channel) that incise both Newmarket Till and Lower sediments. The YSA is interpreted to occur within a Thorncliffe channel, with possible vertical connection to younger ORM channels and lateral connection to inter-channel Lower sediments. Thorncliffe channel deposits consist of fining-upward transitions from coarse gravel, to sand, to rhythmically bedded mud interpreted to be deposited within a channel – esker – subaqueous fan complex. Upper Thorncliffe channel mud facies and overlying Newmarket Till provide a capping aquitard. The YSA conceptual model benefits from a strong understanding of facies changes in the Thorncliffe Formation. The deposits with highest permeability occur within up to 80 m thick gravel and sand sequences at the base of the Thorncliffe channel, with transmissivity ranging from 1500 to 4500 $m^2$/day. Groundwater level response to municipal pumping confirms connection along the channel with muted hydraulic response laterally. Thorncliffe channels are interpreted to be up to 20 km long and approximately 2 km wide.

*Key words:* strip aquifer, glaciofluvial, channel, Thorncliffe.

**Résumé :** L'aquifère de la rue Yonge (ARY), dans la région du Grand Toronto du centre-sud de l'Ontario, est un aquifère prolifique utilisé pour l'approvisionnement municipal. Il est considéré comme étant constitué de sable et de gravier chenalisés reliés à une vallée creusée dans le substrat rocheux. Malgré des travaux considérables, le modèle conceptuel fondamental pour l'ARY n'est pas bien établi ou documenté. Un modèle conceptuel de l'aquifère revu à la lumière de données de haute qualité est présenté. Des profils sismiques définissent la géométrie de la stratigraphie régionale comprenant quatre unités distinctes, à savoir : le substrat rocheux, les sédiments inférieurs, le till de Newmarket et des sédiments de la moraine d'Oak Ridges (MOR). Les données sismiques révèlent deux générations de chenaux d'orientation approximativement nord-sud, soit des chenaux plus vieux sous le till de Newmarket dans les sédiments inférieurs (appelés chenaux de Thorncliffe) et des chenaux associés à la MOR (appelés chenaux de MOR) creusés dans le till de Newmarket et les sédiments inférieurs. L'ARY est interprété comme occupant un chenal de Thorncliffe, étant possiblement relié verticalement à des chenaux de MOR plus jeunes et, latéralement, à des sédiments inférieurs entre des chenaux. Les dépôts des chenaux de Thorncliffe présentent des séquences à granulométrie décroissante vers le haut allant de gravier grossier à du sable à des lits d'argile rythmiques interprétés comme ayant été déposés dans un complexe de chenal – esker – cône subaquatique. Le faciès argileux supérieur des chenaux de Thorncliffe et le till de Newmarket sus-jacent tiennent lieu d'aquitard supérieur. Le modèle conceptuel pour l'ARY s'appuie sur une bonne compréhension des changements de faciès dans la Formation de Thorncliffe. Les dépôts présentant la plus grande perméabilité se trouvent dans des séquences de gravier et de sable pouvant atteindre 80 m d'épaisseur à la base des chenaux de Thorncliffe, leur transmissivité allant de 1500 m2/jours à 4500 m2/jours. La réaction du niveau phréatique au pompage municipal confirme la connexion le long du chenal et une faible réaction hydraulique latéralement. Les chenaux de Thorncliffe sont interprétés comme faisant jusqu'à 20 km de long sur environ 2 km de large. [Traduit par la Rédaction]

*Mots-clés :* aquifère en bande semi-confiné, fluvioglaciaire, chenal, Thorncliffe.

## Introduction

### Background

The Yonge Street Aquifer (YSA) is a name long-used to describe relatively deeply buried sand and gravel deposits south of Lake Simcoe in the Aurora, Newmarket, Holland Landing, and Queensville areas of the Greater Toronto Area, south-central Ontario (e.g., International Water Consultants Ltd. 1991; AECOM Canada Ltd. 2014; Fig. 1). Another earlier name for the aquifer (prior to 1991) included the Yonge St. Channel (International Water Consultants

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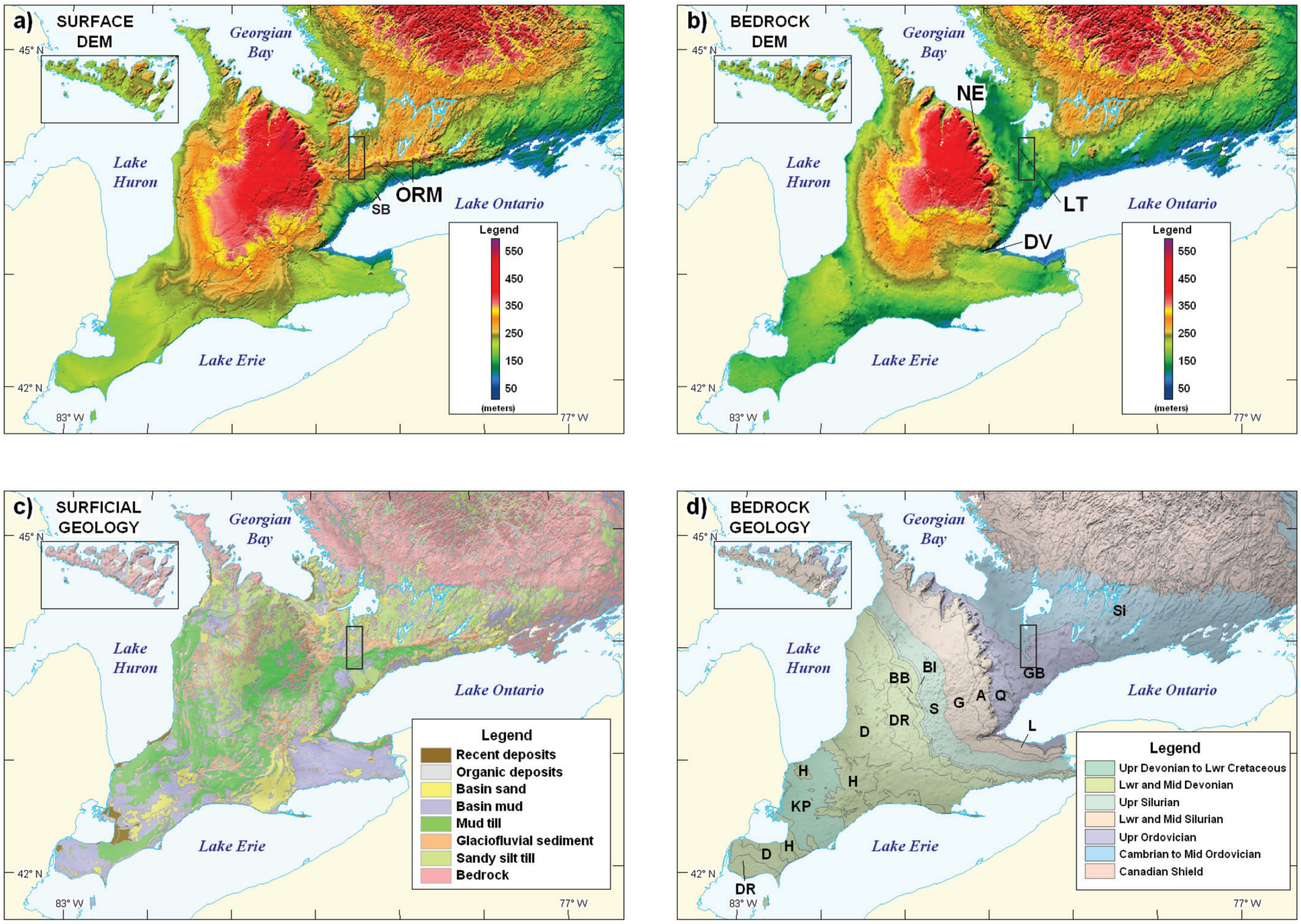
**Fig. 1.** Regional southern Ontario setting with location of Yonge Street study area (black rectangle). (*a*) Digital elevation model (DEM) of the ground surface (data source: Gao et al. 2006) (modified from Ontario Minstry of Natural Resources 2006). ORM, Oak Ridges Moraine landform; SB, Scarborough Bluffs. (*b*) DEM of the bedrock surface (data source: Gao et al. 2006). LT, Laurentian trough (dark green on the DEM from Georgian Bay to Lake Ontario); DV, Dundas Valley; NE, Niagara Escarpment. (*c*) Simplified surficial geology with a ground surface DEM drape (modified from Barnett et al. 1991; Ontario Geological Survey 1997). (*d*) Bedrock geology draped on bedrock surface DEM. Letters designate major formations or groups. Si, Simcoe; GB, Georgian Bay; Q, Queenston; L, Lockport; A, Amabel; G, Guelph; S, Salina; BI, Bass Island; BB, Bois Blanc; DR, Detroit River; D, Dundee; H, Hamilton; KP, Kettle Point (data sources: Ontario Geological Survey 1991, 1993; Gao et al. 2006) (modified from Hinton et al. 2007).

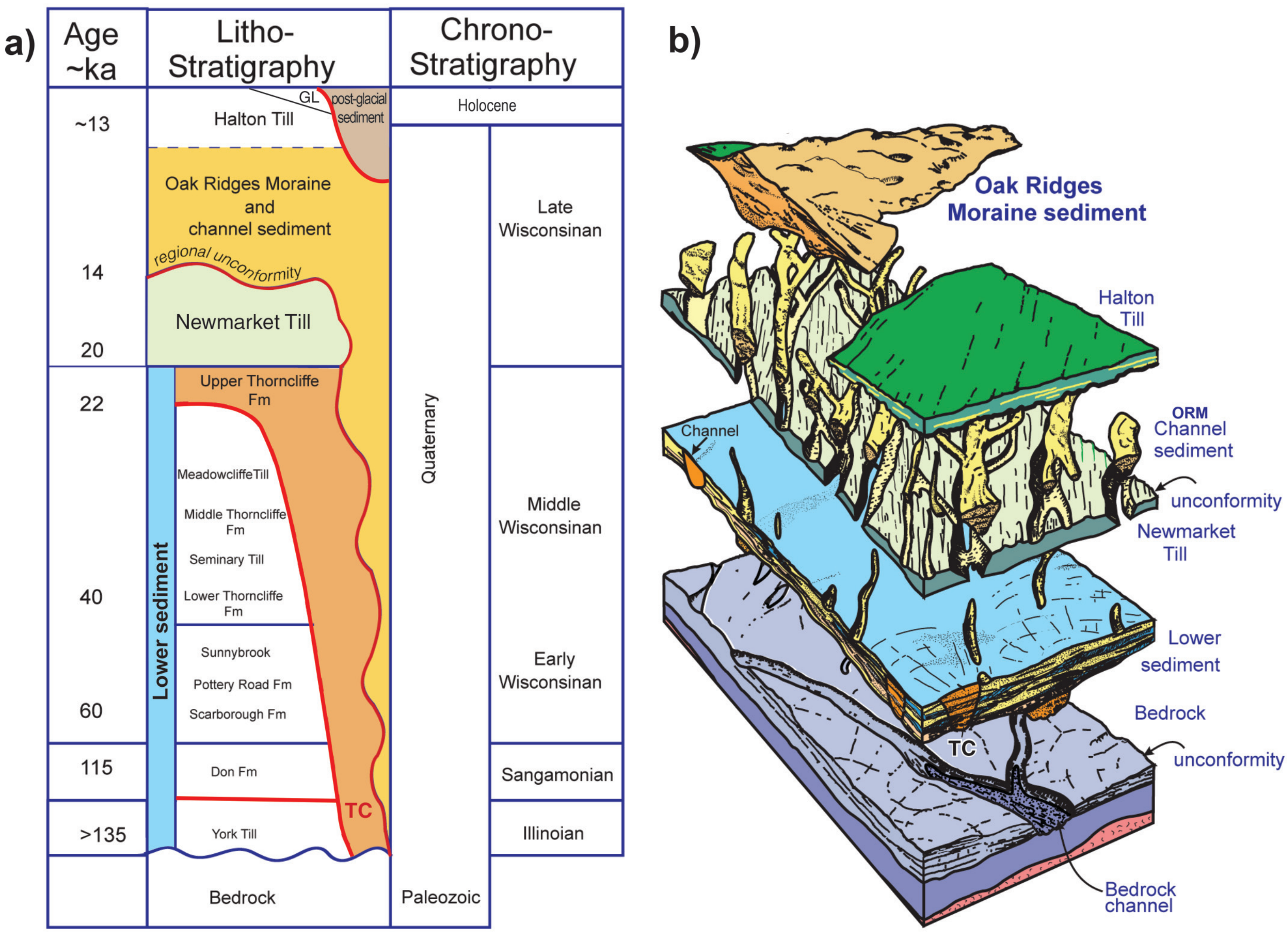



Ltd. 1977). Municipal water supply is obtained from the YSA and associated exploration, development, and permitting work has resulted in numerous consultant-led studies over the past 40 years (e.g., International Water Consultants Ltd. 1991; Gartner Lee Limited 2004; AECOM Canada Ltd. 2014). The YSA Permit to Take Water (York Region) currently allows for the extraction from all wells in the system of up to 42 000 m$^3$/day (486 L/s) (AECOM Canada Ltd. 2014). In the past, the YSA was generally considered to be the deepest aquifer of three aquifers, the others referred to as the intermediate and shallow aquifers (International Water Consultants Ltd. 1983, 1991). The deep aquifer sediments (deep and intermediate aquifers), situated beneath the Newmarket Till, have previously been attributed to the Scarborough Formation or Thorncliffe Formation (Fig. 2*a*). The aquifer has also been described as discontinuous, perhaps channelized and possibly associated with buried bedrock valleys (International Water Consultants Ltd. 1991). The hydraulic connectivity has been described as localized with different municipal well fields in different stratigraphic units (Thorncliffe Formation and Scarborough Formation) having hydraulic interconnectivity (Gartner Lee Limited 2004). Much of the information available on the YSA has been obtained from data at a few municipal well locations. Although much of the data has been collated into a database, the analyses and interpretations largely remain scattered in various consulting reports. Hence, there is a need to synthesize and integrate much of the historical and recent geological and hydrogeological work, including numerical groundwater flow modelling. This integration is best carried out by using new sedimentological and geophysical data, coupled with analyses of long-term groundwater level responses, to develop a unified geological and hydrogeological framework (i.e., conceptual model) for the YSA. Such a framework may have application beyond the study area.

## Physical setting

Southern Ontario is underlain by Paleozoic bedrock (Fig. 1) that is covered by Quaternary surficial sediment that can exceed 200 m in thickness (Gao et al. 2006). The buried bedrock surface is characterized by a series of exposed escarpments (e.g., Niagara Escarpment) that are flanked to the east–northeast by a deep bedrock trough (e.g., Laurentian trough). The bedrock surface also has secondary valleys that are smaller in scale and were formed by a combination of fluvial, glacial, and glaciofluvial processes with

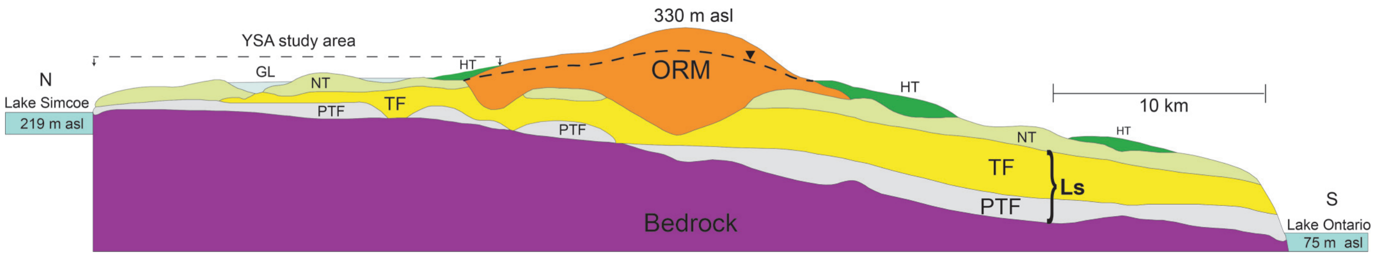
**Fig. 2.** Stratigraphic framework for south-central Ontario (modified from Sharpe et al. 2011). (*a*) Age, lithostratigraphy, and chronostratigraphy; note that a regional (channel) unconformity (long sloping red line) is present beneath both Oak Ridges Moraine (ORM) and upper Thorncliffe Formation (TF) sediments; Lower sediment (blue sequence) comprises a series of formations and units below Newmarket Till and resting on bedrock, which are difficult to trace separately across the area. (*b*) Schematic geological interpretation of the major strata that can be mapped on surface and (or) identified on seismic profiles (except Halton Till); note that ORM consists of channel and ridge sediments as part of the landform architecture; Lower sediment is a group of poorly mapped formations and units recognized primarily in lake sections at Scarborough Bluffs (e.g., Karrow 1967) but difficult to trace across the area except for TF; note the depiction of Thorncliffe channels (TC) in Lower sediment unit.




possible lithologic and structural control (Fig. 1*b*; e.g., Russell et al. 2006*b*; Gao 2011). In the northern part of the YSA study area, such as beneath Lake Simcoe, the Simcoe Group (Lindsay Formation) limestone subcrops whereas beneath Newmarket and Aurora, Georgian Bay Formation shale commonly subcrops (Fig. 1*d*). The thickest surficial deposits east of the Niagara Escarpment are coincident with the Laurentian trough and the Oak Ridges Moraine (ORM; Fig. 1*a* and 1*b*). The complete Quaternary stratigraphy for the area, including regional unconformities, is presented in Fig. 2. A generalized north–south geological cross-section shows the regional strata between lakes Simcoe and Ontario (Fig. 3). The classic Quaternary stratigraphy of south-central Ontario (north of Lake Ontario) has been described from the Scarborough Bluffs (e.g., Karrow 1967) and mapped in the subsurface northward to the Alliston and Barrie area (e.g., Eyles et al. 1985; Sharpe et al. 2011; Bajc et al. 2014*b*) and eastward to the Bowmanville area (Kelly and Martini 1986; Martini and Brookfield 1995). Preserved Quaternary sediments represent an assemblage of glacial and interglacial units that have been deposited over the last approximately 135 000 years (Mulligan and Bajc 2018). Pre-Wisconsinan and Early Wisconsinan deposits are recognized based on their fossil and (or) organic content and stratigraphic position beneath the Newmarket Till (Karrow 1967; Eyles and Williams 1992).

Hydrogeologically, several units are significant in terms of their ability to transmit and yield large quantities of groundwater. Noteworthy sub-Newmarket Till units include Scarborough and Thorncliffe formations (Gerber and Howard 2002). Scarborough sediments are well-known from the Lake Ontario bluffs (Kelly and Martini 1986) and Thorncliffe and Scarborough equivalents have been identified in core north to Barrie (Bajc et al. 2014*b*). Regionally, Thorncliffe Formation sediments form up to a 100 m thick sequence across most of the Laurentian trough (Sharpe et al. 2007, 2018) and vary from cross-bedded to cross-laminated fine sand and mud at Scarborough (e.g., Eyles and Eyles 1983) to thick successions of rhythmites at Nobleton (e.g., Logan et al. 2008) and at Schomberg (Davies et al. 2008). Depositional equivalents of the Thorncliffe Formation have been recognized to the east (e.g., Bowmanville, Martini and Brookfield 1995; Pontypool, Russell et al. 2003*a*; Purplewoods, Knight et al. 2016*a*) and to the northwest (Mulligan and Bajc 2018). Seismic reflection data at Aurora and Schomberg reveal truncated seismic stratigraphy. Channels that erode tabular Lower sediment in a general north–south direction

**Fig. 3.** North–south geologic cross-section from Lake Simcoe to Lake Ontario shows the context of the Yonge Street Aquifer (YSA) setting (boxed area Fig. 1). The main geological units are identified: (*i*) bedrock; (*ii*) PTF, pre-Thorncliffe Formation portion of Lower sediment (Ls), includes Sunnybrook drift and Scarborough Formation; TF, Thorncliffe Formation part of Lower sediment, mainly channel and overlying mud sediment in the YSA area (note undulating base to channels); (*iii*) NT, Newmarket Till; (*iv*) ORM, Oak Ridges Moraine; HT, Halton Till; GL, glaciolacustrine sediment fill, on seismic profiles, continuous core and regional isopach maps (Sharpe et al. 2007). Dashed line represents approximate position of the water table beneath the ORM (up to 30–40 m below ground surface); beyond the ORM the water table is generally within a few metres of surface (5–10 m).




are greater than 2 km wide, can be greater than 80 m deep, and are likely of Upper Thorncliffe Formation age (e.g., Sharpe et al. 2011). Channel fills consist of fining-upward sequences of gravel, sand, and mud (Sharpe et al. 2011).

The regionally-extensive Late Wisconsinan Newmarket Till (see northern till, Boyce and Eyles 2000) is stratigraphically younger than Lower sediment (Fig. 2), and has a drumlinized and channelized upper erosional surface (Sharpe et al. 1997, 2002). Newmarket Till can be up to 50 m thick, and is very dense to the south of the ORM where it forms a regional seismic marker horizon with seismic velocities exceeding 2400 m $s^{-1}$ (Boyce et al. 1995; Pugin et al. 1996). The drumlinized surface of Newmarket Till (Fig. 2) and the anabranched pattern of subglacial (tunnel) channels (ORM channels) form a regional unconformity interpreted to have resulted from subglacial meltwater erosion (Shaw and Gilbert 1990; Sharpe et al. 2004). The till is characterized as a regional aquitard, limiting the vertical movement of water between shallow sediments (above Newmarket Till) and underlying units (beneath Newmarket Till). The younger channel surfaces locally truncate Newmarket Till and Lower sediment (Pugin et al. 1999) and are mapped as features linked to the ORM (Russell et al. 2003*b*, 2006*a*). This unconformity is overlain locally by thick ORM channel, ridge, and fan sediments (Fig. 3), which extend from the Niagara Escarpment eastward to Trenton (Sharpe et al. 2007). ORM sediment (Fig. 2) is considered to be a good aquifer consisting of 50–100 m thick silt, sand, and gravel with only minor clay and diamicton (Duckworth 1979; Paterson and Cheel 1997; Gilbert 1997; Barnett et al. 1998; Russell and Arnott 2003; Russell et al. 2003*c*, 2005). Along the flanks of the ORM, muddy lacustrine-rich Halton/Kettleby tills form the final episode of moraine sedimentation (Barnett et al. 1998; Sharpe and Russell 2016). Adjacent to the ORM, glaciolacustrine sand and silt were deposited in post-glacial lakes Peel, Schomberg, Algonquin, and Iroquois (Karrow et al. 1995).

The ORM largely functions as a surface water and groundwater divide between Lake Simcoe and Lake Ontario (Fig. 3). Recharge across the study area is variable with sandy sediment and hummocky terrain of the ORM having estimated recharge rates exceeding 300–400 mm/year with flanking till units (e.g., Halton Till) having estimated recharge rates of approximately 100–150 mm/year (Gerber and Howard 2000).

## Yonge Street aquifer—previous work and definition

The Yonge Street Aquifer is a term historically used to describe a system of deep semiconfined regional aquifers occurring between 150 and 200 m asl (International Water Consultants Ltd. 1991) that extend in a general north to south direction along Yonge Street from Oak Ridges in the south, through Aurora, Newmarket, and Holland Landing to Queensville in the north (Fig. 4; International Water Consultants Ltd. 1977, 1983, 1991; Gartner Lee Limited 1986). Numerous hydrogeological investigations have been conducted within the study area since the mid-1900s relating to municipal water supply (e.g., exploration, well construction and testing, and permits). Many of these investigations describe the YSA as a channel of sand and gravel in a generally north–south direction loosely associated with bedrock valleys. In general, historical drilling has found that the sand and gravel units within the study area are thicker and coarser grained (gravel) in the central zone and thin and become finer grained laterally towards the flank areas. Lateral lower-permeability boundary conditions were observed during most pumping tests within the aquifer system (e.g., International Water Consultants Ltd. 1977). These boundary conditions were interpreted to occur within 500 m of Yonge Street near Davis Drive (Newmarket PW1 and PW2), within 800 m of Yonge Street near Mulock Drive (Newmarket PW13 and PW16), and within 550 m of the Aurora wells PW1 to PW4 (International Water Consultants Ltd. 1977). Based on these pumping test analyses, the coarse-grained part of the aquifer is estimated to be less than 1.6 km wide, which is compatible with geologic data suggesting channel widths with basal sand and gravel of 1–2 km (discussed below).

The Bradford aquifer situated to the west (Fig. 4), lying beneath the deep Holland Marsh surface valley, parallels the YSA and is reported to be a series of thin inter-fingering layers of sand and gravel situated below an elevation of 150 m asl (International Water Consultants Ltd. 1991). The Bradford aquifer is most likely an ORM channel deposit (Sharpe et al. 2013) but has also been termed valley fill sediment (Bajc et al. 2012, 2014*b*).

Many communities within the study area have obtained a municipal water supply from groundwater for decades. In the 1950s, Aurora had a population of 2700 and had a water supply from eight flowing wells between 28 and 43 m deep screened within ORM sediment (Hainstock et al. 1948, 1952). Aurora is situated on the north slope of the ORM in an area of many flowing wells and springs as the shallow aquifer system pinches out. Prior to 1937, the Town of Newmarket obtained a municipal water supply from three flowing wells installed at depths of 46, 61, and 92 m below ground surface. In 1937 a new well was installed at a depth of 81 m below ground surface (Hainstock et al. 1952). The current municipal groundwater supply extracted from the YSA is provided by six wells in Aurora, five wells in Newmarket, two wells in Holland Landing, and four wells in Queensville, ranging in depth from 75 to 122 m below ground surface. The well locations and the year of initial operation are shown on Fig. 4. The first municipal wells installed within the YSA system include Newmarket PW11, which was installed in 1941, and Aurora PW1 and Newmarket PW1, which were both installed in 1957. Prior to 1971 the wells were operated by the individual Towns (e.g., Town of Aurora, Town of Newmarket). The Regional Municipality of York was incorporated in 1971 and at that time assumed responsibility for municipal

**Fig. 4.** Study area on a digital elevation model (graded colours) with (*a*) municipal supply well and monitoring well locations and approximate Yonge Street Aquifer (YSA) outline (dashed corridor); location of cross-section shown, and (*b*) west–east cross-section shows a historical depiction of the Bradford, Yonge Street, and Mount Albert aquifers, from International Water Consultants Ltd. 1991.

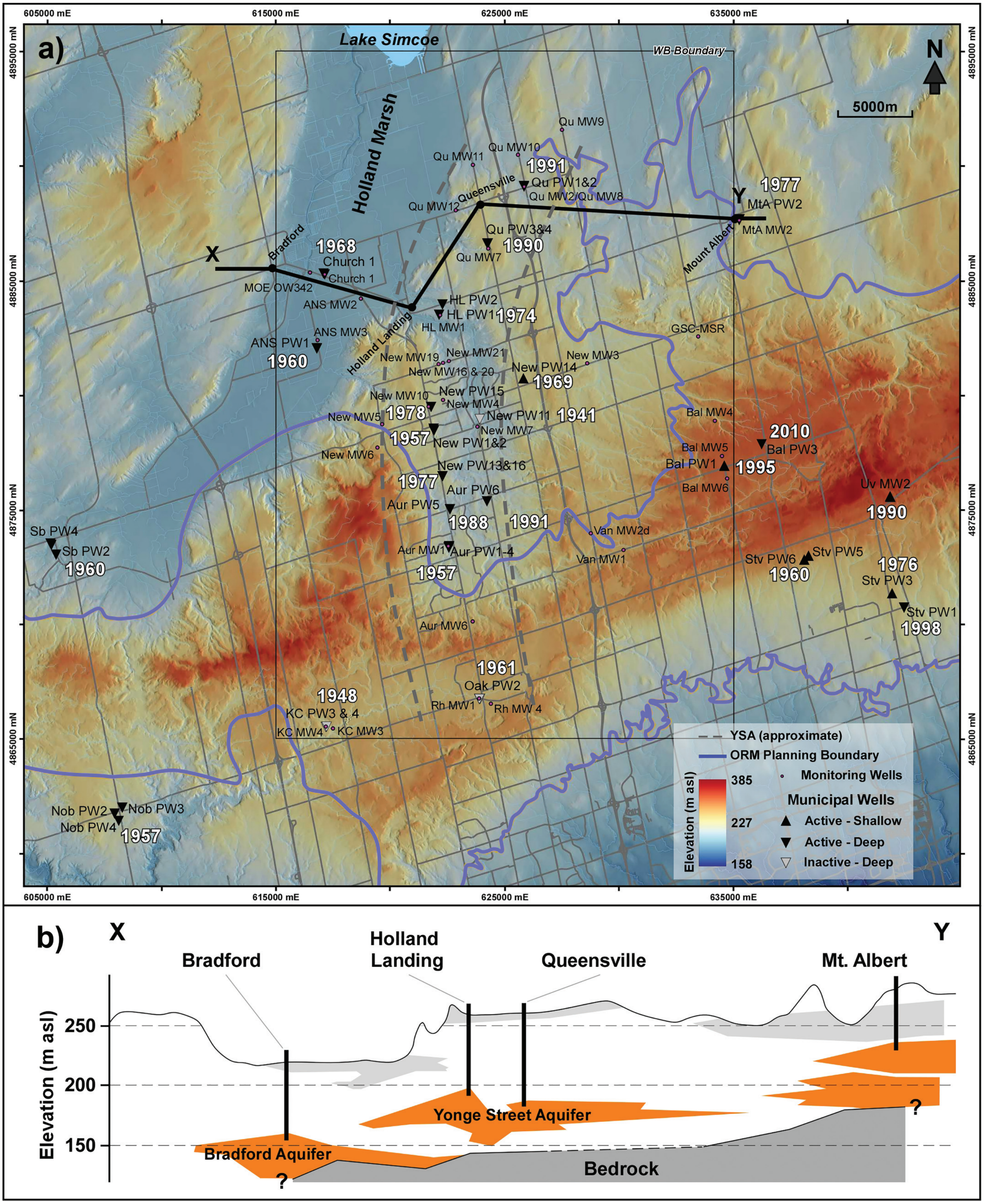


**Table 1.** High-quality geological sites in the Yonge Street Aquifer region.

| Seismic profile (Fig. 5) | Core (m) | Main features | Figure | Reference |
|---|---|---|---|---|
| Aurora (C-34) | 142 | YSA; ORM and TF channels (~400 rhythmites) | 6*a*, 7*a* | Sharpe et al. 2011 |
| Kennedy Rd. (KR) | — | ORM and TF channels | — | Pugin et al. 2011 |
| Nobleton* | 192 | ORM and TF channels; all area strata | 6*a* in Sharpe et al. 2018 | Knight et al. 2008; Sharpe et al. 2018 |
| Schomberg* | 155 | ORM and TF channels | 6*b* in Sharpe et al. 2018 | Sharpe et al. 2018 |
| 15th Ave.* | — | ORM and TF channels | 6*c* in Sharpe et al. 2018 | Pugin et al. 1999; Sharpe et al. 2018 |
| Queensville (QuN, QuS) | 96 | YSA; TF channel (~400 rhythmites) | 6*b*, 7*b* | |
| St. John's Side Rd., (W, E) | — | YSA; ORM and TF channels | 8 | Sharpe et al. 2011 |
| Vandorf | 132 | Probable YSA; ORM channel | — | Pugin et al. 1999; Sharpe et al. 2003*a* |
| Ballantrae (BAL) | 159 | No YSA; ORM channel | — | Pugin et al. 1999; Sharpe et al. 2003*a* |
| **Cores Only** | | | | |
| King City* | 115 | YSA? ORM ~100 m deep channel; TF | 8 | — |
| Kleinburg* | 105 | ORM channel, 100 m deep; TF? | — | — |
| Mount Albert* | 99 | NT upland; thick (85 m), TF | — | — |
| McCowan (87) | 101 | YSA? ORM (~50 m deep), TF channels | 8 | Pugin et al. 1999; Sharpe et al. 2003*a* |
| Green Lane (19) | 154 | NT over YSA, TF channel (~400 rhythmites) | 8 | AECOM Canada Ltd. 2014 |
| Vaughan* | 155 | Deep ORM channel (>100 m deep) | — | Russell et al. 2003*b* |
| Bradford West* | 98 | OGS12-7; ORM channel fill | — | Bajc et al. 2012 |

**Note:** Sites marked with an asterisk (*) are shown on the inset map (Fig. 5). Seismic profiles with sediment cores also have downhole geophysics. Abbreviations: YSA, Yonge Street Aquifer; ORM, Oak Ridges Moraine; TF, Thorncliffe Formation; NT, Newmarket Till.



water treatment and distribution. Currently all YSA wells are operated as a single water supply system under one permit to take water. Since 2001, groundwater from these various wells is blended with surface water from Lake Ontario to provide a municipal supply for the northern half of York Region (i.e., north of the ORM). The municipal YSA groundwater use and recently incorporated lake-based supply quantities are discussed later. For the communities of Aurora and Newmarket, the ratio of lake water to groundwater increased significantly in 2008. The groundwater system response to this 2008 change offers a unique opportunity to analyse the observed groundwater level responses and trends, thereby gaining insight into the YSA flow system. In more recent years, other communities in York Region have also started to augment or replace their groundwater municipal supplies with lake-based water (e.g., Stouffville in January 2010; King City in July 2011; Kleinburg in October 2012; Holysh and Gerber 2014).

### Outline

This paper integrates continuous core, seismic profiling, and downhole geophysical data to define the geological context of the YSA in the Aurora – Newmarket – Holland Landing – Queensville area of southern Ontario. It describes a Thorncliffe channel–fan-hosted gravel–sand succession as the principal aquifer unit beneath upper fan muds and the regional Newmarket Till aquitard. These data are supported by long-term, multi-decadal groundwater extraction and monitoring data that illustrate the hydraulic characteristics of the YSA. The paper highlights the value of integrated data analysis and the need for the collection of both high-quality geological and hydrogeological datasets to advance understanding of Quaternary aquifer extent and settings in regions of intense and multi-purpose land use and resource allocation. The discussion comments on the conceptual model of the YSA system serving as a possible example for understanding other confined and semiconfined (leaky) aquifers in the region and perhaps in Ontario.

## Methods and datasets

This study utilizes geologic, geophysical, and hydrogeologic datasets that have been collected over the last few decades. These datasets have a wide range in quality and reliability. Higher quality geologic datasets include cored boreholes, and seismic surveys along with borehole geophysics collected from various studies (e.g., Sharpe et al. 2003*a*, 2003*b*, 2011; Table 1). Interpretations from these higher quality datasets have been augmented with other geologic and hydrogeologic information for regional interpretations (e.g., Ontario Ministry of the Environment and Climate Change (MOECC) water well records). Uniquely, this study integrates a wealth of geologic and geophysical data that has previously been published in peer-reviewed journals, with hydrogeological (pumping and groundwater level) information that is largely unpublished ultimately leading to the development, refinement, and presentation of a conceptual model for the study area.

### Geologic and geophysics data

Key high-quality datasets were used to build a geological framework of the YSA: detailed geological mapping (Sharpe et al. 2006, 2007; Fig. 5), high-resolution reflection seismic profiles (list in Table 1), and continuously cored boreholes with sediment logs and downhole geophysics (list in Table 1). Seismic profiles at Queensville and Aurora with a cumulative length of 14 km, and two correlated cored boreholes (one 96 m deep and the other 142 m deep) provide the main data for analysis of the YSA. Seismic profiles, at Kennedy Road, St. John's Side Rd., Schomberg, 15th Ave., Nobleton, Vandorf, and Ballantrae, of more than 50 line km length provide sediment architecture for the regional geological context. Continuously cored boreholes at Green Lane, Mount Albert, McCowan Rd, Ballantrae, Vandorf Side Rd., King City, Nobleton, Kleinburg, and Vaughan with a cumulative length of 1500 m (Tables 1 and 2) provide important detailed sedimentology to support the key YSA data. Detailed methods for geophysical and borehole logging techniques are presented in Pugin et al. (2011), Crow et al. (2018), and Knight et al. (2008).

### Hydrogeologic data

High quality hydrogeological datasets include pressure transducer and manual groundwater level measurements within monitoring wells, and total daily pumping quantities from

**Fig. 5.** Study area and data support around the Yonge Street Aquifer (YSA). Surficial geology: GL, glaciolacustrine mud (blue) covers the Aurora–Queensville basin; GL Sand (yellow), glaciolacustrine sand; GF Fan, glaciofluvial fan (dark brown); Newmarket Till, light green; Halton Till (darker green; includes Kettleby Till); ORM (orange), Oak Ridges Moraine; red lines, seismic profiles Queensville (QuN, QuS), Kennedy Road (KR), St. John's Side Rd. West and East (W, E), Ballantrae (BAL); black lines, cross sections with YSA boreholes and wells (coloured squares); labelled wells are the key monitoring sites; M rd, McCowan Road. The coloured squares indicate borehole data used for the geological cross-sections (see Fig. 8): green for AA′, blue for BB′, purple for CC′; note that there is some overlap. Section AA′ is considered to be located slightly east of the main Thorncliffe channel (see Fig. 4). Location numbers are listed in the supplemenatry data (MAP_# ID, Table S1[2]), which provides full location names. Well name short forms are as follows: Qu, Queensville; HL, Holland Landing; New, Newmarket; Aur, Aurora; Ans, Ansnorveldt; Bal, Ballantrae; Van, Vandorf. Inset map shows locations of supporting data sites outside of YSA study area.

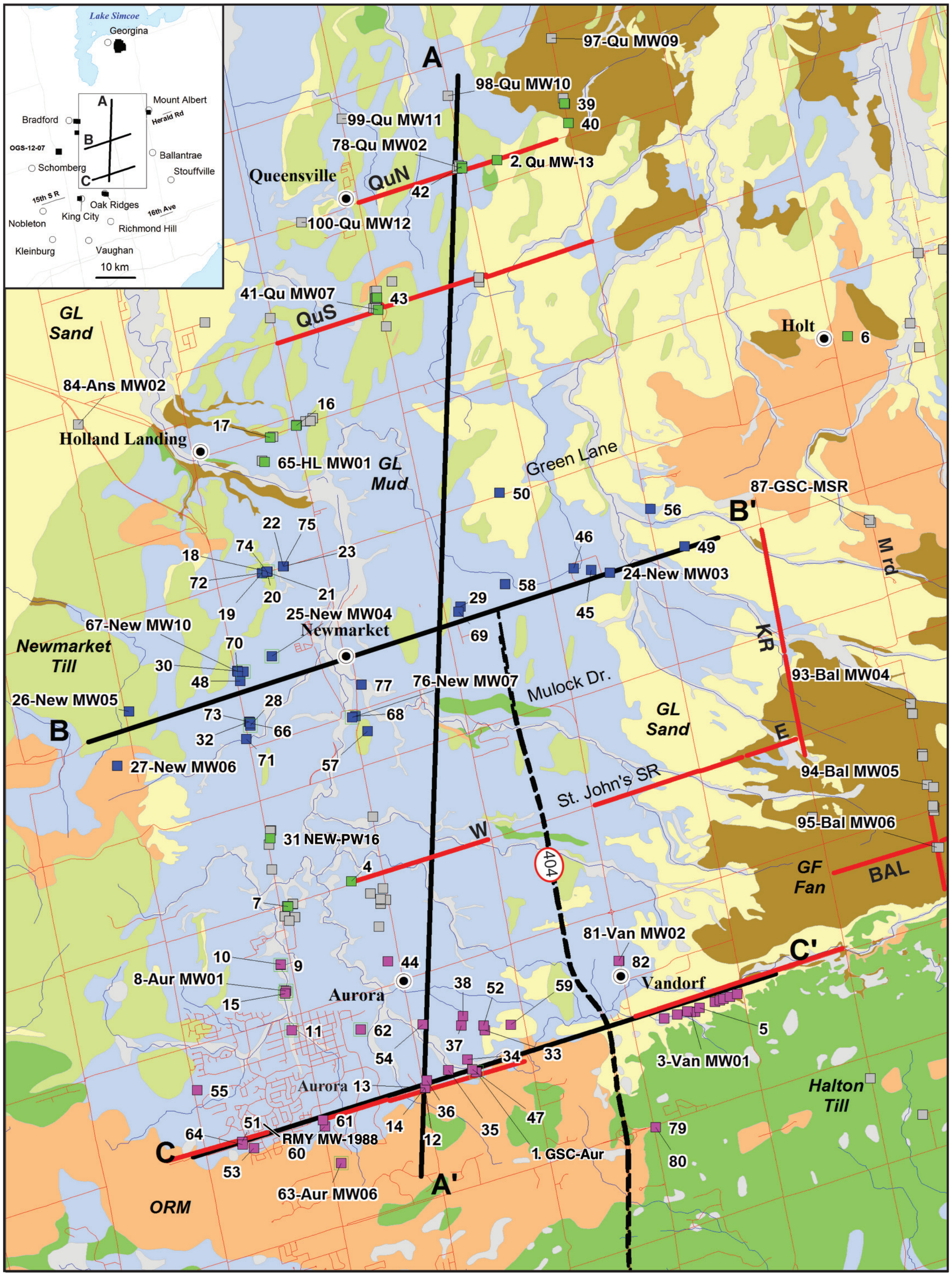


**Table 2.** Sediment thickness related to Yonge Street Aquifer and area context.

| Site (m asl/sediment thickness (m)) | Hal/Ket | ORM | Newmarket | Thorncliffe (aquifer) | LS[a] | SF | Don | York | Bedrock (OGS.br)[b] (m asl) | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| **York—north of ORM** | | | | | | | | | | |
| Georgina* (254) | 0 | 0 | 27 | 45 | 45 | — | — | 2 | 180 | NT drumlins over TF esker fan (northeast–southwest); NT interbeds. |
| 39. Warden north (262/90) | 0 | 0 | 6 | 84 | 84 | — | — | — | 179 (172) | 38 m aquifer in TF gravel–sand–mud rhythmite sequence. |
| 2. Queensville (254/92) | | 0 | 10 | 82 | 82 | — | — | — | 172 (162) | 20 m aquifer in TF gravel–sand–mud rhythmites (~400). |
| Mount Albert* (275/98) | 0 | 0 | 5 | 85 | 93 | — | — | 8? | 177L (177) | Thin NT, upland; thick (~80) TF sand–mud sequence (55 m). |
| 6. Holt (268/88) | 0 | 0 | 25 | 63 | 63 | — | — | — | 165 | No mud on top of TF, 63 m thick aquifer; OGS 93-14. |
| 87. McCowan (292/102) | 0 | 63 | 0 | 19 | 19 | np | — | 20? | 178 | ORM, possible TF channels with TF debris flow facies. |
| 19. Green Lane (260/93) | 0 | 0 | 26 | 67 | 67 | — | — | — | 146 | TF = 28 m sand–gravel fines to 41 m of rhythmites (~400). |
| Ballantrae* (331) | 0 | 109 | 0 | 30 | 50 | np | — | 20? | ~174W (160) | East of LT; ORM and possible TF channel; TF debris flow? |
| 3. Vandorf (304/133) | 0 | 88 | 8 | 37 | 37 | np | — | — | 172 (171) | Re-assessed TF; 15 sand; 5 rhythmites, 12 debris flow. |
| 1. Aurora-GSC (267/139) | 4 | 26 | 0 | 109 | 109 | — | — | — | 128W | Shallow ORM and deep TF channels. |
| 51. RMY-TW1 (280/180) | 5 | 75 | 5 | 45 | 95 | — | — | — | 100 | ORM and TF channels; RMY TW1-1988. |
| **York—south of ORM** | | | | | | | | | | |
| King City* (280/103) | 3 | 100 | 0 | 0 | — | — | — | — | 145 | Linked to seismic 15th Ave.; 25 m mud at top ORM sands. |
| Nobleton* (269/190) | 7 | 59 | 0 | 64 | 63 | 41 | 20 | — | 80L | Deep ORM channel; truncates NT and TF channel. |
| Vaughan* (274/155) | 15 | 135 | | | 5 | — | — | — | 119W | Deep ORM channel truncates all older sediments; (V4-4). |
| Kleinburg* (251/105) | 36 | 59 | 0 | 0 | 10 | — | — | — | 148L | Deep ORM channel truncates all older sediments. |

**Note:** Sites marked with an asterisk (*) are shown on the inset map (Fig. 5); site numbers, e.g., 6. Holt, refer to the location map (Fig. 5; Table S1[2]). Sediment logs at Ballantrae, Nobleton, and Vandorf are revised from those reported in Sharpe et al. (2003*a*). SF replaced by TF (B,V). np (not present) indicates sediment re-interpreted Scarborough Formation to Thorncliffe Formation from Sharpe et al. (2003*a*). Abbreviations: Hal/Ket, Halton/Kettleby; ORM, Oak Ridges Moraine; LS, Lower sediment; NT, Newmarket Till; TF, Thorncliffe Formation; LT, Laurentian trough; B, Ballantrae; V, Vandorf.

[a]LS (Lower sediment) represents the total of all sediment below NT.

[b]OGS bedrock elevation model (Gao et al. (2006)); in bracket (borehole data); W, Whitby shale; L, Lindsay limestone.

municipal supply wells (Fig. 4) that have been collected by the Regional Municipality of York since 1956. Manual groundwater level measurements within monitoring wells were measured using electrical dipper tapes. Pressure transducer groundwater level measurements have also been collected using dataloggers with data collected on time intervals ranging from 10 min to 2 h. Pressure transducer measurements are qualitatively assessed by comparison to manual groundwater level measurements. All water level measurements are recorded to the nearest millimetre. This study also benefits from regional and pumping well area analyses that have been conducted utilizing numerical groundwater flow modeling (e.g., MODFLOW, GSFLOW; Earthfx Inc. 2006, 2014). Higher quality hydrogeologic datasets have also been augmented with other groundwater level information for regional interpretations. For example, the regional groundwater flow directions are interpreted from groundwater level observations contained within the Ontario Ministry of the Environment and Climate Change water well record database. Consulting hydrogeological reports that have produced and utilized a wide range of data sets have been reviewed and referenced. The reports mainly relate to exploration, construction, permitting, and operation of the municipal wells and generally include any of the following types of information:

- Borehole drilling including collection of continuous core;
- Groundwater pumping tests;
- Falling or rising head tests (i.e., slug tests);
- Surface (seismic) and borehole geophysics;
- Groundwater level measurement (manual and pressure transducer);
- Groundwater sampling and chemical analysis; and
- Numerical flow modelling.

## Geology and hydrogeology

The regional stratigraphy of the YSA area is advanced progressively from seismic stratigraphy to continuous core sedimentology and borehole geophysics. The seismic profile data subdivide the stratigraphy into four key architectural elements or packages: (*i*) bedrock, (*ii*) Lower sediment (Ls), (*iii*) Newmarket Till, and (*iv*) post-Newmarket sediments including ORM sediment and Halton Till units (Fig. 2*b*). A north–south cross-section (Fig. 3) frames the YSA study area between lakes Simcoe and Ontario, including showing the Thorncliffe Formation at the top of unit (*ii*), Lower sediment. Continuous core and associated downhole geophysical data provide ground-truth for interpretation of major seismic reflection horizons, characterization of seismic facies, and sedimentological analysis. These data are integrated with the regional

[2]Supplementary data are available with the article through the journal Web site at http://nrcresearchpress.com/doi/suppl/10.1139/cjes-2017-0172.

stratigraphic framework (e.g., Sharpe et al. 2004; Sharpe et al. 2018), and with the stratigraphic nomenclature from the Scarborough Bluffs (e.g., Karrow 1967, 1974; Eyles and Eyles 1983). Core samples provide physical property information that is linked to downhole geophysical interpretation (e.g., Pullan et al. 2002; Crow et al. 2018). The architecture and character of YSA strata are defined from two key sites, Aurora and Queensville, where seismic profiles and continuously cored borehole datasets support construction of a refined geological understanding. The results from these reference sites are correlated across the area with additional seismic, core data and well records to help define the extent, thickness, and facies trends in the YSA (Table 2).

## Seismic stratigraphy

Analysis of seismic data in the study area reveals that reflector strength and pattern permit division of the strata into four regional stratigraphic packages (Fig. 3). Inclined reflection surfaces of varying reflector strengths may occur within seismic units or truncate and cross-cut strong reflector surfaces. The deepest, strong reflector surface, assigned as bedrock, is relatively horizontal with minor (less than 10 m) undulations at the two reference sites (Aurora and Queensville; Fig. 6). Seismic reflection data reveal bedrock elevation ranges between approximately 190 and less than 100 m asl across the area framing the YSA (Table 2); more typical, the surface undulates within a range of 110–165 m asl with smaller bedrock valleys. The second strong reflector is coincident with the upper surface of Newmarket Till, extending to where it is inclined and truncates underlying units; here it may truncate Lower sediment (Fig. 6*a*; west side) to bedrock (Fig. 2*a*). The two defined strong reflector surfaces, and a weak reflector defining the base of Newmarket Till, partition the stratigraphy into four seismic packages: (*i*) bedrock, (*ii*) Lower sediment, (*iii*) Newmarket Till, and (*iv*) post-Newmarket Till including ORM and Halton Till sediment (Fig. 2*b*).

Newmarket Till is a very dense (seismic velocities of 2400 m $s^{-1}$) marker bed and has diffuse seismic facies with strong diffraction patterns (Boyce et al. 1995; Pugin et al. 1996). Where it is thick (greater than 20 m), it attenuates seismic energy and may reduce the resolution of its basal contact and that of underlying seismic-stratigraphic units. In some locations (e.g., Queensville, 15th Ave., Table 3) a moderate yet clear planar reflector occurs at the base of Newmarket Till at 225 m asl. Where sufficient seismic energy was transmitted and or velocity contrast exists below the base of Newmarket Till, then tabular reflectors and distinct angular truncations define the Lower sediment multi-unit seismic package (Sharpe et al. 2018; Fig. 6*a*, A,B,C).

Buried channels occur on seismic profiles across the study region both stratigraphically below and above Newmarket Till (Fig. 2*a*). Pre-Newmarket Till channels occur at five sites: Queensville, Kennedy, St. John's Side Rd., Aurora, and 15th Ave. (Fig. 2; Pugin et al. 2011; Sharpe et al. 2018). Seismic sections reveal channels 0.3–3 km wide and approximately 100 m deep, situated below Newmarket Till: they truncate a tabular, undulating-to-horizontal seismic reflector package at Aurora (Fig. 6*a*, A,B,C) that is 40–100 m thick, resting on bedrock. Channel margins are weakly resolved yet lower-strength horizontal reflectors provide distinctive seismic properties outside channel margins. At Queensville (Fig. 6*b*), sub-horizontal (A) reflectors 30 m thick, below Newmarket Till, are cut by a channel in two west–east sections. The Queensville channel is 0.8 km wide in the northern (N) profile and becomes narrower (0.4 km) and deeper in the southern (S) profile.

Seismic facies of Lower sediment channel fill at Aurora (Fig. 6*a*) comprise two transitional elements. The channel form is infilled with horizontal reflectors that are strong at the base and weaken upward. The basal seismic facies overlying bedrock has distinctive strong, hummocky seismic reflectors that are 30–40 m thick (Fig. 6*a*, D). This distinct seismic facies can be traced laterally across the 2 km width of the channel. This hummocky facies at St. John's Side Rd. West (Table 3) has reflectors that dip southwest. Downhole seismic data indicates p-wave seismic velocities of 3000 m/s (Pullan et al. 2000) indicative of gravel. Overlying the hummocky facies is a 30–50 m thick package of weaker reflectors that extend across the channel and have a consistent density and a p-wave velocity of 1800 m/s (Sharpe et al. 2011). Weak inclined seismic reflections within this upper unit appear to be foreset bedding with a component of dip toward the west. These Lower sediment channels are considered to be Upper Thorncliffe Formation in age (Sharpe et al. 2011).

Channels stratigraphically younger than Newmarket Till occur at the lower portion of the ORM (Pugin et al. 2011). They are prominent, large (3–5 km wide), and 100 m deep (Russell et al. 2003*b*; Brennand et al. 2006) beyond the study area; they are less prominent within the YSA study area (Tables 1 and 2). At Schomberg and Nobleton, ORM channels extend completely to bedrock and truncate Newmarket Till and underlying tabular to horizontal reflectors in Lower sediment (Pugin et al. 1999; Sharpe et al. 2018). Diffuse, irregular reflectors occur within channels in contrast with truncated tabular seismic reflectors outside channels. To the east of the YSA study area, seismic reflectors along Kennedy Road – St. John's Side Rd. define a clear channel margin that cuts across Newmarket Till and lower parallel reflectors and the inclined margins of a 1.5 km wide channel extend to bedrock (Pugin et al. 2011). At Aurora, the ORM channel has very strong reflectors forming a shallow (30 m deep) structure cut into upper diffuse facies of the underlying Thorncliffe channel (Fig. 6*a*, F).

## Stratigraphic sequence

### *Bedrock*

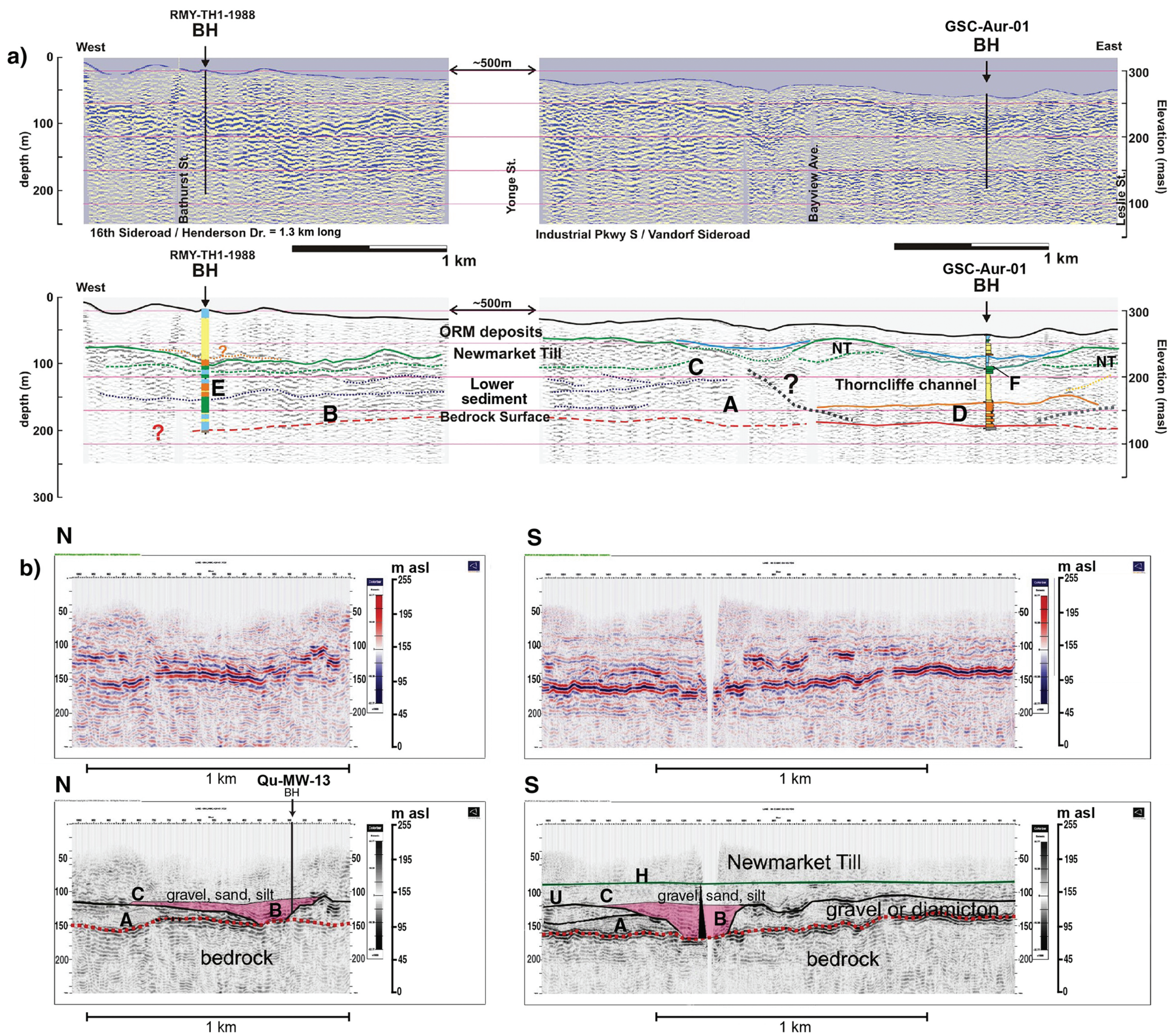
Georgian Bay Formation shale occurs in the southern part of the study area, whereas Lindsay Formation (Simcoe Group) limestone occurs in the north (Fig. 1*d*; Sharpe et al. 2018). The regional bedrock surface is gradational along the eastern slope of the broad 150 m deep Laurentian trough (Fig. 1*b*). Seismic reflection data, along with wells and boreholes drilled in the area, reveal bedrock elevation ranges between 110 and 190 m asl across the YSA area (Table 2). Smaller valleys were identified on this surface such as a 2–4 km wide, 40 m deep valley along Kennedy Road that dips from 155 to 115–120 m asl within a few kilometres (Pugin et al. 2011; Table 3). At Aurora a shallow south–west-oriented bedrock low is inferred from 110 to 127 m asl. Four kilometres north of the Aurora seismic profile (Fig. 6*a*) shale bedrock occurs as a low at 80 m asl along St. John's Side Rd. West (Sharpe et al. 2011). However, no parallel north–south bedrock valley occurs below the trace of the north–south YSA. Rather, bedrock generally slopes from north to south along the YSA from Queensville at 172 m asl to Aurora at 110 m asl (Table 2).

### *Regional Lower sediment*

Based on the seismic architectural analysis, the thick (50–150 m) regional Lower sediment succession (Fig. 2) has two distinct elements: (*i*) sub-horizontal, tabular seismic units in inter-channel areas; and (*ii*) channel fill successions (see Aurora and Queensville borehole cores, Fig. 7). The older tabular-to-undulating seismic stratigraphy beneath the Aurora channel unconformity is seldom intersected by core in the YSA area (except see RMY-TH1-1988, Fig. 6*a*). However, southwest of the YSA study area at the Nobleton reference site (Logan et al. 2008), continuous core provides a high-resolution characterization of the full Lower sediment succession, which is described in Sharpe et al. (2018) and briefly highlighted below.

Several formations comprise Lower sediment (Fig. 2*a*), for example, Don, Scarborough, Thorncliffe, and other strata, Sunnybrook drift. Sediment characteristics and warm-climate fossils of the Don Formation support a fluvial to shallow lacustrine setting in low base-level, inter-glacial times (Karrow 1967). Organic material is common in the Scarborough Formation as black oxidized

**Fig. 6.** Seismic profiles at Aurora and Queensville shown as processed (top) and interpreted (below) sections. Borehole log details for RMY-TH1-1988 from Gartner Lee Limited 1988. Borehole log details for GSC-Aur-01 and Qu-MW-13 shown on Fig. 7. (*a*) Aurora, a 6 km long west–east profile (with a gap) records complex reflector architecture. Packages of sub-horizontal reflectors (A, B, C) occur above indistinct reflections on bedrock; sediment reflections are truncated by a channel (dashed line labelled Thorncliffe channel; channel margin is poorly defined) below very strong reflectors (Newmarket Till, NT). Sediments logged in continuous core (borehole GSC-Aur-01, Fig. 7*a*) relate to seismic facies; for example, strong hummocky reflectors (D) represent hard, lower channel sediment in gravel. Note that borehole RMY-TH-1988 intercepts a thick Lower sediment sequence (including a shallow Thorncliffe channel (E), with a fining-upward gravel–mud fill), NT, and Oak Ridges Moraine (ORM) sediments (a fining-upwards gravel–sand–mud sequence). Note that reflector contrast in a shallow channel structure at F indicates compact mud on Thorncliffe channel sand. Log colours: green, diamicton/till; orange, gravel; yellow, sand; and blue, mud (silt–clay). Adapted after Sharpe et al. 2011. (*b*) Queensville includes two east–west profiles (N and S) located about 2 km apart. Different collection parameters led to lower resolution profiles than at Aurora; they show less detail within the sediment package but show very strong reflectors on bedrock (in part because bedrock is limestone). There are three main seismic packages on bedrock: A, sub-parallel reflectors below a discontinuous strong undulating reflector surface, U. The undulating surface U truncates the sub-parallel reflectors A, in part as a channel eroded to bedrock. B, channel fill reflectors, strong at the base weakening upward to the top of the channel and into very weak to opaque reflectors beyond the channel to the base of a weak horizontal reflector, H at the base of Newmarket Till (level basal reflector); C comprises very weak to opaque reflections beyond the channel margins, B. The colour bar in the process profile indicates reflector strength (red is high strength). Black narrow triangle indicates a fining-upward trend in sediments based on decreasing reflector strength upward.




sandy sediment; the formation is interpreted as glaciolacustrine deltaic sediment containing cool-climate fossils (Karrow et al. 2001). Both the Don and Scarborough formations have been observed in small bedrock valleys below 100 m asl in the Nobleton area (Sharpe et al. 2018). Most bedrock in the YSA area is greater than 110 m asl, and hence, these water-level-controlled formations are less likely to form significant deposits in the area of the YSA. The previous correlation of Scarborough Formation to Vandorf

**Table 3.** Seismic features and architecture in the Yonge Street Aquifer area.

| Site (km) | Core | Channel | Width (km) ORM/TF | Depth (m) ORM/TF | Seismic facies reflector strenth | Structure | Truncated strata | Bedrock elevation (m asl) | Sediment | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| Aurora (4.8) | Yes | ORM/TF | 1/2 | 30/100 | High, low-strength | Channel | NT; LS | Level, 128 | Gravel, sand, silt | ORM and TF channels truncate sub-horizontal reflectors; see Fig. 6*a*. |
| Ballantrae (4) | Yes | ORM | 1.5 | 50 | Low-strength | Channel | NT; LS | Level, 174 | Gravel, fine sand | ORM channel and ridge elements (Fig. 5, BAL). |
| Queensville (10) | Yes | TF | 0.5–1.0 | >50 | High, medium, low-strength | Channel | NT; LS | Slopes, 162 | Fines up | North–south profiles show TF channel cut to rock; northeast—southwest-trending (Fig. 5, QuN, QuS). |
| Herald Rd.* (2.3) | No | ORM | 1.5 | 80 | High to low-strength | Hummocky | NT; LS to Br | Low undulating | Gravel | Mounded reflectors; esker?; channel, ridge features. |
| Kennedy (7) | No | ORM/TF | 2/3 | 150/30 | High, low-strength, diffuse | Inclined, mounds | NT; LS to Br | >115 | Sand, silt, gravel | 40 m deep bedrock valley; ORM channels above TF erosion (Fig. 5, KR). |
| St. Johns Side Rd. East* (4) | No | ORM | >2.5 | 100 | High, low-strength | Channel | NT; LS | Level 138 | — | Clean truncation by ORM channel; level bedrock; (Fig. 5, E). |
| St. Johns Side Rd. West (2.5) | | ORM/TF | 1.5/>2 | >50/70 | High, low-strength | Inclined | LS | 119–135 | — | TF channel seismic facies; inclined southwest; (Fig. 5, W). |
| Vandorf (4) | Yes | ORM | <3 | 100 | High to low-strength | Cut-fill | NT; LS to Br | 172 | Gravel, sand, silty sand | Channel–ridge architecture; eroded to bedrock (level); (Fig. 5, Vandorf). |
| 15th Ave.* (4) | No | ORM/TF | 0.5/1.5 | 20/70 | Medium to low-strength | Horizontal | NT; LS | Undulating | Sand–silt | ORM ridge, channel elements; westerly inclined reflectors in ridge; portion of 1.5 km wide, 70 m deep TF channel. |
| Nobleton* (8.3) | Yes | ORM/TF | 5/2 | 200/50 | High, low-strength, diffuse | Medium hummocky | NT; LS to Br | 80 | Gravel, sand, silty | ORM channel truncates all older parallel reflectors, NT, LS 1.5 km, 50 m deep bedrock valley; >1 km wide TF channel; 1.5–2.0 km wide, 150 m deep ORM channel. |
| Schomberg* (9) | Yes | ORM/TF | 5/>3 | 175/80 | High, low-strength, diffuse | Hummocky, 10–15 m mounds | NT; LS to Br | Valley, 60–97 | Gravel, sand, silty | ORM ridge overlies ~5 km wide, ~80 m deep channel; 3 km wide, 60 m deep TF channel. |

**Note:** See Fig. 5 for site locations; for sites marked with an asterisk (*) see Sharpe et al. 2018. Similar sand facies and upward facies transitions have been observed in a nearby Thorncliffe basal channel sequence (Sharpe et al. 2018; Table 3). Abbreviations: ORM, Oak Ridges Moraine; TF, Thorncliffe Formation; NT, Newmarket Till; LS, Lower sediment; Br, bedrock.

**Fig. 7.** Continuous-core borehole logs with numbered core photographs. (*a*) Aurora is a 142 m core grounded in shale, overlain by two fining-upward, continuous-sediment sequences resting on eroded surfaces: (*i*) Thorncliffe Formation channel gravel, fines upward to sand and clay rhythmites (~340 annual cycles), interrupted by an 11 m sandy silt diamicton (debris flow) sequence; (*ii*) Oak Ridges Moraine (ORM) channel gravel fines up to sand and mud diamicton (Halton sediment) interbeds, and glaciolacustrine rhythmites (approximately 90) of former Lake Schomberg. The ORM channel rests unconformably on Thorncliffe post-channel capping rhythmites. (*b*) Queensville is a 96 m core grounded in limestone, overlain by a fining-upward, continuous-sediment sequence resting on an unconformity. Thorncliffe channel gravel, fines upward to sand and clay rhythmites (~400 annual cycles), overlain conformably by Newmarket Till (NT) (recall level reflector at base of NT in seismic profile, Fig. 6*b*). Geochemical trends in the fining-upward sediments support the interpretation of continuous sedimentation in these sequences (Knight et al. 2015, 2016*b*) apart from identified unconformities. Note that a cored borehole at Green Lane (Table 2), part way between cores a and b (site 31, Fig. 5), has a similar Thorncliffe channel sequence with post-channel rhythmites (approximately 400) overlain by NT.



(180 m asl), Ballantrae (210 m asl), and Newmarket (210 m asl) of Sharpe et al. (2003*a*) is now correlated within the elevation range for the Thorncliffe Formation (greater than 150 m asl; Table 3).

*Thorncliffe Formation*

The Thorncliffe Formation comprises more than 50% of the Lower sediment sequence in the region (Sharpe et al. 2018). At the Nobleton reference site, a basal gravel–sand unit represents an initial subaqueous fan sequence at the base of a thick tabular seismic architecture observed around the site of a cored borehole (Sharpe et al. 2018). Overlying regional muddy Thorncliffe Formation sediments contain approximately 1000 graded fine sand–silt to clay rhythmites (Logan et al. 2008). Rhythmites are typical of lower Thorncliffe Formation sediments at the Scarborough Bluffs (Karrow 1967) where approximately 1000 silt and clay rhythmites occur. These low-energy sediments, with a few sandy episodes, are considered to represent a long period of glaciolacustrine sedimentation prominent across the broad Laurentian trough (e.g., Mulligan and Bajc 2018; Sharpe et al. 2018). These low-energy sediments are truncated by channels, approximately 1–3 km wide and 60–100 m deep at Schomberg and Nobleton (Table 3; Sharpe et al. 2018). Channel sediments are overlain by approximately 500 rhythmites at Schomberg. These rhythmites cap the channel yet most extend beyond channel margins. These post-channel rhythmites are in addition to the approximately 1000 pre-channel rhythmites in lower Thorncliffe Formation strata. Hence regionally, the Thorncliffe Formation represents stable glaciolacustrine sedimentation of at least 1000 years (as inferred from annual rhythmites), interrupted by high-energy meltwater floods, followed by a return to low-energy glaciolacustrine sedimentation for about 500 years after meltwater floods (Sharpe et al. 2018).

***Upper Thorncliffe Formation channel sediments (Thorncliffe Channel)***

In the YSA area, seismic facies at Aurora, Queensville (Fig. 6), and St. John's Side Rd. (West) are correlated with sediment core from the Aurora and Queensville boreholes (Fig. 7). These reference cores, 20 km apart, have a similar 81–84 m thick gravel–sand–mud fining-upward sequence with variations in facies thickness and arrangement. Trends in natural gamma and conductivity also identify the overall fining-upward pattern at Aurora (Sharpe et al. 2011). The Thorncliffe Formation consists of 38 and 11 m of gravel–sand facies association, overlain by 42 and 11 m of sand, and by 19 and 60 m of mud facies associations (Fig. 7*a* and 7*b*), resting on bedrock. Facies descriptions from the two reference sites are supplemented by additional core analysis (Tables 1 and 2) to provide the most complete assessment of YSA sediments.

*Gravel–sand facies association*

The 40 m thick gravel–sand facies association directly overlying bedrock at Aurora consists of alternating 5–10 m thick fining-upward gravel–sand layers. Gravel is sub-angular to rounded and estimated to be 20%–25% of the unit with 80% being pebbles and the rest granules or cobbles. Clast lithology is carbonate (70%) and Precambrian shield (30%). Gravel units are well-defined in downhole geophysical logs (Sharpe et al. 2011) by an increase in spectral density, and high P- and S-wave velocities. Thinner gravel at Queensville (11 m) occurs as sharp-based 0.2–2 m thick beds of well-rounded cobble to boulder gravel, with sand inter-beds, also occurring directly on bedrock.

*Sand facies association*

The sand facies association at Aurora gradationally overlies the gravel–sand association. It is up to 41 m thick and mainly comprises 1–2 m thick graded sand beds (Fig. 7*a*, core 6). Coarse-to-fine graded sand units occur in 18–50 cm thick beds, with sharp and gradational lower contacts. Sub-rounded to sub-angular granules and pebbles occur at the base of some beds. Sand is also cross-bedded, cross-laminated, or planar with bed sets 30–40 cm thick. Planar and ripple cross-lamination structures are defined by dark heavy mineral concentrations (garnet-rich) that exhibit an erratic pattern on magnetic susceptibility logs (Sharpe et al. 2011). Sand grades upward and is interbedded with diamicton, then is overlain by diamicton and laminated to rhythmically bedded silt and clay. The downhole gamma counts increase near the top of the sand unit (70–60 m depth), within the overall upward-fining sand package. A small amount of total organic carbon (0.1%–0.3%) is present in the sand unit. A pungent odour (suspected hydrogen sulfide) was apparent in the sand unit between 65 and 100 m below ground surface (201–166 m asl).

*Diamicton—mud facies association*

The diamicton mud facies association is up to 27 m thick and gradationally overlies the sand facies association in the Aurora core (Fig. 7*a*). An 11 m thick sandy silt stoney diamicton with a silty interval is interbedded with sand in the lower 6 m. It is overlain by a 16 m thick mud succession consisting of three distinct units, a lower 5 m of clay rhythmites, and an 11 m thick unit of deformed, brecciated mud that is laminated in the top 6 m. The lower clay rhythmites (340; Fig. 7*a*) have sharp-based silt horizons that are gradational to overlying thinner, millimetre- to centimetre-scale, clay units. The cumulative number of rhythmites in the three units is approximately 400 (Fig. 7*a*). Cores to the north in the Green Lane – Queensville area have 46–57 m of laminated mud (clay silt) (Fig. 7*b*), and a similar number (approximately 400) of rhythmites. These estimates of post-channel rhythmites are similar to the approximately 500 rhythmites identified at Schomberg. Of note at Aurora, the gamma counts in the silty diamicton are higher than usual (80 compared to 40–60 cps) for sequences of Newmarket Till; thus, silty diamicton observed in core at Aurora is different than Newmarket Till.

Pre-channel rhythmites (approximately 1000) found in the deeper trough west of the YSA (e.g., Nobleton) have not been found in the YSA area. Inter-channel sediments appear to be variable. On the west side of the YSA, approximately 45 m of inter-channel sediments consist of diamicton, mud, and minor sand (Fig. 8*c*, site 51); whereas, at Mount Albert 80 m of inter-channel sediment is primarily sand (55 m) with lesser mud (15 m) and gravel (less than 10 m) over thin diamicton (Table 2).

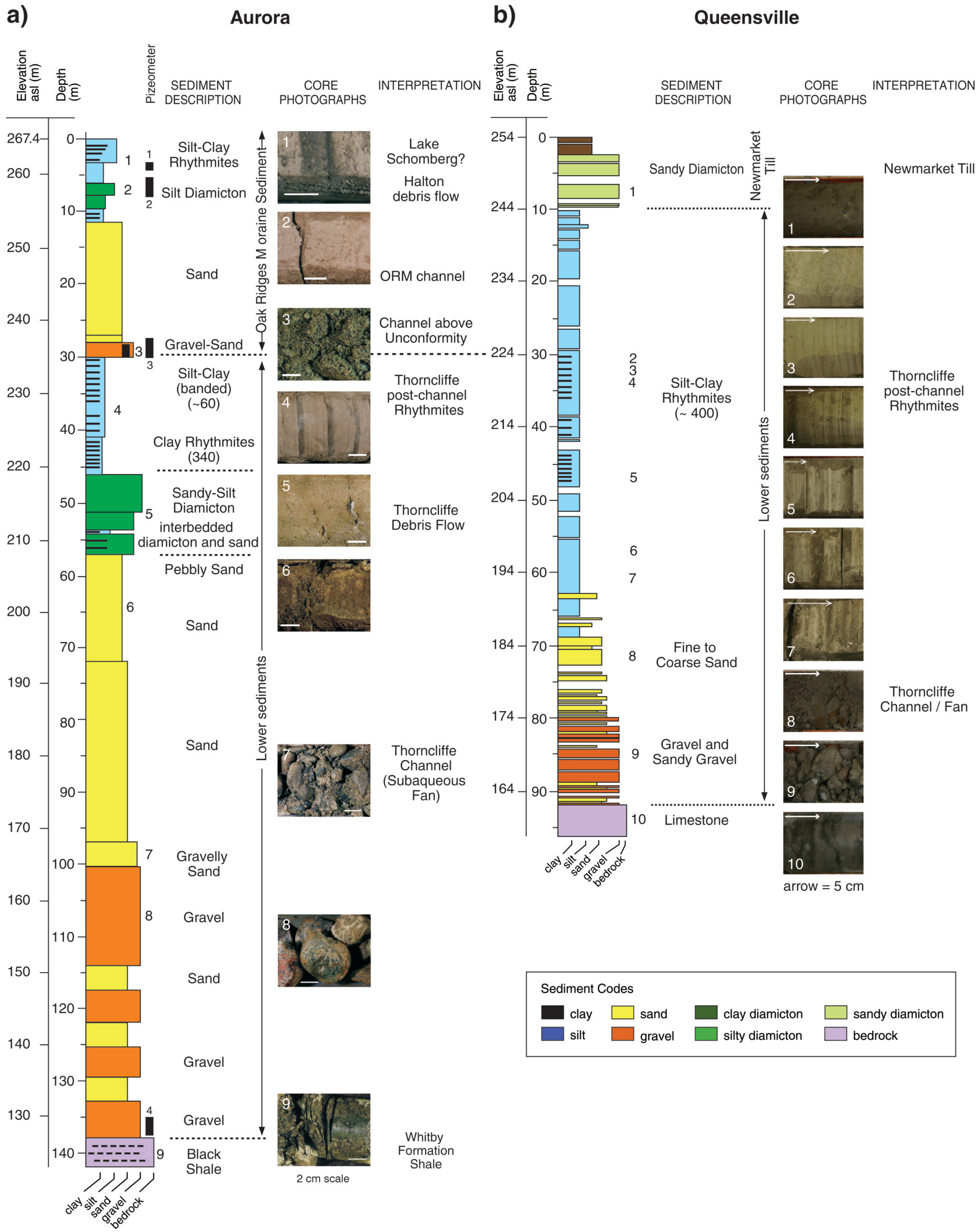
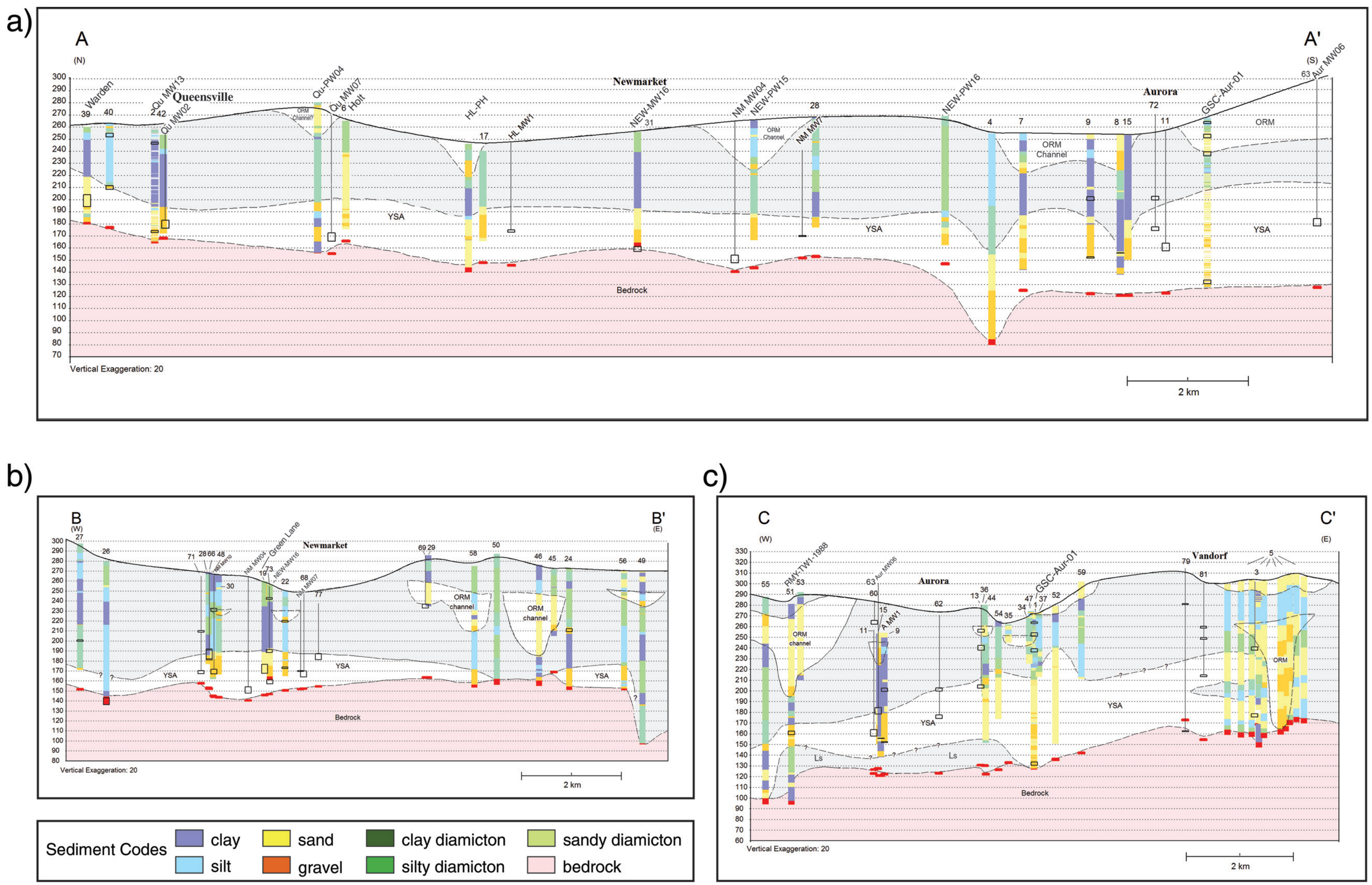

a)
Aurora
Elevation asl (m)
Depth (m)
Pizeometer
SEDIMENT DESCRIPTION
CORE PHOTOGRAPHS
INTERPRETATION
Silt-Clay Rhythmites
Silt Diamicton
Sand
Gravel-Sand
Silt-Clay (banded) (~60)
Clay Rhythmites (340)
Sandy-Silt Diamicton
interbedded diamicton and sand
Pebbly Sand
Sand
Sand
Gravelly Sand
Gravel
Sand
Gravel
Gravel
Black Shale
Oak Ridges Moraine Sediment
Lower sediments
Lake Schomberg?
Halton debris flow
ORM channel
Channel above Unconformity
Thorncliffe post-channel Rhythmites
Thorncliffe Debris Flow
Thorncliffe Channel (Subaqueous Fan)
Whitby Formation Shale
2 cm scale
clay silt sand gravel bedrock
b)
Queensville
Elevation asl (m)
Depth (m)
SEDIMENT DESCRIPTION
CORE PHOTOGRAPHS
INTERPRETATION
Sandy Diamicton
Newmarket Till
Silt-Clay Rhythmites (~ 400)
Fine to Coarse Sand
Gravel and Sandy Gravel
Limestone
Lower sediments
Newmarket Till
Thorncliffe post-channel Rhythmites
Thorncliffe Channel / Fan
arrow = 5 cm
clay silt sand gravel bedrock
Sediment Codes
clay
silt
sand
gravel
clay diamicton
silty diamicton
sandy diamicton
bedrock

**Fig. 8.** Geological cross-sections of the Yonge Street Aquifer (YSA). See Fig. 5 for locations of cross-sections and supporting borehole locations. (*a*) North–south section A–A′ (~20 km) from Queensville to Aurora shows continuity in tens of metres of sand and gravel in YSA; this is overlain by 50–60 m of aquitard (Thorncliffe Formation (TF) post-channel mud, Newmarket Till, glaciolacustrine mud); site 1 is Aurora core (1. GSC-Aur; Figs. 5 and 7*a*; Table S1[2]), site 2 is Queensville core (2. Qu MW-13; Figs. 5 and 7*b*; Table S1[2]). (*b*) East–west Davis Drive section B–B′ (~11 km) shows YSA sediment to be ~2–6 km wide centred around Newmarket; note small, shallow Oak Ridges Moraine (ORM) channels above YSA. (*c*) East–west Aurora west – Vandorf section C–C′ (~12 km) shows YSA sediment is wider, perhaps 6–10 km wide around the Aurora reference borehole (1. GSC-Aur; Figs. 5 and 7*a*; Table S1[2]). Well screens are small open rectangles. Red, bedrock core. Light grey areas are aquitard (Thorncliffe post-channel mud, Newmarket Till, and glaciolacustrine clay in Aurora lowland basin). Cross-section locations are shown on Fig. 5. Ls, Lower sediment.



*Interpretation and sedimentary setting*

The Thorncliffe Formation in the YSA area was deposited in a subaqueous fan setting based on the fining-upward gravel–sand–mud sequence at the Aurora and Queensville reference sites (Fig. 7). This is consistent with the regional basin model, that is that the Thorncliffe Formation formed within rising-water levels as advancing ice blocked eastward drainage (St. Lawrence valley) to create a large, deep (approximately 100 m) lake against the Niagara Escarpment (Mulligan and Bajc 2018; Sharpe et al. 2018). YSA sediments were deposited in an ice-controlled channel–esker (Queensville) to more distal subaqueous fan (Aurora; Fig. 9; Sharpe et al. 2011). Inter-channel sediments represent low-energy distal fan glaciolacustrine sediments with areas of underlying diamicton on bedrock. In places where pre-channel rhythmites are absent, a new esker–channel–fan system, such as at Holt, may occur. The 63 m of sand and gravel at Holt have no overlying mud and likely represents the proximal esker portion of the system at the edge of the basin (Fig. 10). This system may extend eastward to include the 55 m of Thorncliffe Formation sand at Mount Albert.

Based on work at the Scarborough Bluffs, the Thorncliffe Formation has been previously interpreted as deltaic (Karrow 1967; Eyles and Eyles 1983), which is a widely adopted inference (e.g., Earthfx Inc. 2006, 2014). No evidence to support this interpretation has been found in the YSA area (Sharpe et al. 2011) although alternatives to the subaqueous fan scenario are considered in the Discussion. Pertinent to this discussion is that the Thorncliffe Formation has been traced using high-quality data from the Scarborough Bluffs via river valley outcrops, core and seismic data to the YSA study area (Sharpe et al. 2006, 2007).

We expand on the proximal, channel, subaqueous fan setting for the Thorncliffe Formation and the YSA. There is a consistent presence of fining-upward gravel–sand rhythmite sequences across the YSA study area and westward (e.g., northwest of Holland Marsh; Bajc et al. 2014*b*; Table 2). These fining-upward sequences are interpreted to record a series of subaqueous fans at an ice-sheet grounding line, either subglacial or ice-marginal. Typically, the base of the gravel is coincident with the base of 50–100 m deep channels (Fig. 7) eroded through older sediment to bedrock (Fig. 9). Deep channels imply an erosive high-energy, possibly pressurized, ice-contact, subaqueous setting (Russell et al. 2003*c*). High-energy subaqueous discharge, deep erosion, and deposition of coarse gravel are compatible with channel-wall failure, slumping, and deposition of debris flows during a rapid flood event (Russell et al. 2007). Debris flows would account for the diamicton at the top of the gravel–sand sequence at Aurora (Fig. 7*a*). Overlying silt–clay rhythmites (approximately 400) are interpreted as annual rhythms and a return to seasonal glacial melt cycles (e.g., Gilbert 1997). The absence of mud, in the lower ~80 m gravel–sand lower channel sediments at Aurora, and the similar 30 m thick sediment at Queensville, supports rapid, continuous sedimentation, likely as an Icelandic-style glacial flood event (jokulhlaup, e.g., Russell et al. 2007; Burke et al. 2011). The Aurora channel gravels can be traced for 20 km from Queensville to south of Aurora through additional borehole log records (Fig. 5) and across a possible channel width of at least 1–2 km (core gravel, Fig. 8*b* and 8*c*); such a deposit exceeds the scale of many recent glacial flood event deposits in Iceland (e.g., Russell et al. 2007).

An esker – subaqueous fan interpretation for the thick sand and gravel sequence at Holt (Table 2) indicates a separate meltwater–sediment influx point to the east of the YSA. Another separate setting has been interpreted in Upper Thorncliffe Formation sediments to the east at Markham (Sharpe et al. 2011) and broader subaqueous fan sandy sediments have been identified by the authors further downflow to the south along Duffins Creek and to the Scarborough Bluffs.

***Newmarket Till***

In the central Yonge Street corridor, Newmarket Till is a 2–25 m thick (Table 2), dense, pebbly (5%–8%), sandy silt diamicton. It occurs in upland settings 220 m asl as drumlinized outcrops, above Thorncliffe Formation post-channel rhythmites (Fig. 7*b*) and on seismic profiles as an undulating strong reflector horizon. This strong reflection can be traced for 7 km with gaps (e.g., GSC-Aur) along the Aurora seismic profile (Fig. 6*a*). It is mapped between ORM channels (e.g., Sharpe et al. 1997; Russell et al. 2004) north of the ORM. The diamicton is commonly massive with 3–10 m thick beds, separated by less than 1 m thick sand and silt inter-beds and rare striated clast horizons. At Georgina, diamicton has silt, sand, and gravel inter-beds 5–10 m thick (Table 2; Interim Waste Authority 1994*a*).

*Interpretation and sedimentary setting*

Newmarket diamicton in uplands is interpreted to be a subglacial till with various depositional models invoked by previous workers; perhaps lodgement (Gwyn and DiLabio 1973) or deformation till (Boyce and Eyles 2000). Newmarket Till inter-beds are glaciofluvial (Boyce and Eyles 2000) and glaciolacustrine sediment deposited in a subglacial environment (e.g., Shoemaker 1991). At the Aurora borehole, diamicton previously interpreted to be a thin debris flow facies of Newmarket Till (Sharpe et al. 2011) has been re-interpreted here as a debris flow diamicton at the top of the Thorncliffe coarse-grained, rapidly filled channel. The overlying post-channel rhythmite sequence (approximately 400; Fig. 7*a*) rules out Newmarket Till because the same post-channel rhythmites occur below Newmarket Till at Queensville (Fig. 7*b*), Green Lane, and Schomberg. Newmarket Till is therefore absent at the Aurora borehole, having been eroded by an ORM channel (Fig. 9). Newmarket Till was likely relatively continuous across the region with a thickness of tens of meters before it was locally eroded to form drumlins or was incised by meltwater channels (Sharpe et al. 2004; Brennand et al. 2006).

***Oak Ridges Moraine (ORM) sediment association***

ORM sediment is mapped across the south portion of the study area (Russell et al. 2005; Sharpe et al. 2007) as part of an east–west ridge that overlies the ORM channel unconformity (Table 2; Fig. 3). ORM sediment in core (channel and ridge) in the YSA study area varies from 30 to 108 m thick and consists of several fining-upward sequences (Table 2). A shallow channel structure at Aurora (Fig. 6*a*) sharply overlies Thorncliffe post-channel mud. Elsewhere within the YSA study area, ORM channels may truncate Newmarket Till and Thorncliffe Formation to bedrock (e.g., Vandorf, Table 2).

ORM channel-fill sediment forms a 30 m thick fining-upward sequence of gravel–sand–silt–clay, with inter-bedded mud diamicton at Aurora (Fig. 7*a*). Gravel deposits range from 1 to 10 m thick (compare with 17 m at Nobleton) and comprise pebble-to-cobble clasts. Gravel is gradationally or sharply overlain by variable sand facies that fine upward into thick (tens of metres), ripple-scale cross-laminated fine sand. In places (e.g., Henderson Road, King City, Vandorf, and Ballantrae core), north–south ORM channel sequences (Table 2; Pugin et al. 1996) are overlain by sandy east–west-oriented fan wedges 50 m thick. At Aurora sand is transitional to thin (less than 10 m) overlying mud sequences (Fig. 7*a*). Similar small channel sequences (0.1–1 km wide; 20–50 m deep) are observed on the YSA cross-sections (Fig. 8).

*Interpretation and sedimentary setting*

The ORM has been interpreted to have two sedimentary architectures in the YSA area (Fig. 9): (*i*) steep-walled, infilled, and buried north–south channels (e.g., Pugin et al. 1996, 1999; Russell et al. 2003*c*); and (*ii*) east–west subaqueous fan ridges (Russell and Arnott 2003). Channel sediment has basal gravel yet is commonly dominated by medium-fine sand fining up to silty fine sand (south

**Fig. 9.** Schematic three-dimensional geologic model (interpretation) of the Yonge Street Aquifer (YSA). Oak Ridges Moraine (ORM) sediments, drumlinized Newmarket Till uplands and upper Thorncliffe Formation (TF) mud overlie YSA between Queensville (N) and Aurora (S). Thorncliffe channels eroded into shale bedrock and pre-channel Lower sediment package. YSA channel sediments form a fining-upward sequence, gravel (orange), sand (yellow), gradational into silt–clay rhythmites (~400; light blue) that extends beyond the channel margins. The base of ORM has channels, with a fining-upward gravel–sand rhythmite fill sequence that incised the upper TF clay–sand sequence. Glacial–lacustrine sediments occur at Aurora in lowland areas, between drumlinized Newmarket Till, as part of the Aurora clay basin (Fig. 5). In detail, YSA comprises a Thorncliffe channel (dark orange) and fan (yellow) system that broadens down flow (south). The channel sediments form the central high-transmissivity zone of the YSA. Flow south from the channels expands in an area of less confinement to form sandy fan sediments (yellow wedge - YSA). Thorncliffe channels are similar to overlying ORM-age channels, in orientation and in fining-upward channel fill. Where ORM channels cut into Thorncliffe channel sand intervals (upper fan), C, there may be direct connection between ORM and TF channels.

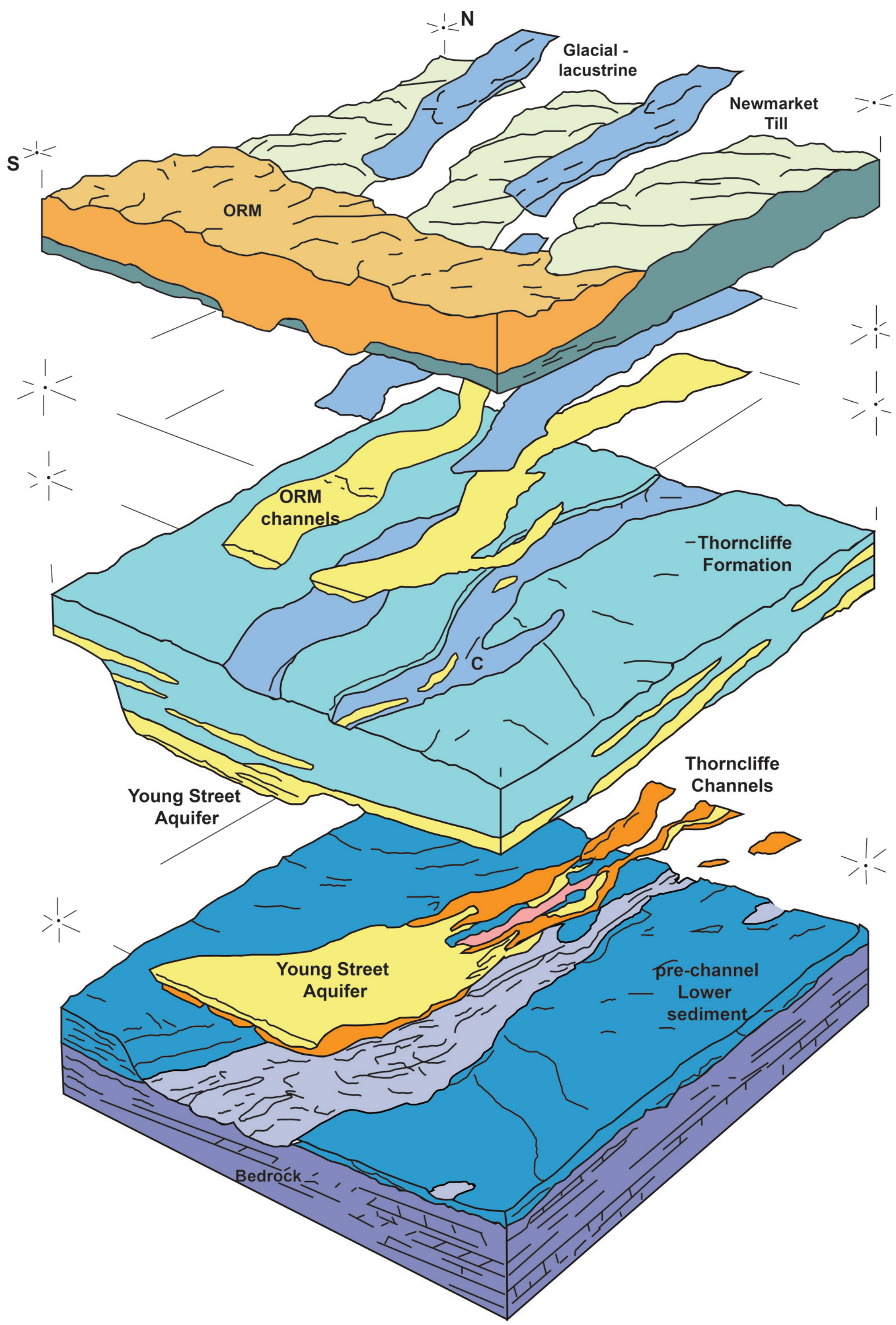
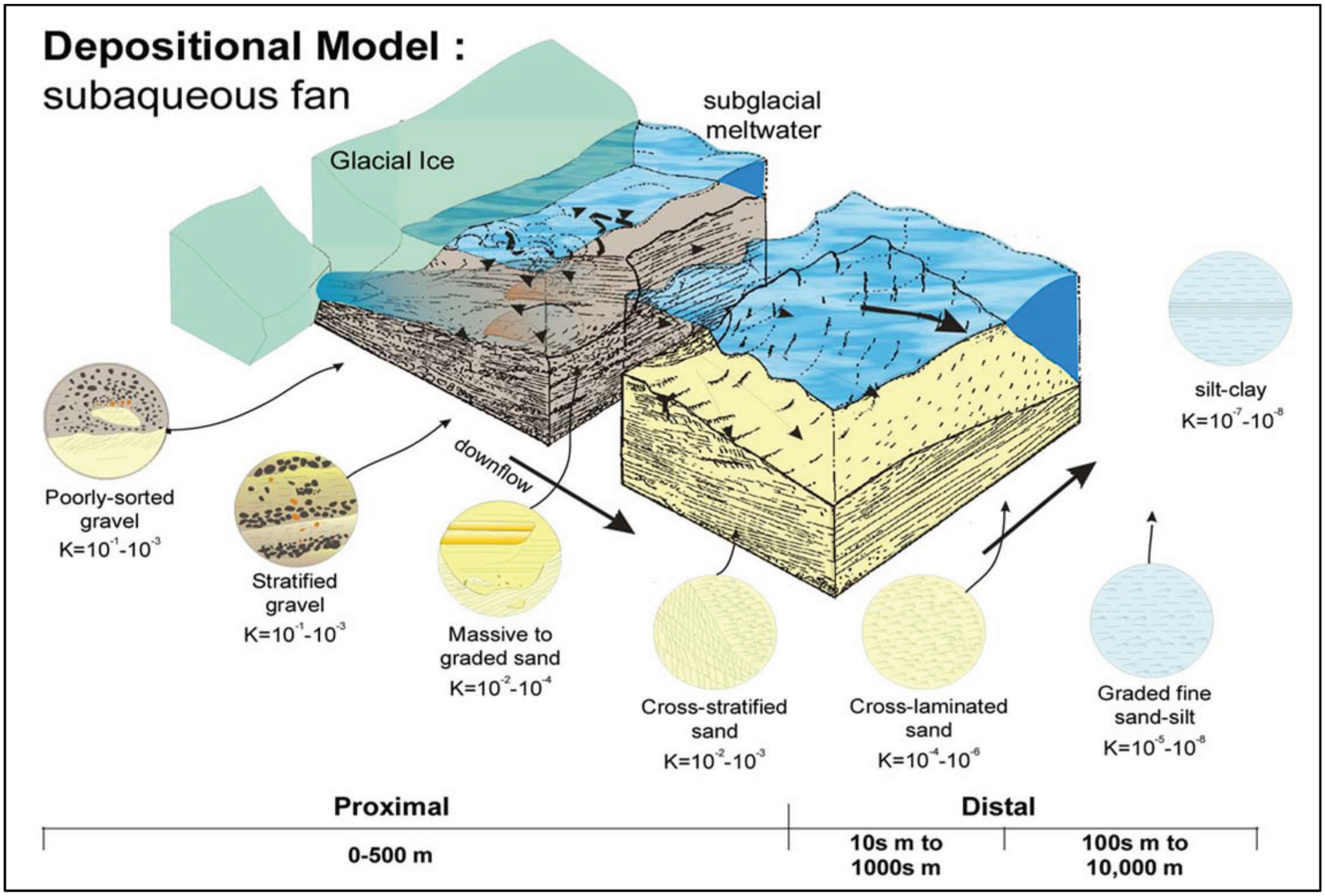


**Fig. 10.** Subaqueous fan depositional setting. A jet of channelized subglacial meltwater disperses sediment in an organized array at a glacier grounding line into deep standing meltwater. A sequence of gravel, sand, mud sedimentary facies typically occur down flow and up-sequence from any such meltwater jet. Illustrated sediment facies change from disorganized to better-organized facies from proximal fan to distal fan, hence this depositional setting provides a predictive framework for sediment facies and related hydrofacies properties (estimated *K* values in m/s). Figure modified from Russell and Arnott 2003.






Aurora, King City, Vaughan IWA, Table 2) interpreted to be deposited within a zone of flow expansion and deceleration in a subaqueous fan environment (Russell et al. 2003*c*). A number of small channel sequences observed above the YSA (Fig. 8) are interpreted to be shallow ORM channels.

East–west-oriented fan deposits occur atop either Newmarket Till and (or) a channel fill sequence such as across the south portion of the study area (Fig. 5; Russell et al. 2005). A typical proximal subaqueous fan depositional setting (Fig. 10; also applies to the Thorncliffe Formation fans) consists of cross-stratified, horizontally bedded, and massive sand and gravel, and more distal deposits are massive to cross-stratified fine sand, silt, and rare clay laminae (Russell et al. 2005). Based on physical theories of downflow plume development (Russell and Arnott 2003), strata fine rapidly down flow and upward with facies changes from massive gravel grading to cross-stratified sand over 10–100 m (Fig. 10).

### *Halton Till sediments*

Inter-bedded, fine-grained sediment less than 15 m thick overlies ORM sediment on the north flank of the ORM ridge (Figs. 3 and 5). Mud diamicton, glaciolacustrine beds, and rhythmites grade upwards from ORM sediment to a 30 m thick unit of graded sand, silt, and clay (Fig. 7*a*). These overlying facies associations are variable and discontinuous: 2–4 m thick mud diamicton is interbedded with lacustrine mud and interstratified sand up to 7 m thick. The beds are stratigraphically similar to Halton Formation (Sharpe et al. 2013), and north of the ORM, Halton Till sediment includes Kettleby Till and related mud (Gwyn and DiLabio 1973).

*Interpretation and sedimentary setting*

Halton Till sedimentary setting consists of an oscillating, subglacial to ice-marginal glaciolacustrine depositional environment that followed high-energy, waning meltwater discharge related to ORM ridge deposition (Sharpe and Russell 2016). Alternative interpretations regarding well-documented transitional ORM–Halton sequences are discussed elsewhere (Sharpe et al. 2018). Glaciolacustrine sedimentation was mud-rich with rhythmites, diamicton, and sand inter-beds, likely formed as ice-marginal sediment suspension, gravity, and debris flows in the YSA area.

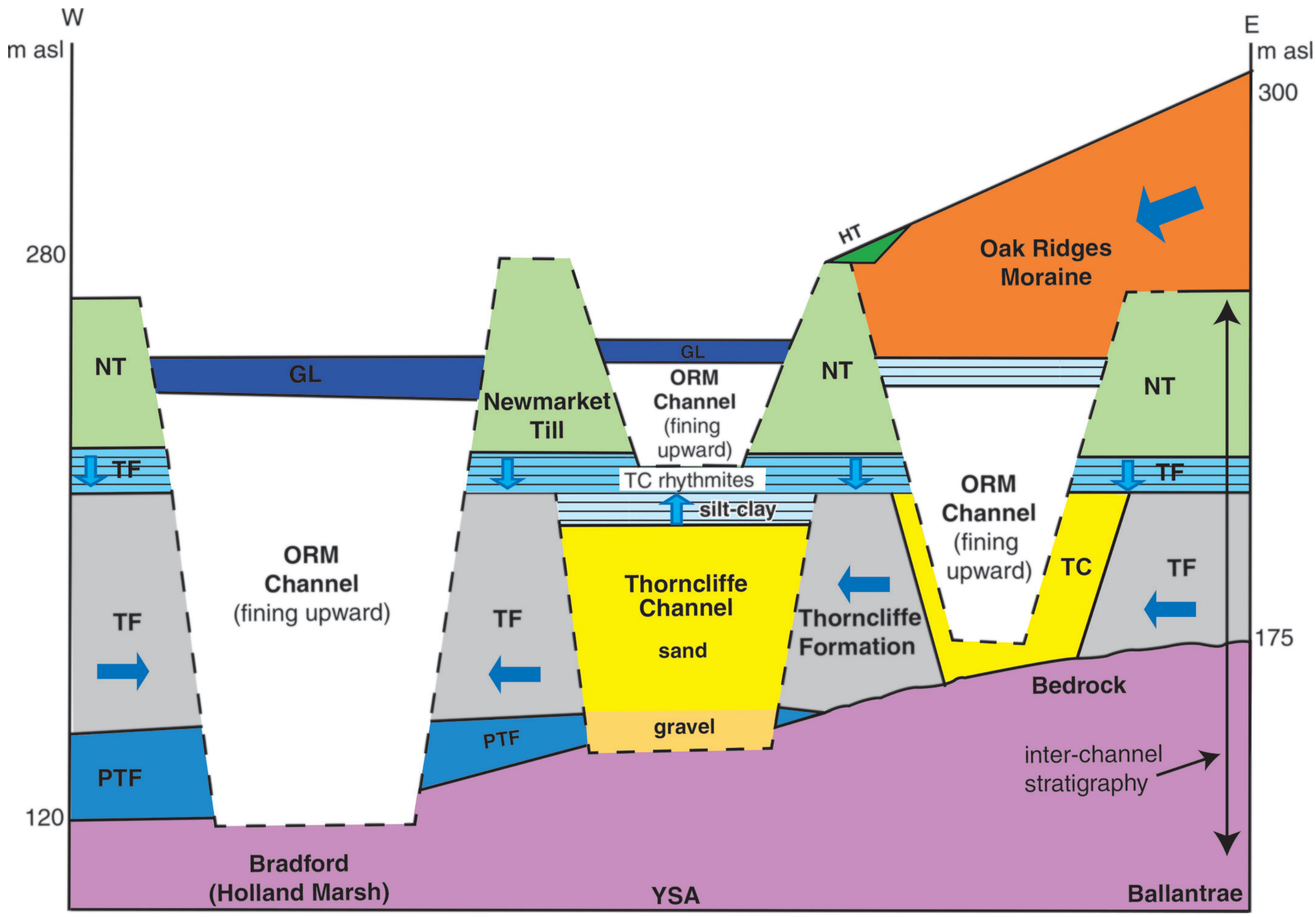
### *Glaciolacustrine sediments*

Rhythmically laminated silt–clay couplets and inter-bedded mud, fine sand, and silt diamicton occurs as 5–15 m thick sequences primarily in depressions across the area, such as the Aurora basin (Figs. 2 and 5). An 8 m sequence is recorded at Aurora (Fig. 7*a*) and includes 60 silt–clay rhythmites. The underlying 4 m Halton sediment includes 10 silt–clay rhythmites. Gwyn and DiLabio (1973) counted 90 rhythmites in this sequence in the Newmarket area.

### *Interpretation and sedimentary setting*

Deposition occurred in an ice-supported water body (at least tens of metres deep) that captured a modest annual glacial melt-

**Fig. 11.** Yonge Street Aquifer (YSA) conceptual model depicted in a west–east view (~St. John's Side Rd.) perpendicular to its main approximately north–south geological trend. Bedrock slopes from ~175 m asl near Ballantrae to ~120 m asl near Bradford; thus lower sediment formations such as Scarborough (elevation constrained) are likely limited to the western portion of the YSA region, if present above 120 m asl. Widespread Thorncliffe Formation (TF) sediments (and older till; not shown) are truncated (mainly to bedrock in YSA) by Thorncliffe channels. Thorncliffe (meltwater) channels are filled with fining-upward gravel–sand–mud sequences. Silt–clay rhythmites (TC rhythmites) cap Thorncliffe channel fill and extend beyond its margins to provide a regional aquitard. Newmarket Till (NT) covered these thick TF sediments and capping rhythmites, prior to being truncated by Oak Ridges Moraine (ORM) meltwater channels, leaving remnant NT uplands. ORM channels are deep beyond YSA (Holland Marsh) and shallow within YSA, where they may be overlain by ORM ridge sediments. Glaciolacustrine sediment occurs in lowlands between NT uplands. Strata are not drawn to scale. Arrows indicate general groundwater flow directions in these components of the YSA flow system.




water–sediment flux that lasted for less than 100 years. Glaciolacustrine sedimentation possibly occurred during waning flow to channel filling, or during ORM ridge building events as the underlying sandy sediments separated from mud during inflow—deposition of suspended mud followed. These are likely glacial Lake Schomberg sediments (Gwyn and DiLabio 1973).

## Groundwater flow system

The geologic component of the YSA conceptual model (Fig. 9) has been developed on key high-quality data, continuous cored boreholes, and seismic data. This model includes a YSA-specific Thorncliffe channel–fan erosional–depositional setting (Fig. 10). In developing the YSA conceptual model, the delineated geologic stratigraphy can also be further refined based upon high-quality hydrogeological information (e.g., water level responses to groundwater pumping) as well as broader groundwater-related observations from water wells records (e.g., water found or well screen positioning). By incorporating hydrogeological information, the established geological framework of the YSA (Fig. 9) can be tested and refined. In general, the groundwater flow system can be considered to consist of shallow and deep components separated by the Newmarket Till, which functions as a regional aquitard. Shallow aquifers occur in higher hydraulic conductivity (sand and gravel) units within ORM sediments. Some domestic-scale supply is extracted from thin sand and gravel units within the Newmarket Till and within glaciolacustrine sediments. The water table beneath the ORM can be up to 30 m below ground surface, whereas north and south of the Moraine the water table is often within 5 m of ground surface (Fig. 3).

The deep component of the flow system within Lower sediments can be divided into two distinct settings (Fig. 11), namely (*i*) Thorncliffe channel aquifers (we use channel as a simple term to include the transitional channel–esker–fan assemblage); and, (*ii*) inter-channel areas where there is more variable sediment with greater geological uncertainty. These two Lower sediment settings are characterized by variable and contrasting hydraulic conductivity. The highest hydraulic conductivity deposits are associated with Thorncliffe channels (and younger ORM channel areas where they are deeply eroded) that include basal fining-upward gravel–sand sediment successions. Inter-channel sediment consists of pre-Newmarket Till sediments, which west of the YSA (Fig. 11), mainly consist of sand, silt, clay, and till. Within the YSA study area, inter-channel Thorncliffe Formation has sandy sediment to the east (e.g., Mount Albert) and more fine-grained sediment to the west (e.g., New_MW05) of the YSA (Fig. 5). Domestic wells drilled through the Newmarket Till – Thorncliffe Formation rhythmite aquitard obtain water from intake screens set into the underlying Lower sediments or from channel–esker sediments east of the YSA (e.g., Holt aquifer). Analyses of pumping from the YSA municipal wells screened within a Thorncliffe channel shows that a groundwater level response within inter-channel sediments can be detected considerable distances laterally away from the main YSA Thorncliffe channel. It may also be unmapped fan sediments lateral to the YSA channel, or it may be an adjacent channel system (e.g., Holt). In addition, numerical modelling studies suggest considerable groundwater flow through Lower sediments that eventually supplies groundwater discharge to the lower reaches of the many streams flowing off of the flanks of the ORM (Earthfx Inc. 2006, 2014). This groundwater discharge naturally occurs where, or near where, Lower sediments outcrop along river valleys. In keeping with the established geological understanding, it is likely that Upper Thorncliffe-age channel–fans have off-channel fine sands of sufficient permeability to allow significant groundwater movement within the inter-channel Lower sediments (Fig. 10). Until further high-quality data are collected, the Lower sediments in the inter-channel areas are characterized as a regional aquifer (east of the YSA where the basin becomes shallower; Fig. 11) recognizing that there exists a wide contrast in hydraulic conductivity. The YSA is interpreted to occur within a Thorncliffe channel system (Fig. 8). In the YSA study area, groundwater quantities sufficient for municipal water supply are generally restricted to the Thorncliffe channel or ORM channel features (Fig. 8).

To determine the longitudinal and transverse geometry of the YSA, the extents of sand, gravel, and mud were mapped (with uncertainties noted) from reference sites in three cross-sections (one north–south and two west–east; Fig. 8). The 20 km long north–south section (Fig. 8*a*) is subparallel to the paleo-depositional axis of the Thorncliffe channel deposits and subparallel to Yonge Street from Aurora north to Queensville (Fig. 5). The two west–east sections extend for approximately 10 km along Davis Drive (Hwy 9; Fig. 8*b*), and 8 km to the south, for approximately 10 km from Aurora east to Vandorf (Fig. 8*c*). Data from cored boreholes and municipal monitoring and pumping wells were projected on to these sections (Fig. 8). Bedrock (shale) is intercepted at Aurora and Queensville but not at all of the intervening boreholes. Estimated bedrock elevation is plotted along the section based on the regional bedrock topography (Gao et al. 2006). Overlying bedrock, a continuous 10–80 m thick, sand and gravel Thorncliffe channel fill is overlain by 10–80 m of Thorncliffe channel mud – Newmarket Till aquitard (Fig. 8*a*).

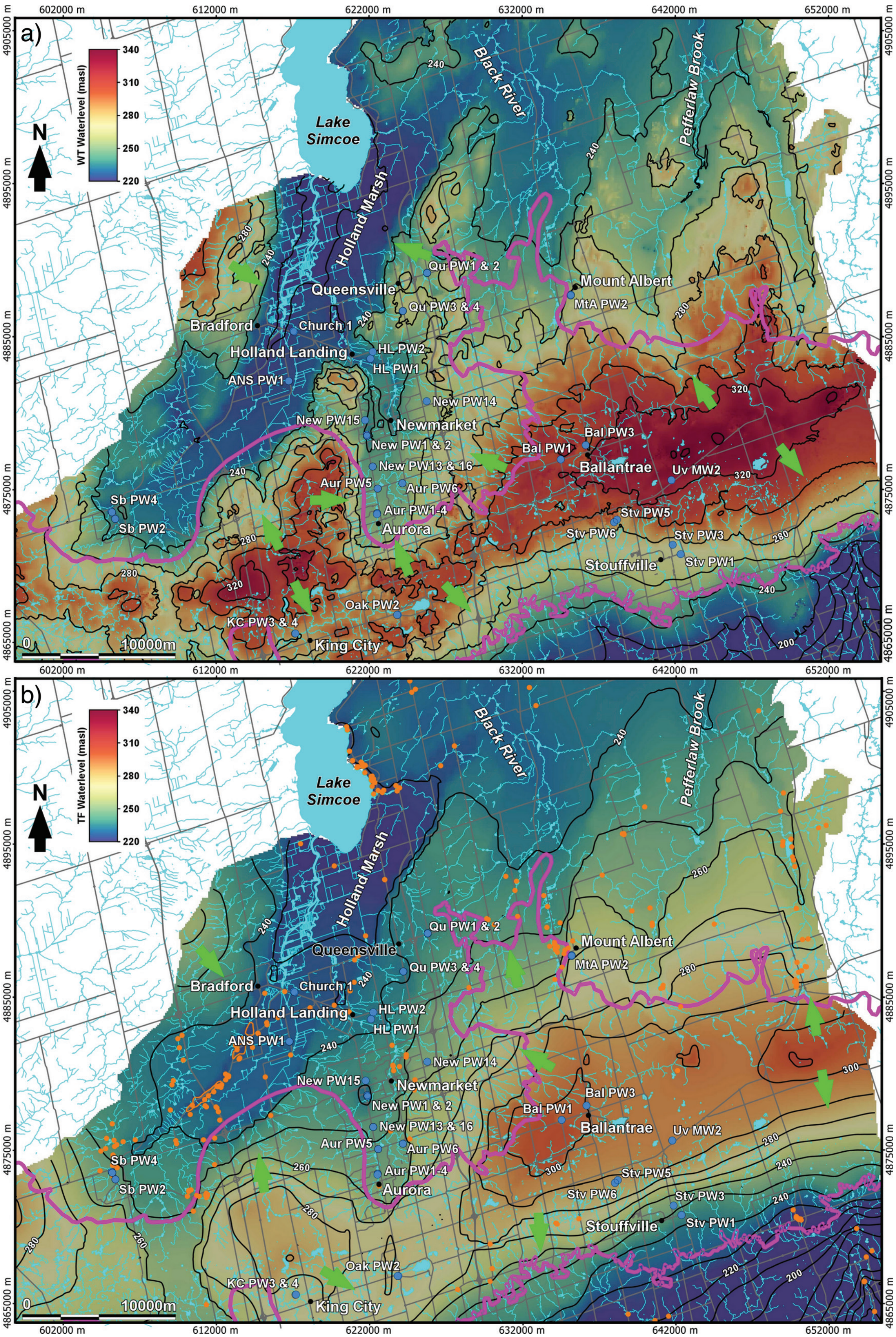
Wells projected to the north–south section define an approximate 3 km wide zone of gravel and sand with hydraulic connection along the entire length of the section. Seismic profiles (observed 1–2 km wide channels with 30–40 m thick sand–gravel in the Aurora area; Fig. 6*a*; Table 3) support the estimated width of the aquifer zone shown with sparse borehole coverage (Fig. 8). Along the 5 km east–west Davis Drive section, sparse wells (Fig. 8*b*) intercept an approximately 6 km wide, 20 m thick sand and gravel interval, thinning to 10 m further east at McGowan Road (Fig. 5), where bedrock rises to approximately 175 m asl outside the Laurentian trough. This sand and gravel thickness and width zone may indicate multiple sub-parallel channels in the northern part of the YSA (Fig. 9). In the vicinity of the section shown in Fig. 8*c*, the channel width estimates may even be extended by hydraulic data where hydraulic responses have been observed at more distant sites. Wide YSA zones thin eastward against rising bedrock elevation (Figs. 8*c* and 11; Table 3). The average sand and gravel thickness along the YSA is 30–40 m (thicknesses up to 80 m) although these are minimum estimates because boreholes do not always intercept bedrock. There appears to be increased thickness of YSA from north to south. The top of the sand and gravel sequence varies in elevation from 160 to 220 m asl with local relief of up to approximately 10–20 m. The vertical facies identified in the reference sites at Aurora and Queensville (Fig. 7) can also be identified as a coarse basal gravel unit and an overlying sand-dominated unit that fines upwards, and, thins and fines horizontally away from the axis of the aquifer in cross-section. The overlying capping Newmarket Till – Thorncliffe mud, which functions as an aquitard, is up to 80 m thick (New_PW16; Fig. 5).

***Groundwater flow***

Regional groundwater flow directions within both shallow (ORM sediment and water table) and deep parts of the flow system (Lower sediment) mimic ground topography (Figs. 11, 12*a*, and 12*b*). The system is replenished by infiltration of precipitation with the highest recharge rates occurring over sandy upland areas (Figs. 5 and 11). Discharge zones generally occur within lowland areas and along topographic breaks in slope such as along the north and south flanks of the ORM (Fig. 3), and along river valleys that drain into Lake Simcoe (Fig. 4; Gerber and Howard 2002; Earthfx Inc. 2014). Figure 12*b* illustrates observed hydraulic head values for wells screened within the Thorncliffe Formation. In general, higher groundwater elevations are associated with the groundwater divide that coincides with the ORM with flow occurring towards the north and south moving laterally away from the height of land along the Moraine crest (Fig. 3). North of the ORM, regional flow occurs from south to north–northwest from the north Moraine flank, ultimately converging on the Holland Marsh and Lake Simcoe area. In general, downward groundwater flow to the Lower sediments occurs beneath upland areas with naturally upward groundwater flow from the Lower sediments to the lowland areas (Holland Marsh, river valleys). In the YSA Thorncliffe channel, groundwater pumping has locally reversed the upward flow to downward groundwater flow to the Thorncliffe channel. The regional horizontal hydraulic gradient is approximately 0.006 with higher gradients occurring in areas of sloped topography associated with the north flank of the ORM and along river valleys. Local flow systems, with discharge to the main streams (e.g., Black Creek, Pefferlaw Brook) occur in the northeast due to thinning of the Quaternary sediment package as bedrock rises towards the Canadian Shield. To the south of the ORM, regional groundwater flow is from north to south towards Lake Ontario at horizontal hydraulic gradients up to 0.01 (Gerber and Howard 2000), with local deflections (and increasing horizontal hydraulic gradients) towards river valleys.

The deep part of the flow system (Lower sediment) is replenished by vertical groundwater flow (Fig. 11) as Lower sediments do not outcrop in the YSA study area. Lower sediments outcrop outside of the study area in deep river valleys, where groundwater discharge occurs. The principal control on vertical groundwater flow to the Lower sediments (and to the YSA) is the two-component regional aquitard consisting of Newmarket Till and (or) underlying Thorncliffe mud (Fig. 11). Vertical leakance will control groundwater flow through the overlying aquitard and is defined as the average vertical hydraulic conductivity of the confining unit ($K'_v$) divided by the aquitard thickness ($b'$). Direction of flow through the overlying aquitard will be either upwards or downwards depending on the vertical hydraulic gradient ($i_v$) across the overlying aquitard. Groundwater pumping from the YSA has changed the magnitude and locally the direction of vertical hydraulic gradients in the study area. For example, in 1957 Aurora PW1 (screened in the YSA) flowed at approximately 6500 $m^3$/day with a measured piezometric level 2 m above ground surface (Hydrology Consultants Limited 1970, 1977). At the time,

**Fig. 12.** (*a*) Observed water table interpreted from static water levels for wells <20 m deep and river elevations for Strahler Class 4 and above. (*b*) Observed potentiometric surface for wells screened within the Thorncliffe Formation. Green arrows, groundwater flow directions; pink line, Oak Ridges Moraine Planning boundary; blue dots, municipal well locations; orange dots, flowing well locations. All groundwater level measurements in panels *a* and *b* from MOECC water well record database.



the water table in this area occurred at or just below ground surface. Groundwater levels in the YSA at this location now average 18 m below ground surface, and downward vertical hydraulic gradients are observed. The lowest groundwater levels in the YSA at Aurora PW1 were approximately 40 m below ground surface in late 2006, which corresponded with a period of maximum municipal groundwater pumping. In general, more significant downward vertical flow to the YSA occurs in areas characterized by hydraulic head differences of tens of metres between the shallow and deep flow system (e.g., approximately 40 m in the Queensville area, R.J. Burnside & Associates Limited 2002). In contrast, upward vertical gradients from the Lower sediments towards shallow aquifers occur over topographically lower areas such as along the Holland Marsh, the Aurora–Newmarket valley area, and along deep valleys associated with rivers flowing north to Lake Simcoe (Fig. 12*b*).

### *Hydraulic properties*

Groundwater flow through porous media is determined by the hydraulic properties of the unit including hydraulic conductivity ($K$) and porosity, along with the hydraulic gradient. The response of a flow system to various stresses (e.g., pumping, change in recharge) is largely determined by these parameters along with storage. The sediments within the study area exhibit a wide range of hydraulic conductivity estimates over many orders-of-magnitude, typical of the heterogeneity present within glaciated terrains (e.g., Gerber and Howard 2000). A summary of transmissivity ($T$), storativity ($S$), and hydraulic conductivity ($K$) estimates from short-term (24–72 h in duration) pumping tests are included in Table 4. All YSA wells (Table 4) are screened within either basal gravel or overlying sand of the Thorncliffe channel. All of the YSA wells have estimated local transmissivities greater than 1000 $m^2$/day to a maximum of 4500 $m^2$/day at Newmarket PW1 and PW2, consistent with the thick gravel–sand sediments found along the YSA and discussed above (Fig. 8*a*). Short-term pumping tests conducted within YSA sediments typically exhibit boundary effects where increased drawdown at later pumping times is interpreted to indicate that lower permeability materials are encountered at the limits of higher transmissivity sediment (e.g., International Water Supply Ltd. 1988*a*). Figure 13*a* illustrates a short-term pumping test response for Aurora PW5, which is typical for short-term pumping responses for wells within the YSA. The regional transmissivity estimates for inter-channel Lower sediments are less than 1000 $m^2$/day, and often less than 500 $m^2$/day based on estimates contained within the various references summarized in Table 4. This is consistent with a fining of channel-related sediment (i.e., lower $K$) away from the coarse-grained gravels in the channel core (e.g., Fig. 10). This is also consistent with observations that much of the Lower sediment assemblage consists of silty sand or finer-grained materials with hydraulic conductivities less than $1 \times 10^{-4}$ to $1 \times 10^{-5}$ m/s (Gerber and Howard 1996, 2000; Earthfx Inc. 2006, 2014; Interim Waste Authority 1994*a*, 1994*b*). The thickest coarse-grained units (sand and gravel) are up to 80 m thick within Thorncliffe channels with hydraulic conductivities on the order of $1 \times 10^{-3}$ m/s (Table 4). An exception to this pattern occurs at Oak Ridges located at the southern extent of the mapped YSA (Fig. 5) where local and regional transmissivity is reported as 640 and 1000 $m^2$/day, respectively. The higher regional transmissivity may reflect interaction with coarser Thorncliffe channel deposits to the north (Fig. 8*a*). This location, south of Aurora, is interpreted to be screened in the distal fan sediments associated with the esker–channel–fan sequence of the Thorncliffe channel (YSA).

Based on $^{14}C$ age estimates of groundwater from the deep aquifer system at Aurora PW4, which range from 1800 to 4000 years old, Gartner Lee Limited (1986) estimate vertical hydraulic conductivity ($K'_v$) for the aquitard overlying the YSA at $3 \times 10^{-9}$ m/s. This estimate utilizes an average groundwater age (and travel time) of 2900 years to reach YSA Thorncliffe channel sediment based on the average $^{14}C$ age of 3 samples leading to a downward flow rate of 0.03 m/year. Other assumptions leading to this estimate include a porosity ($n$) of 0.25, an observed downward vertical hydraulic gradient ($i_v$) of 0.1, and a 100 m thickness of silty and clayey sediments overlying the aquifer (Gartner Lee Limited 1986). This bulk $K'_v$ estimate for the sediments overlying the YSA channel aquifer in the Aurora area is similar to regional bulk $K'_v$ estimates of $5 \times 10^{-10}$ to $5 \times 10^{-9}$ m/s for the Newmarket Till discussed in Gerber and Howard (2000). It should be noted that in some areas the Newmarket Till is interpreted to have been eroded and subsequently infilled (ORM channels). In these areas, the hydraulic conductivity will vary according to the infill sediment (sand, silt, clay).

### Groundwater level response and trends

The variable municipal groundwater pumping regime within the YSA study area over the decades (since approximately 1941) has locally generated a long-term transient groundwater flow system response. Recent trends have seen large changes in the magnitude of groundwater takings within the study area (Fig. 14) related to (*i*) the switch of municipal water supplies from groundwater-based to partially or completely lake-based to serve the needs of a rapidly-expanding population, and (*ii*) the need for groundwater control during multi-year large infrastructure projects (e.g., trunk sewer installation). Some of these large magnitude changes in groundwater stress are listed in Table 5. Both the groundwater level drawdown and recovery in response to changes in pumping regimes are controlled by the three-dimensional arrangement of hydraulic properties within the various geologic units and particularly by the properties of the capping aquitards that control vertical groundwater flow to the YSA. Analysis of groundwater level hydrographs that encompass these pumping changes informs the understanding of the flow system behavior. Using the significant decline in groundwater pumping that occurred in the YSA, largely at the Aurora pumping wells in February 2008 as a benchmark, this section examines groundwater hydraulic head data to investigate hydraulic connections within the YSA and possible connections between the YSA and nearby communities through inter-channel sediments. This analysis of the long-term hydraulic response focusses on determining the nature and extents of the YSA. Discussed first are the observations and interpretations from short-term aquifer tests (hours to days), followed by discussion of long-term (decades) groundwater level trends.

### *Short-term hydraulic response*

Many short-term (24 to 72-hour duration) pumping tests have been conducted within the YSA study area to estimate aquifer system hydraulic properties and connections. Reported transmissivity estimates from these tests are summarized in Table 4. Figure 13*a* illustrates a typical short-term pumping test response for the YSA (Thorncliffe channel) using Aurora PW5 as an example. Here the pumping rate was 53.2 L/s for a duration of 24 h on 22 February 1988 (International Water Supply Ltd. 1988*a*). Key observations reported from this test include a highly transmissive core ($T$ = 4000 $m^2$/day, as indicated by the early data and reflected in the "slope" line on Fig. 13*a*). The rapidly increasing drawdown slope after about 150 min reflects the effects of lateral boundaries of lower permeability material with an estimated transmissivity of 670 $m^2$/day. The early- and late-time transmissivity values correspond to an early-time slope of approximately 0.2 and a late-time slope of approximately 1.2 utilizing the Cooper–Jacob straight-line method (Cooper and Jacob 1946). The authors suggest that the separation of the drawdown and recovery curves could be due to the presence of boundary conditions, and also perhaps from the effects of pumping from other YSA wells (Aurora and Newmarket). The separation of drawdown and recovery curves could also be due to the short duration of the pumping test (24 h),

**Table 4.** Summary of deep aquifer system estimated hydraulic properties (from municipal well exploration pumping tests).

| Source | Location | Ground elevation (m asl) | Reported aquifer Top (m asl) | Reported aquifer Bottom (m asl) | Storativity | Aquifer thickness (m) | Transmissivity Local ($m^2$/day) | Transmissivity Regional ($m^2$/day) | Hydraulic conductivity Local (m/s) | Hydraulic conductivity Regional (m/s) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Aurora (YSA)** | | | | | | | | | | |
| Hydrology Consultants Limited 1970 | Aurora PW2* | — | — | — | 6.5E–04 | 13.1 | 1615 | — | — | — |
| Gartner Lee Limited 1988 | Aurora MW7 | 300.0 | 186.9 | 166.8 | — | 20.1 | — | — | — | — |
| Hydrology Consultants Limited 1978*a* | Aurora PW4* | 253.3 | 183.8 | 145.7 | 1.0E–04 | 38.1 | 4098 | 1490 | 1.2E–03 | 4.5E–04 |
| Gartner Lee Limited 1987 | Aurora MW5* | 255.0 | 184.9 | 143.7 | 1.0E–04 | 41.2 | 3040 | — | 5.8E–03 | — |
| Gartner Lee Limited 1987; International Water Supply Ltd. 1988*a* | Aurora PW5* | 255.0 | 166.6 | 142.8 | 4.0E–04 | 23.8 | 4000 | 670 | 1.9E–03 | 3.3E–04 |
| Gartner Lee Limited 1989; International Water Supply Ltd. 1992*a* | Aurora PW6 | 260.0 | 191.0 | 169.0 | 4.0E–04 | 22.0 | 500 | 190 | 2.6E–04 | 1.0E–04 |
| Gartner Lee Limited 1987 | 87-1 (Bayview) | 262.0 | 213.2 | 166.3 | 1.0E–04 | 46.9 | 190 | — | 8.5E–05 | — |
| **Newmarket (YSA)** | | | | | | | | | | |
| Gartner Lee Limited 1987 | Newmarket MW9 | 255.0 | 191.0 | 185.0 | 1.0E–04 | 6.0 | 28 | — | 5.5E–05 | — |
| Gartner Lee Limited 1987 | Newmarket MW3 | 272.0 | 212.9 | 206.4 | 1.0E–04 | 6.5 | 86 | — | 1.0E–04 | — |
| International Water Supply Ltd. 1983 | Newmarket PW13, PW16* | 269.0 | 167.2 | 158.0 | — | 9.1 | 1450 | 460 | — | — |
| International Water Supply Ltd. 1976 | Newmarket PW13* | 270.4 | 168.6 | 159.5 | 5.4E–04 | 9.1 | 2484 | 348 | 3.1E–03 | 4.4E–04 |
| International Water Supply Ltd. 1976 | Newmarket PW1, PW2* | 268.6 | 186.3 | 172.6 | 2.7E–06 | 13.7 | 4446 | 416 | 3.8E–03 | 3.5E–04 |
| International Water Consultants Ltd. 1977 | Yonge St #1* | 268.6 | 186.6 | 172.6 | — | 14.0 | 1418 | 344 | 1.2E–03 | 2.8E–04 |
| International Water Consultants Ltd. 1977 | Newmarket PW11* | 250.0 | 184.5 | 170.7 | — | 13.7 | 2422 | 120 | 2.0E–03 | 1.0E–04 |
| International Water Consultants Ltd. 1977 | Srigley #2 (TW1/61) | 237.6 | 189.1 | 179.4 | — | 9.8 | 492 | 56 | 5.8E–04 | 6.6E–05 |
| International Water Consultants Ltd. 1977 | TW6/54 Green Lane | — | — | — | — | — | — | 78 | — | — |
| International Water Consultants Ltd. 1977 | Sutton Rd TW6/69 | — | — | — | — | — | 217 | 112 | — | — |
| International Water Consultants Ltd. 1977 | King Cole Duck W2 | — | — | — | — | — | 478 | 170 | — | — |
| International Water Supply Ltd. 1978 | TW1/78 | 266.8 | 189.6 | 169.2 | 4.7E–04 | 20.4 | 447 | 286 | 2.5E–04 | 1.6E–04 |
| **Holland Landing (YSA)** | | | | | | | | | | |
| International Water Consultants Ltd. 1977 | Holland Landing PW1* | 247.5 | 189.5 | 167.0 | — | 22.6 | 3279 | 437 | 1.7E–03 | 2.2E–04 |
| International Water Supply Ltd. 1988*b* | Holland Landing MW4* | 263.7 | 174.0 | 148.0 | — | 26.0 | 3725 | 1400 | 1.7E–03 | 6.2E–04 |
| **Queensville (YSA)** | | | | | | | | | | |
| International Water Supply Ltd. 1988*c* | Queensville MW1, MW2* | 253.5 | 187.5 | 172.5 | — | 15.0 | 2680 | 890 | 2.1E–03 | 6.9E–04 |
| International Water Supply Ltd. 1988*c* | TW6/88 | 275.3 | 194.3 | 183.3 | — | 11.0 | — | — | — | — |
| International Water Supply Ltd. 1988*c*; International Water Supply Ltd. 1989 | Queensville MW4* | 280.5 | 177.5 | 165.5 | — | 12.0 | 3000 | 900 | 2.9E–03 | 8.7E–04 |
| **Oak Ridges (YSA)** | | | | | | | | | | |
| Dixon Hydrogeology Limited 1997 | Well2 (1968)* | — | — | — | 3.5E–04 | — | 640 | 1050 | — | — |
| **Mount Albert** | | | | | | | | | | |
| International Water Supply Ltd. 1975 | TW5/75 | 280.4 | 256.9 | 206.6 | 5.0E–04 | 50.3 | 186 | — | 4.3E–05 | — |
| International Water Supply Ltd. 1990 | Mount Albert MW1 | 279.5 | 226.5 | 211.5 | — | 15.0 | 210 | — | 1.6E–04 | — |
| **Ballantrae** | | | | | | | | | | |
| International Water Supply Ltd. 1996 | Ballantrae PW2 | 331.9 | 240.0 | 222.0 | 3.0E–04 | 18.0 | 700 | 310 | 4.5E–04 | 2.0E–04 |
| International Water Supply Ltd. 1998*b* | Ballantrae PW1, PW2 | 331.9 | 240.0 | 222.0 | 1.5E–04 | 18.0 | 600 | 350 | 3.9E–04 | 2.3E–04 |
| Azimuth Environmental Consulting Inc. 2010 | Ballantrae PW3 | 340.1 | 245.6 | 239.5 | — | 6.1 | 518 | 80 | 9.8E–04 | 1.5E–04 |
| **Bradford** | | | | | | | | | | |
| Jagger Hims Limited 1996 | Church PW1, PW2 | — | — | — | 1.7E–04 | 10.0 | 550 | — | 6.4E–04 | — |
| Jagger Hims Limited 1996 | 8th Line PW | — | — | — | 1.0E–04 | 3.3 | 185 | — | 4.2E–04 | — |





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**Table 4** (*concluded*).

| Source | Location | Ground elevation (m asl) | Reported aquifer Top (m asl) | Reported aquifer Bottom (m asl) | Storativity | Aquifer thickness (m) | Transmissivity Local ($m^2$/day) | Transmissivity Regional ($m^2$/day) | Hydraulic conductivity Local (m/s) | Hydraulic conductivity Regional (m/s) |
|---|---|---|---|---|---|---|---|---|---|---|
| **King City** | | | | | | | | | | |
| International Water Supply Ltd. 1981 | King City PW4* | 278.3 | 185.0 | 173.1 | 1.0E–05 | 11.9 | 2670 | 621 | 2.6E–03 | 6.0E–04 |
| **Schomberg** | | | | | | | | | | |
| Hydrology Consultants Limited 1978*b*; International Water Supply Ltd. 1980 | Schomberg MW2 | 228.5 | 163.6 | 138.9 | — | 25.9 | 360 | — | 1.6E–04 | — |
| Golder Associated Ltd. 2004 | Schomberg MW4 | — | — | — | — | — | — | — | — | — |
| Genivar Ontario Inc. 2007 | Schomberg PW4 | — | — | — | 1.0E–04 | 9.6 | 500 | — | 6.0E–04 | — |
| **Stouffville** | | | | | | | | | | |
| International Water Supply Ltd. 1998*a* | Stouffville PW1, PW2 | 278.7 | 187.0 | 175.0 | — | 12.0 | 590 | 165 | 5.7E–04 | 1.6E–04 |
| Morrison Environmental Limited 2012 | Stouffville MW21 | 306.9 | 173.4 | 163.9 | — | 9.5 | 13 | — | 1.5E–05 | — |

**Note:** Locations marked with an asterisk (*) are interpreted YSA Thorncliffe-Channel locations. Estimates presented as reported in the various references. Abbreviation: YSA, Yonge Street Aquifer.

which did not allow for stabilization of drawdown to occur. Typical observations during short-term pumping tests along the YSA include the later-time increase in drawdown attributed to boundary conditions along the edges of a channel, and interference from other groundwater pumping centres located along the Aurora – Newmarket – Holland Landing – Queensville corridor.

Another example of a short-term pumping test response within the YSA is provided by observations from a 48 h test conducted by AECOM Canada Ltd. (2014) at Newmarket MW16 situated between Newmarket and Holland Landing (Figs. 4, 13*b*, and 13*c*). The observed drawdown in the pumping well (New_MW16) has been adjusted for non-linear well losses ($CQ^2$ = 1.973 m) based on a step-test described in AECOM Canada Ltd. (2014) who estimate $C$ (nonlinear well loss coefficient) equal to 0.8768 ($min^2/m^5$) and a pumping rate of 1.5 $m^3$/min (25 L/s). The data from four nearby observation wells (New_MW20d, New_MW10, New_MW21d, and HL_MW01) are also shown on the figure. The drawdown versus time plot (Fig. 13*b*) illustrates early-time drawdown at a shallow slope until approximately 700 min. After 700 min the drawdown slope increases as lower transmissivity boundary conditions are encountered, here interpreted as channel boundaries. The late-time slope approaches the half-slope typical of channel aquifers with early-time drawdown straight-line behaviour occurring at a slope less than 0.5 due to radial flow near the pumping well (van der Kamp and Maathuis 2012). Also evident on this plot is the drawdown interference induced by pumping at two other YSA municipal wells (Holland Landing PW1 and PW2). The nearby Newmarket PW15 was not pumping during the two day pumping test. Figure 13*c* shows a composite plot of drawdown versus time illustrating the two drawdown trends. The earlier-time drawdown for the pumping and observation wells exhibits a slope of approximately 0.18, with later drawdown versus time illustrating a much steeper slope (approximately 1.7), here interpreted as characteristic of a buried channel aquifer. Using the Cooper–Jacob straight-line method (Cooper and Jacob 1946), the channel sediments have an estimated transmissivity of approximately 2200 $m^2$/day (slope = 0.18; $Q$ = 1.5 $m^3$/min). Later-time transmissivity is not estimated because the short duration of the test is not considered adequate to determine the long-term effects of adjacent sediments and (or) vertical groundwater flow through the overlying aquitard. It should be noted that not all pumping well and observation well drawdown data plot along a straight-line as per the Cooper–Jacob straight-line method. This is attributed to heterogeneity present within the YSA Thorncliffe channel aquifer (Figs. 9 and 10).

Two longer (days in duration) short-term stress tests have also been conducted that shed light on the nature of the YSA. These include (*i*) a controlled pumping test conducted at Bradford (not part of YSA) (Jagger Hims Limited 1996) in 1996 (64 day duration; July 18 to September 20) and (*ii*) a controlled municipal well pumping test conducted in 2003 (19 day duration; March 24 to April 11) at Holland Landing and Queensville (Gartner Lee Limited 2004). Based on the observations during the first of these two pumping tests, coupled with the results of numerical modelling associated with the Bradford groundwater supply system, Jagger Hims Limited (2000) inferred that the deep aquifer at Bradford is confined to a narrow channel (ORM-age channel on bedrock, Sharpe et al. 2013) that trends north–south beneath the Town of Bradford. This is supported by the absence of any measurable hydraulic response in nearby Holland Landing (Jagger Hims Limited 1996, 2000) from pumping of the Bradford municipal wells. Hence, hydraulic and geological data are in agreement that the Bradford aquifer is not part of the YSA, yet it is also interpreted as a (younger, ORM) channel aquifer.

The 2003 municipal supply well shutdown tests were conducted in the communities of Holland Landing and Queensville (Gartner Lee Limited 2004). Hydraulic connection within the Thorncliffe channel beneath the communities of Queensville and Holland Landing was confirmed, supporting the geological interpretation

**Fig. 13.** Short-term pumping test response. (*a*) 24 h pumping test at Aurora PW5 (February 1988) (modified from International Water Supply Ltd. 1988*a*). (*b*) Drawdown versus time for 48 h pumping test at Newmarket MW16 (June 2013). Data from AECOM Canada Ltd. (2014). (*c*) Composite drawdown plot for 48 h pumping test at Newmarket MW16 (June 2013). Data from AECOM Canada Ltd. (2014). Aur_PW5 and New_MW16 locations shown on Fig. 4.

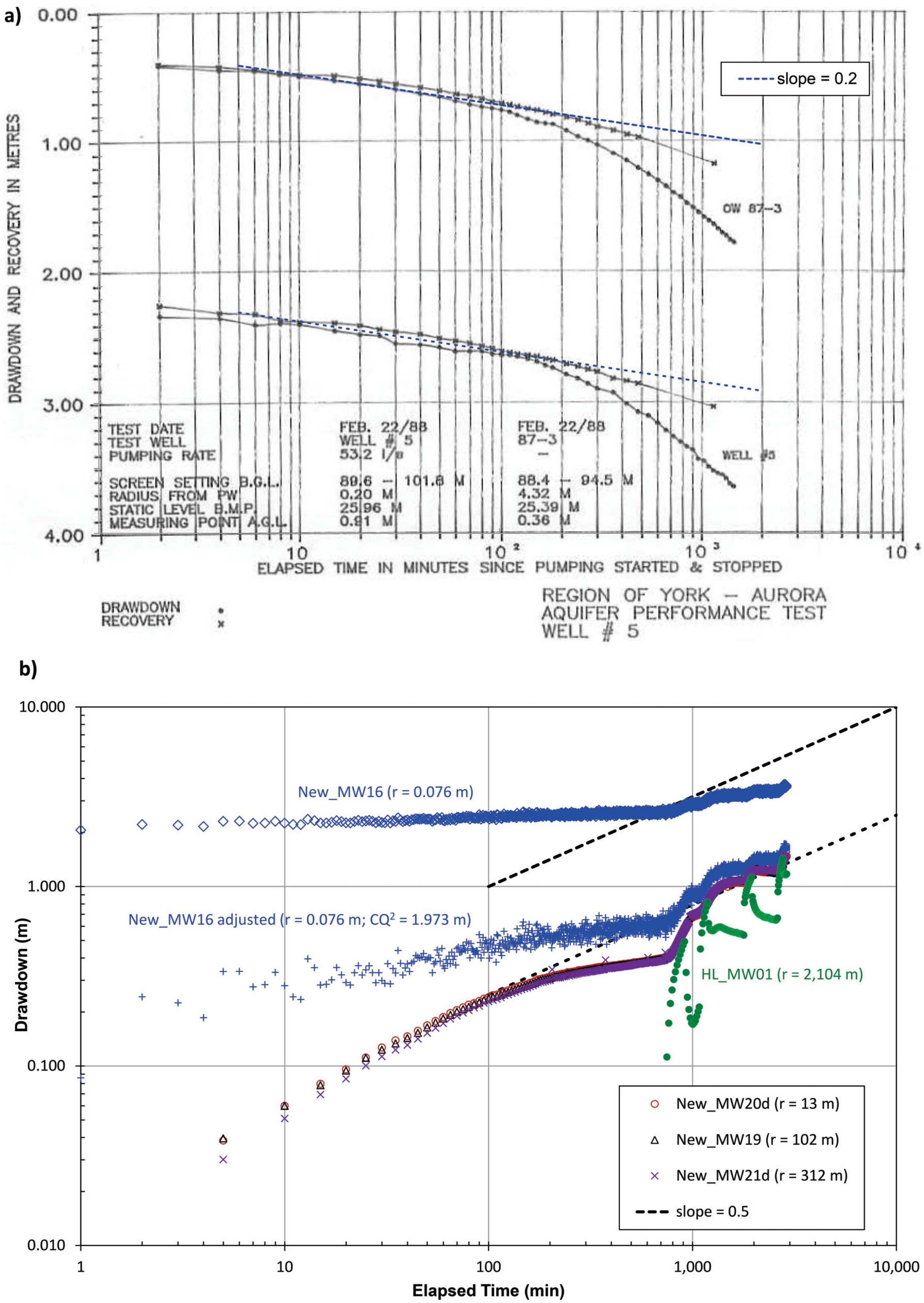
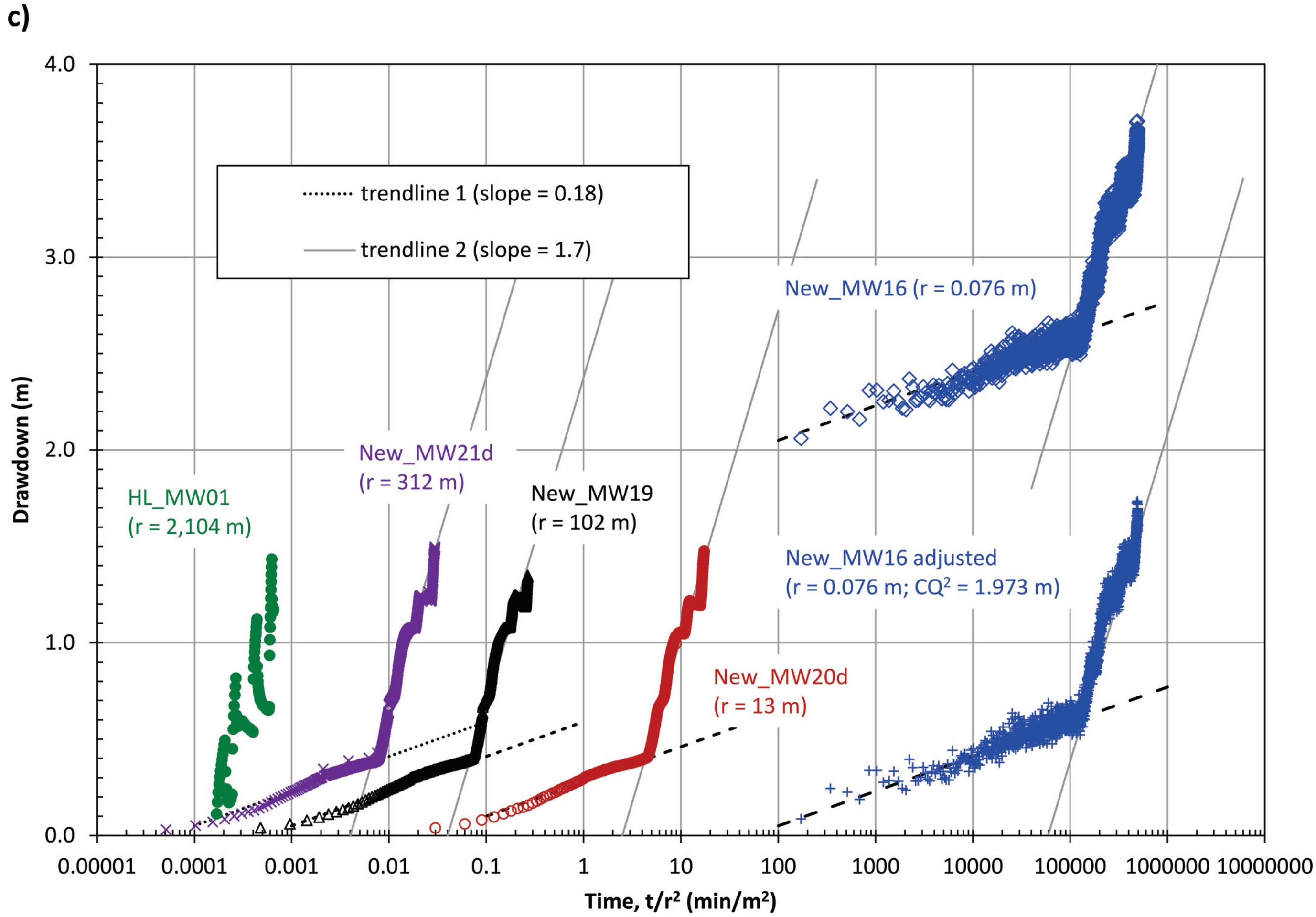


**Fig. 13** (*continued*).






that the two communities are within the YSA (Fig. 8*a*). No response was measured in the Bradford wells, supporting the lack of lateral connection indicated above and consistent with the interpreted presence of ORM channel sediments to bedrock at Bradford. Additionally, the hydraulic test, including groundwater level hydrograph analyses, confirmed that wells screened at various elevations within the YSA aquifer all behave as one hydrostratigraphic unit. These data are consistent with observations from earlier analyses that support the conclusion of a hydraulic connection within the YSA between Queensville, Newmarket (PW13 and PW16), and Aurora (PW5) (Gartner Lee Limited 1987; International Water Consultants Ltd. 1991; International Water Supply Ltd. 1992*b*).

### *Long-term longitudinal hydraulic response*

Groundwater level hydrographs for select monitoring wells situated along the YSA from Oak Ridges (Richmond Hill) in the south to Queensville in the north are shown on Fig. 15. Groundwater level recovery along the YSA is interpreted to range from 15 m in the Aurora–Newmarket area to approximately 9 m in the Queensville area (Fig. 16). The northern extent of the YSA north of Queensville is unknown but may extend to the Georgina area based on information from boreholes where sediments similar to the YSA (possible Thorncliffe channel) were encountered (Fig. 5; Interim Waste Authority 1994*a*). Detailed hydrographs and pumping records for the period just prior to and since significant introduction of lake-based supply to the YSA in February 2008 have similarities in groundwater level fluctuation patterns along the entire length of the YSA, despite significant variability in groundwater pumping quantities at each town (Figs. 16*a* and 16*b*). Groundwater level response induced by pumping changes at Aurora overwhelms any local pumping variability and extends along the entire length of the YSA north to Queensville. Also noticeable on Fig. 16 is that the large decline in pumping at Queensville, initiated in November 2012, resulted in a measured water level response south through Holland Landing and into Newmarket but influence of this event was not detected further south in Aurora.

### *Long-term lateral hydraulic response*

The lateral response to the YSA groundwater recovery is variable from north to south. In the vicinity of north Newmarket, Holland Landing, and Queensville, the lateral response appears to be spatially more limited than in the south near Aurora. In the Holland Landing area the lateral response appears to dissipate within 3 km to the west of Holland Landing (Fig. 17; see lack of response at Ansnorveldt MW02). A rise in groundwater levels in mid-2007 was seen at Ans_MW03, Ans_MW02, and Bradford Church1 in response to a reduction in groundwater pumping at Bradford (1, Fig. 17). No response was observed at Holland Landing (HL_MW01). To the east, the hydraulic response to the 2008 groundwater pumping reduction at Aurora appears to dissipate after a distance of 7 km (2, Fig. 17; see response at New_MW03 and New_MW07). No response was seen at GSC_MSR and Mount Albert MW02 (Fig. 4). A rise in groundwater levels was observed in 2012 at Holland Landing (HL_MW01) and Queensville in response to a groundwater pumping reduction at Queensville (3, Fig. 17). This response appears to be limited to the Holland Landing and Queensville areas. A rise in groundwater levels along the entire length of the

**Fig. 14.** Yonge Street Aquifer (YSA) area municipal water use (*a*) annual totals summary and (*b*) 2000–2016 annual totals summary for each well. Well locations shown on Fig. 4.

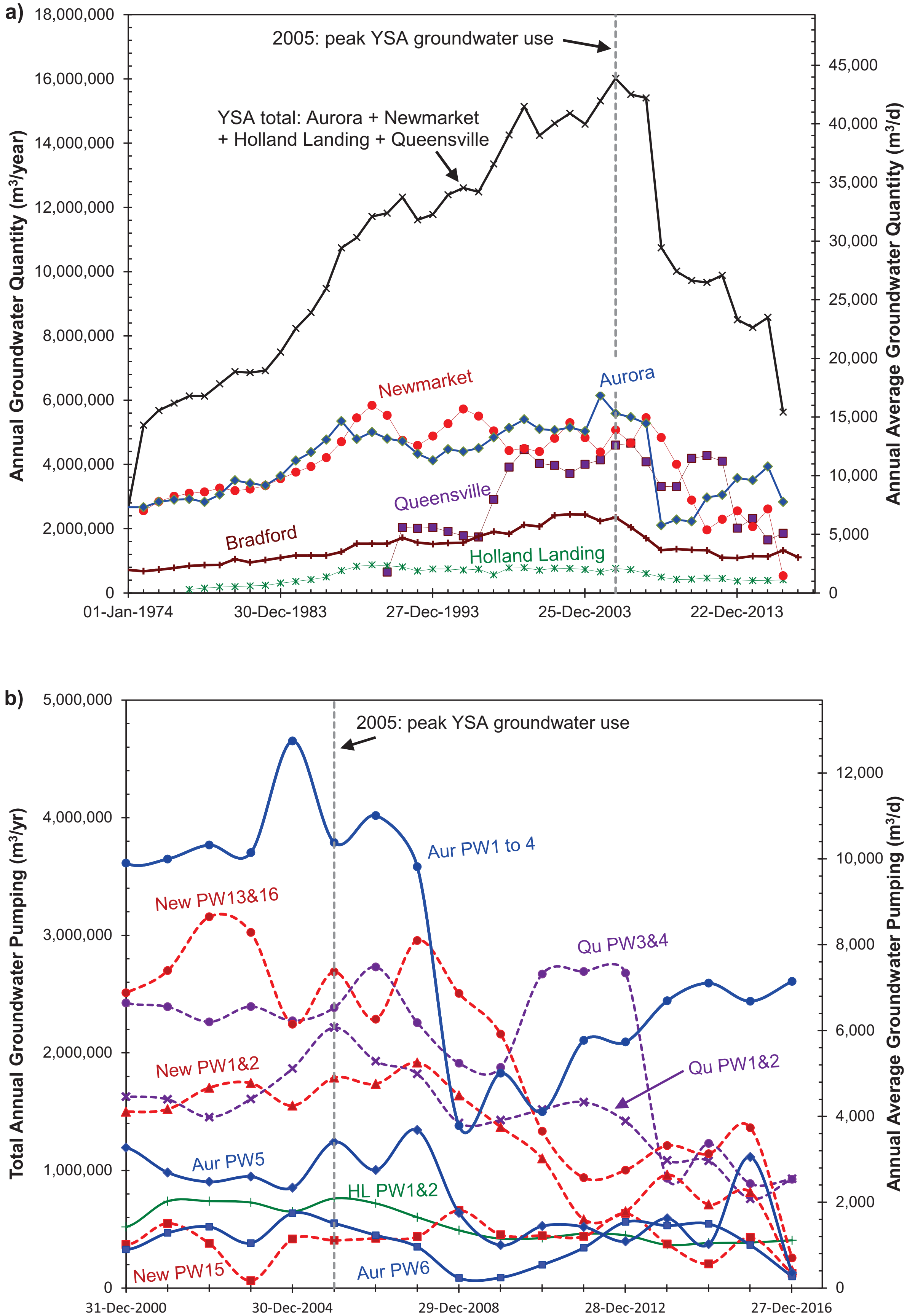
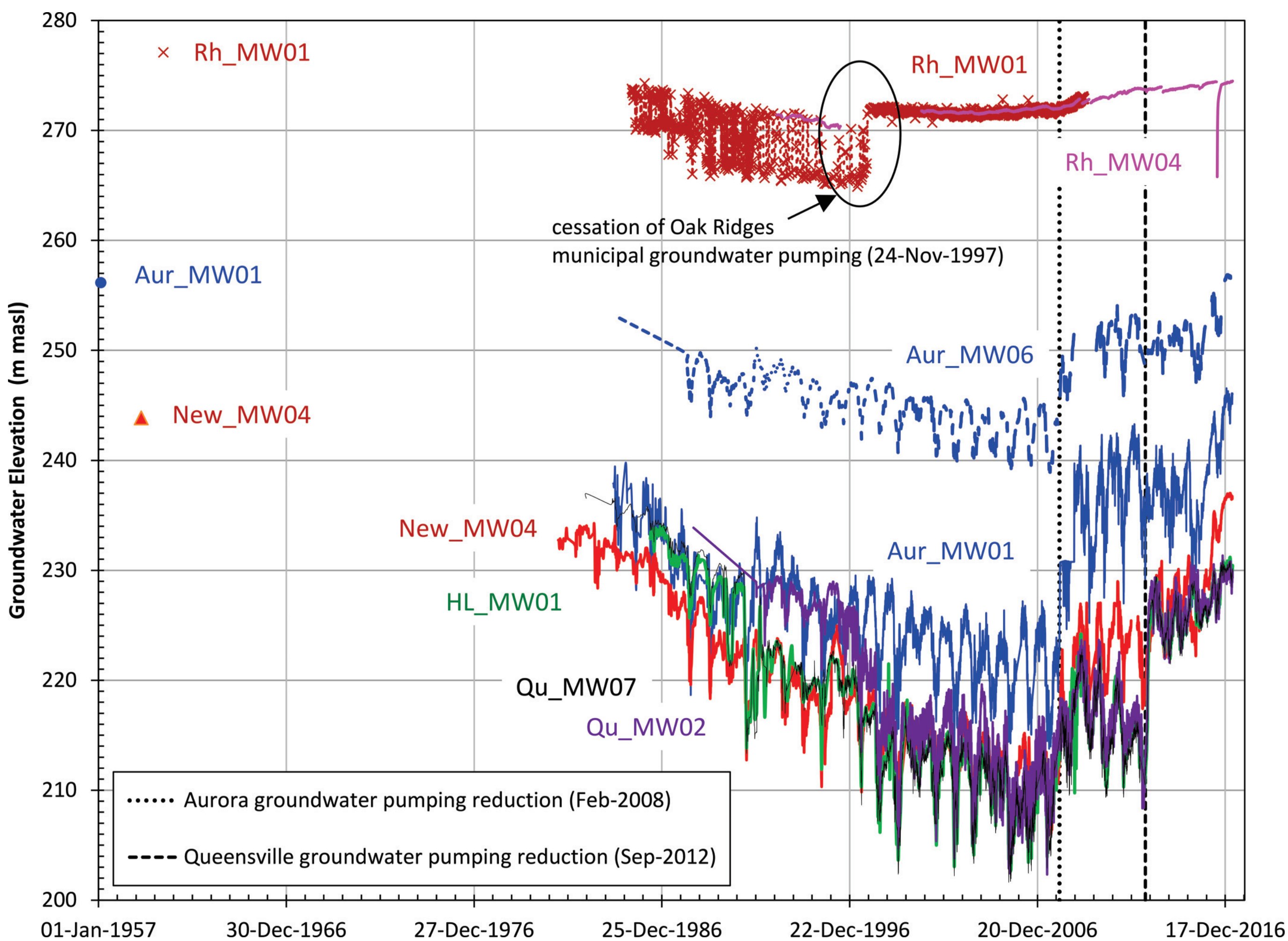


**Table 5.** Groundwater use changes.

| Location | Start date | End date | Comment |
|---|---|---|---|
| Yonge Street Aquifer—Aurora, Newmarket, Holland Landing, and Queensville | 2001 (2008) | — | Introduction of lake-based supply in 2001 with significant import starting February 2008. See Fig. 14 for changes in groundwater pumping quantities. |
| York–Durham Sanitary Sewer—16th Ave. | July 2000 | December 2006 | Groundwater dewatering for infrastructure installation. |
| Bradford | April 2006 | — | Introduction of lake-based supply (Lake Simcoe) to augment groundwater-based system (Jagger Hims Limited 2009). See Fig. 14 for changes in groundwater pumping quantities. |
| Stouffville | January 2010 | — | Introduction of lake-based supply to augment groundwater-based system. |
| King City | July 2011 | 2012 | Introduction of lake-based (Lake Ontario) supply to replace groundwater-based system by 2012. See Fig. 18 for changes in groundwater pumping quantities. |
| Kleinburg | October 2012 | — | Introduction of lake-based supply to augment groundwater-based system. |
| Queensville | November 2013 | — | Introduction of lake-based supply to augment groundwater-based system. See Fig. 14 for changes in groundwater pumping quantities. |

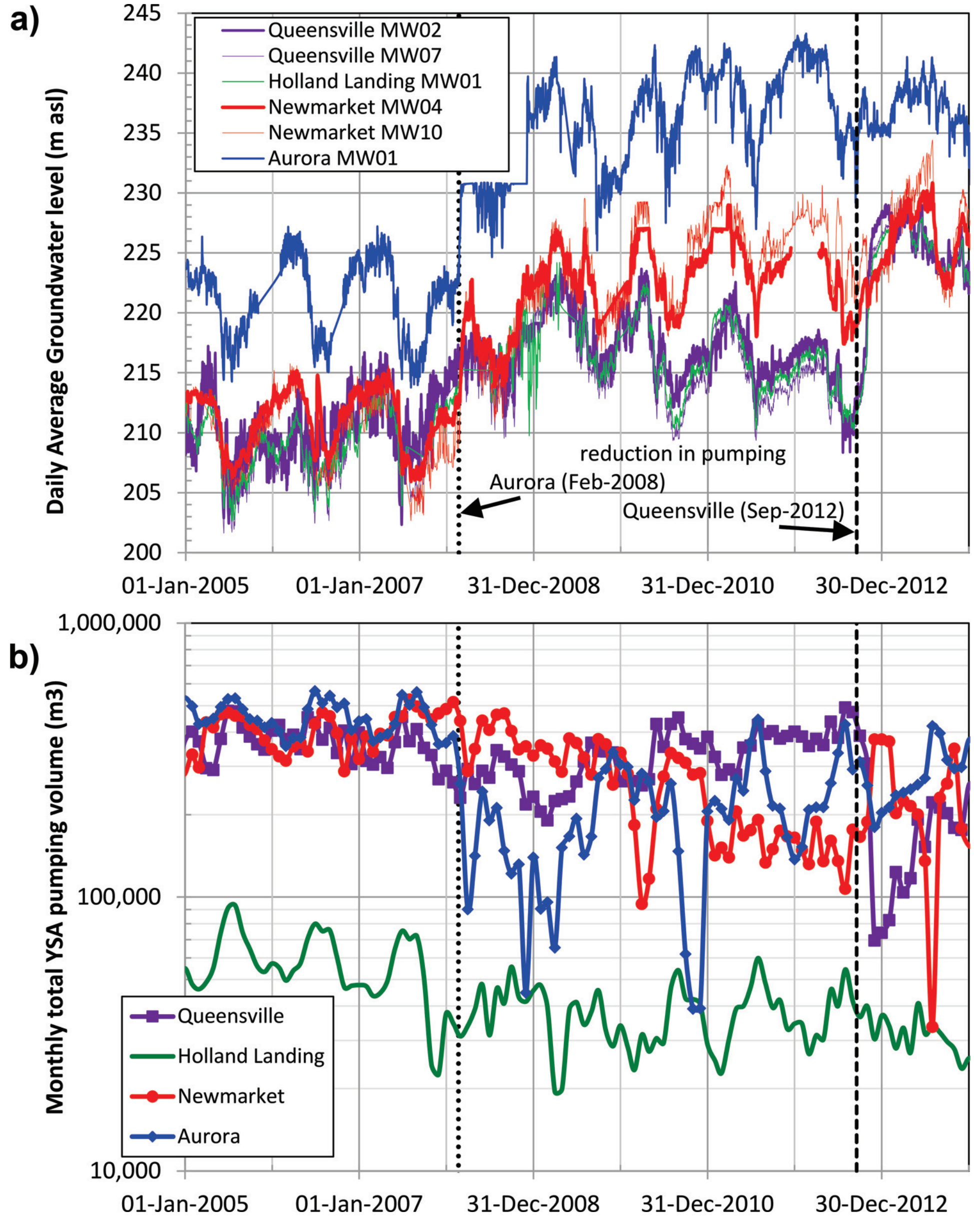
**Fig. 15.** Daily groundwater level hydrograph for monitoring wells along the Yonge Street Aquifer (YSA) from south (Oak Ridges – Richmond Hill) to north (Queensville). Groundwater monitoring wells at Holland Landing and Queensville have similar groundwater elevations. Well locations shown on Fig. 4.




YSA Thorncliffe channel is observed in response to the groundwater pumping reduction at Newmarket in 2016 (4, Fig. 17).

At the southern end of the YSA lateral response appears to be more extensive. For example, to the southwest an approximate 2 m recovery response was observed in 2008 at King City MW03d located 9.5 km from Aurora PW1–PW4 (Fig. 18). The King City municipal supply system converted from groundwater-based to lake-based (Lake Ontario) in 2011. Since July 2011, groundwater

**Fig. 16.** Detailed hydrographs for Yonge Street Aquifer (YSA) (*a*) daily average groundwater level and (*b*) monthly total YSA municipal pumping. Groundwater levels in piezometers at Holland Landing and Queensville have similar groundwater elevations. Well locations shown on Fig. 4.





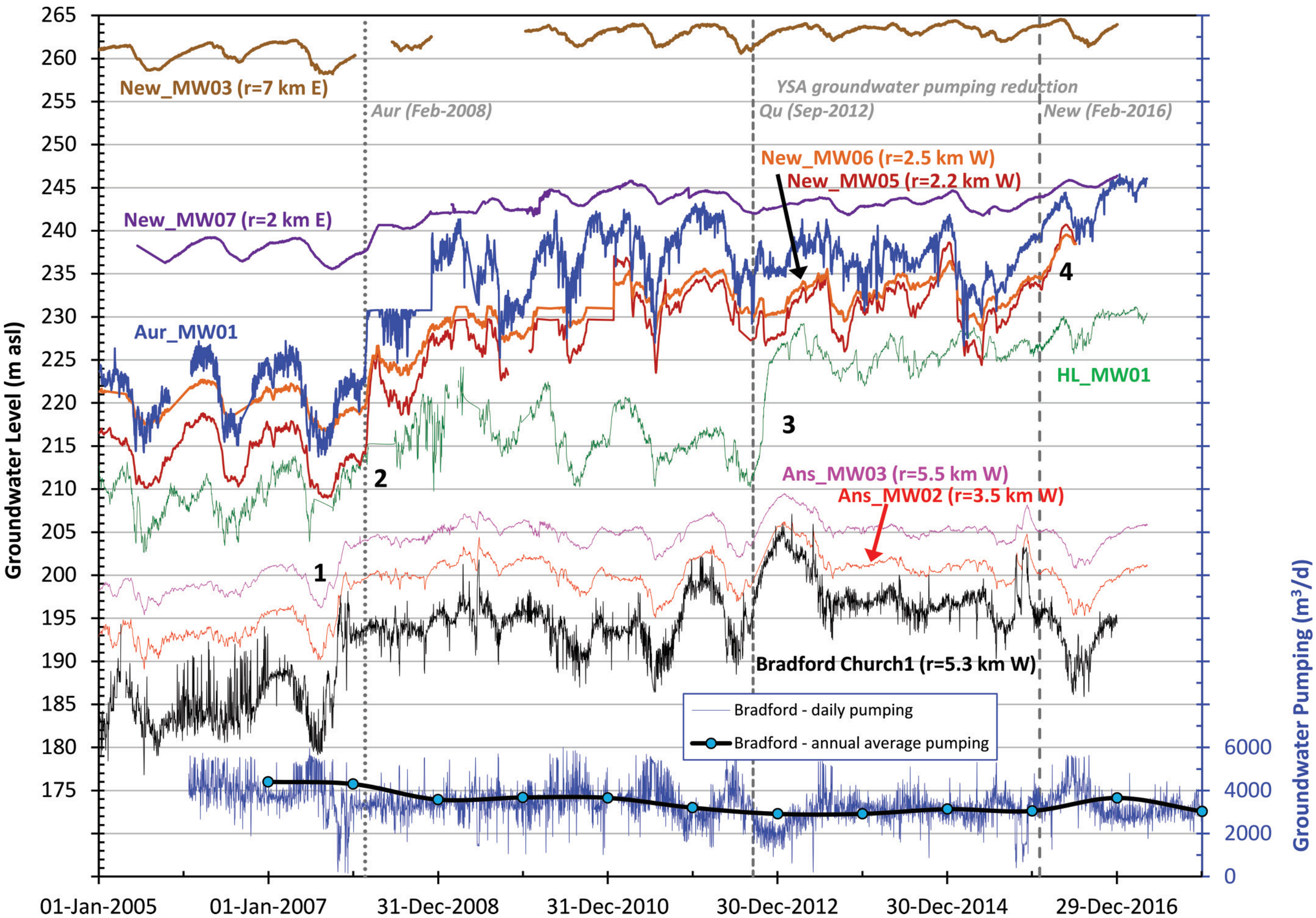

levels within wells screened within the Thorncliffe Formation have shown a gradual rise, interpreted to be induced by cessation of municipal groundwater pumping at King City and reduction in groundwater pumping along the YSA. To the east at the southern end of the YSA, an observed groundwater level rise following the 2008 YSA groundwater pumping reduction is interpreted to occur at Vandorf (Van_MW01, Van_MW02, Fig. 19). No response to YSA groundwater pumping changes are interpreted to occur at Ballantrae (Bal_MW04, Bal_MW05, Bal_MW06; Fig. 19).

Figure 20 provides a summary of the locations and magnitude of the interpreted response of the deep aquifer system (Lower sediments) to the 2008 groundwater pumping reduction along the YSA. The magnitude of the groundwater level rise is greatest along the axis of the Thorncliffe channel denoted by the YSA pumping centres, and dissipates laterally as the response emanates outwardly within inter-channel sediments. This response relates to the variability of the sediment facies changes on the margins of the YSA and the transition from the Thorncliffe channel setting to inter-channel setting.

***Shallow flow system hydraulic response***

With a maximum groundwater level decline on the order of 35 m (Fig. 15) within the YSA over the years, it remains undocumented as to whether the groundwater pumping from the YSA has induced any visible changes to groundwater levels within wells screened within sediments situated above the YSA (post-Thorncliffe Formation sediments). There is a paucity of groundwater monitoring data within the shallow flow system that encompasses the February 2008 period associated with the significant decline in YSA pumping. Seven shallow groundwater monitors having water level records stretching between 1991 and 2015, and found in the Queensville area, are screened within 20 m of ground surface within glaciolacustrine sediments or within the Newmarket Till. A possible response to YSA pumping was mea-

**Fig. 17.** Groundwater level hydrograph for the Bradford, Holland Landing, Newmarket, and Aurora areas. Response 1 in 2007 from Bradford groundwater pumping changes. Response 2 in 2008 from Yonge Street Aquifer (YSA) pumping changes. Response 3 at Holland Landing to Queensville groundwater pumping reduction. Response 4 along YSA to reduction in Newmarket groundwater pumping. *r*, distance from nearest YSA pumping well in kilometres east or west. Well locations shown on Fig. 4.



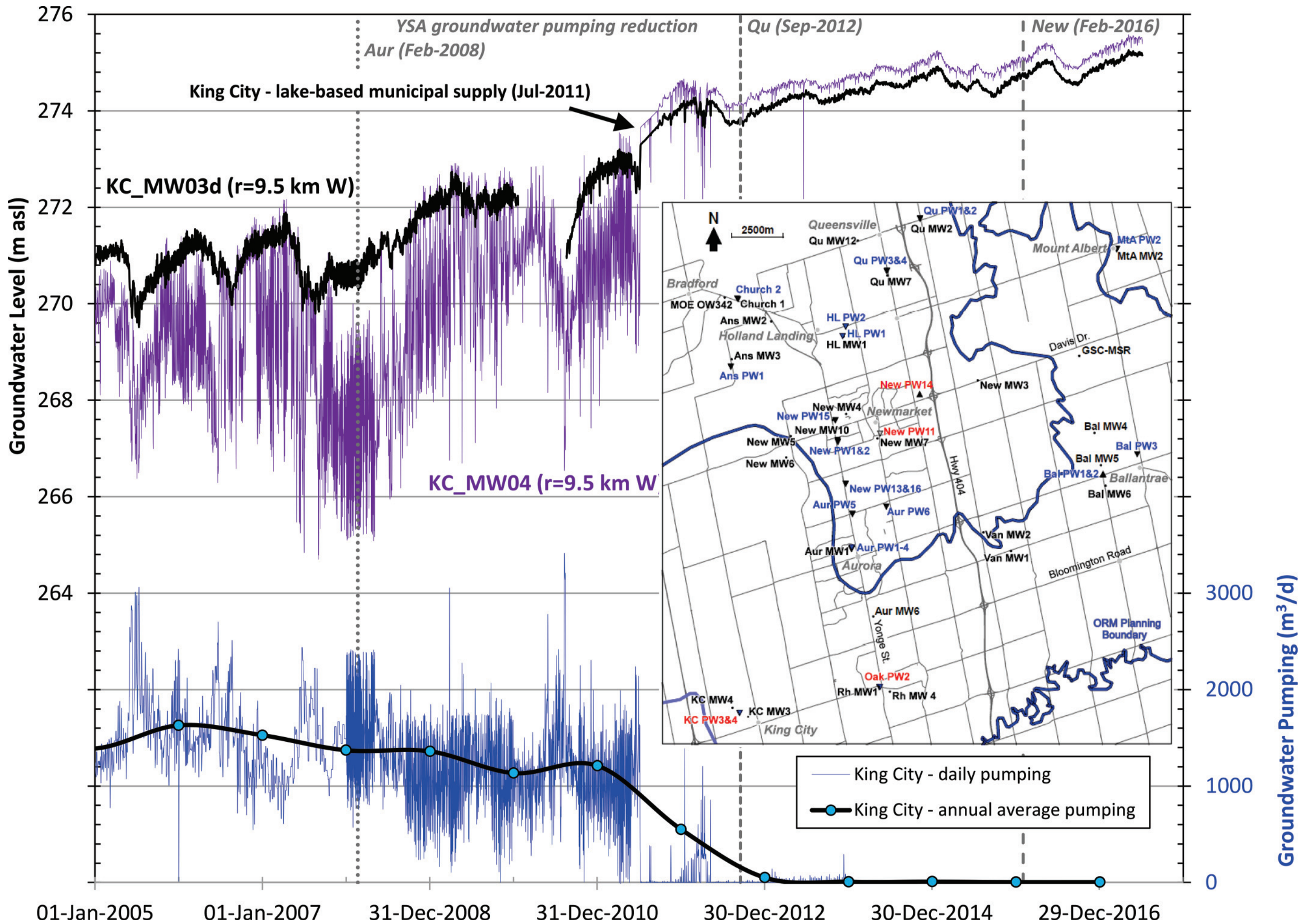

sured in two monitors, Queensville MW10 and Queensville MW11d (Fig. 21), both of these wells are screened at elevations 40 m above the YSA. The response in MW10 occurs following pumping reductions in 2008 and 2012 with a rise of 2 and 4 m, respectively. The response at MW11d is interpreted to be approximately 2 m in 2008 and 1 m in late 2012. It is acknowledged that other factors may be involved in the historical shallow groundwater level trends including, but not limited to, climatic effects, and by extension, the resultant recharge. The long-term decline in shallow groundwater levels at MW10 and MW11 initiated in 1997, which was a year characterized by increased groundwater pumping quantities at Queensville (Fig. 14*a*). The long-term decline in groundwater levels was maintained through variable estimated recharge years until 2008, when significant YSA pumping reductions occurred. Future work should include a detailed analysis of shallow groundwater level fluctuation to determine the extents of the various factors that control the shallow groundwater level response. It is anticipated that this could best be achieved by refining the calibration of the existing numerical groundwater flow model (Earthfx Inc. 2014) to better reflect the entire historical record of groundwater level measurements for the YSA area. In this way, the complex interaction of many factors including variable topography, climate, municipal pumping schedules, and land-use change, along with the geological architecture, can be incorporated.

## Discussion

Geological and hydrogeological data sets have been jointly evaluated to investigate the YSA. The derived YSA conceptual model provides an opportunity to use this improved understanding to assess other nearby aquifer systems and to better delineate their lateral, longitudinal, and vertical extents. The aquifer has been long utilized for municipal water supply along the Yonge Street corridor in the communities of Oak Ridges, Aurora, and Newmarket, and extending north to the local areas of Holland Landing and Queensville, yet the related hydraulic data have been underutilized.

The YSA is well documented at two sites having continuous sediment cores set within an architectural framework only provided by seismic profiles that identified channels 50–100 m deep (Aurora and Queensville). From this and other available geological data, including cited cored borehole data, the YSA appears to be coarser grained and narrower in the north and wider and finer grained to the south. Unfortunately, present seismic studies are incapable of assisting with full YSA delineation since they do not have the signal resolution to adequately penetrate the Newmarket Till where it overlies off-channel YSA and inter-channel sediment. For example, additional coring or perhaps water quality tracer data could help to reduce uncertainty of the YSA dimensions. Similarly, the full longitudinal and lateral extents of the YSA (Thorncliffe channel) sediments cannot be resolved solely with pumping and groundwater response data; however, the in-

**Fig. 18.** Groundwater level hydrograph and municipal pumping for King City. Inset pumping well locations (PW) in blue are currently active, red are inactive.






tegration of these data with the delineated geological interpretation provides an effective means to obtain an overview of the YSA extents. Interpolation of these data suggests a coarse-grained aquifer with a length of at least 20 km, a width of at least 2 km, and a thickness of approximately 50 m. The YSA has been identified as Thorncliffe channel sediments that lie stratigraphically beneath the Newmarket Till (Fig. 9). The channel sediments reflect a fining-upward gravel–sand–mud framework, remarkably similar to younger, previously-studied ORM channels (Fig. 7). These results reflect the primary setting of a channel – esker – subaqueous fan system (Fig. 10).

### Thorncliffe formation—delta or fan?

At the Scarborough Bluffs, sandy sediment with disseminated organic material, near the top of a Thorncliffe Formation sand–mud rhythmite sequence, has been inferred to relate to changing water levels and subaerial influx of water and sediment into paleo Lake Ontario at approximately 130 m asl (e.g., Karrow 1967; Eyles and Eyles 1983). The 130 m asl water plane implies an upland fluvial watershed that drained southward to this level. However, the presence of 30–90 m thick fining-upward sediment sequences to the north in the Aurora–Newmarket–Queensville area (Tables 2 and 3) at elevations up to 250 m asl, appear to be too high for a delta origin, and require deeper water at Lake Ontario Thorncliffe Formation sites. Note that a Thorncliffe water plane projected from Lake Ontario to Newmarket (Green Lane; Fig. 5), including 50 m of northward post-glacial isostatic tilt, leaves the Green Lane rhythmites at least 70 m too low to be a delta-top water plane. Also, observed mud rhythmites lack characteristics of subaerial floodplain, braid plain, or shallow lacustrine deposits (e.g., sand partings, rootlets). The vertical succession of mud (thickness, facies transitions) does not support subaerial deposition within these settings. Rather, rhythmites with thin silt partings, mud thickness and deformed intervals are similar to "deep water" (perhaps approximately 100 m) deposits (e.g., Gilbert 1997) and classical varves interpreted to be deposits of glaciolacustrine basins (e.g., Banerjee 1973). This reconstruction is compatible with regional evidence for rising water levels throughout Thorncliffe Formation sedimentation (Sharpe et al. 2018; Mulligan and Bajc 2018) potentially with levels up to 400 m asl in Lake Thorncliffe near the Niagara Escarpment (Fig. 1*b*).

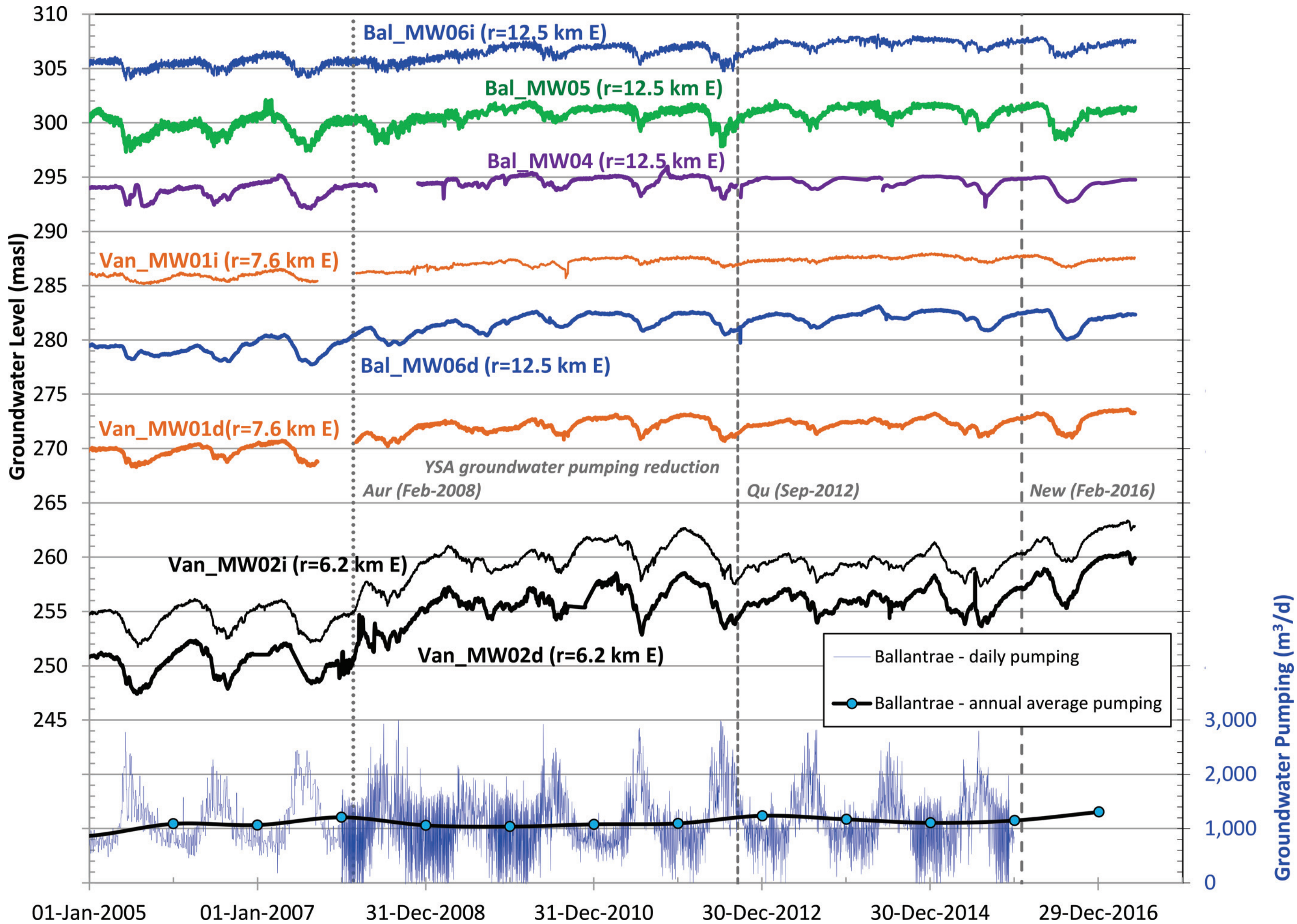
The central evidence of fining-upward, subaqueous fan sequences in upper Thorncliffe Formation sediments has important hydrogeological implications. For example, fining-upward gravel–sand–mud sequences mean that Thorncliffe channel aquifers will have, in addition to where overlying Newmarket Till occurs, at a minimum, thick mud aquitards (50–60 m) in the YSA region and thicker in the broader Thorncliffe basin (Sharpe et al. 2018). This predictable fan sediment sequence means that hydrogeological parameters can be predicted, along with directional properties, in a fan setting (Fig. 10).

## Integrated conceptualization

### *Channelization*

The extensive observed hydraulic responses to the variable YSA pumping conditions over many decades indicate a widespread

**Fig. 19.** Groundwater level hydrograph for Vandorf and the Ballantrae areas. Well locations shown on Fig. 4.






hydraulically well-connected system. Pumping test analyses of wells situated within the YSA yield local transmissivity estimates of 1500–4500 $m^2$/day, with regional transmissivity estimates being less than 1000 $m^2$/day (Table 4). The regional transmissivity estimates are interpreted from later-time drawdown observations within inter-channel lower permeability deposits that are encountered at distances of approximately 1–2 km from actively pumped YSA wells.

The decline in Aurora pumping in February 2008 has elicited a recovery response that appears to migrate all along the full 20 km length of the mapped YSA from Aurora to Queensville. Significant pumping regime changes at Queensville (in 2012) also induce groundwater level fluctuations that migrate south from Queensville through Holland Landing to the north Newmarket area. However, this stress does not seem to migrate further south to the Aurora area. This may reflect the fact that the lower magnitude of the Queensville pumping change is insufficient to induce groundwater level fluctuations along the entire length of the YSA. Alternatively, the lack of water level response further south may result because replenishment of flow in the YSA is from south to north (southeast to northwest) and the deep flow system receives more downward vertical groundwater flux in the south beneath the ORM (Fig. 11). The large stress response observed longitudinally along the YSA is not replicated laterally, perpendicular to the YSA channel. Water level responses decline in magnitude laterally away from the YSA axis (channel gravel) in the adjacent sand strata (inter-channel).

***Lateral connection and inter-channel areas***

The lateral, off-channel hydraulic response is limited in the north (Newmarket, Holland Landing, and Queensville). In this area it is anticipated that the hydraulic response preferentially projects longitudinally along the YSA given the well-defined, narrow high hydraulic conductivity channel sediments in this area. In contrast, in the southern part of the YSA to the west, east, and south of Aurora, a more widespread lateral water level response, albeit somewhat muted, is observed. This suggests that the YSA sediments in this area have broadened laterally and are wider in extent (Fig. 9). In this area, the YSA is also interpreted to intercept, and appears to be laterally hydraulically connected to, pre-channel Lower sediments of the inter-channel areas, essentially extending its geometry (Fig. 11).

Northwards of Aurora, lateral coarse to fine-grained facies transitions (west–east) are very rapid because they are perpendicular to paleoflow (north to south; Fig. 10); these facies transitions explain the occurrence of relatively low-yield wells drilled near productive YSA municipal wells (Gartner Lee Limited 1989; International Water Supply Ltd. 1992*a*). The conceptual model indicates that sediment facies and hydrofacies transitions are much longer along paleoflow (north to south) than perpendicular to paleoflow (Fig. 10).

The hydraulic response is evidence of a lateral facies transition within a channel–esker–fan sequence as it grades from gravel in the north into fine-grained sand laterally across the fan portion of the system in the area southwards from Aurora (Fig. 9). This

**Fig. 20.** Interpreted extent and magnitude of the hydraulic response within the deep aquifer system (Lower sediments—Thorncliffe channel and inter-channel areas) to the 2008 Yonge Street Aquifer (YSA) groundwater pumping reduction.

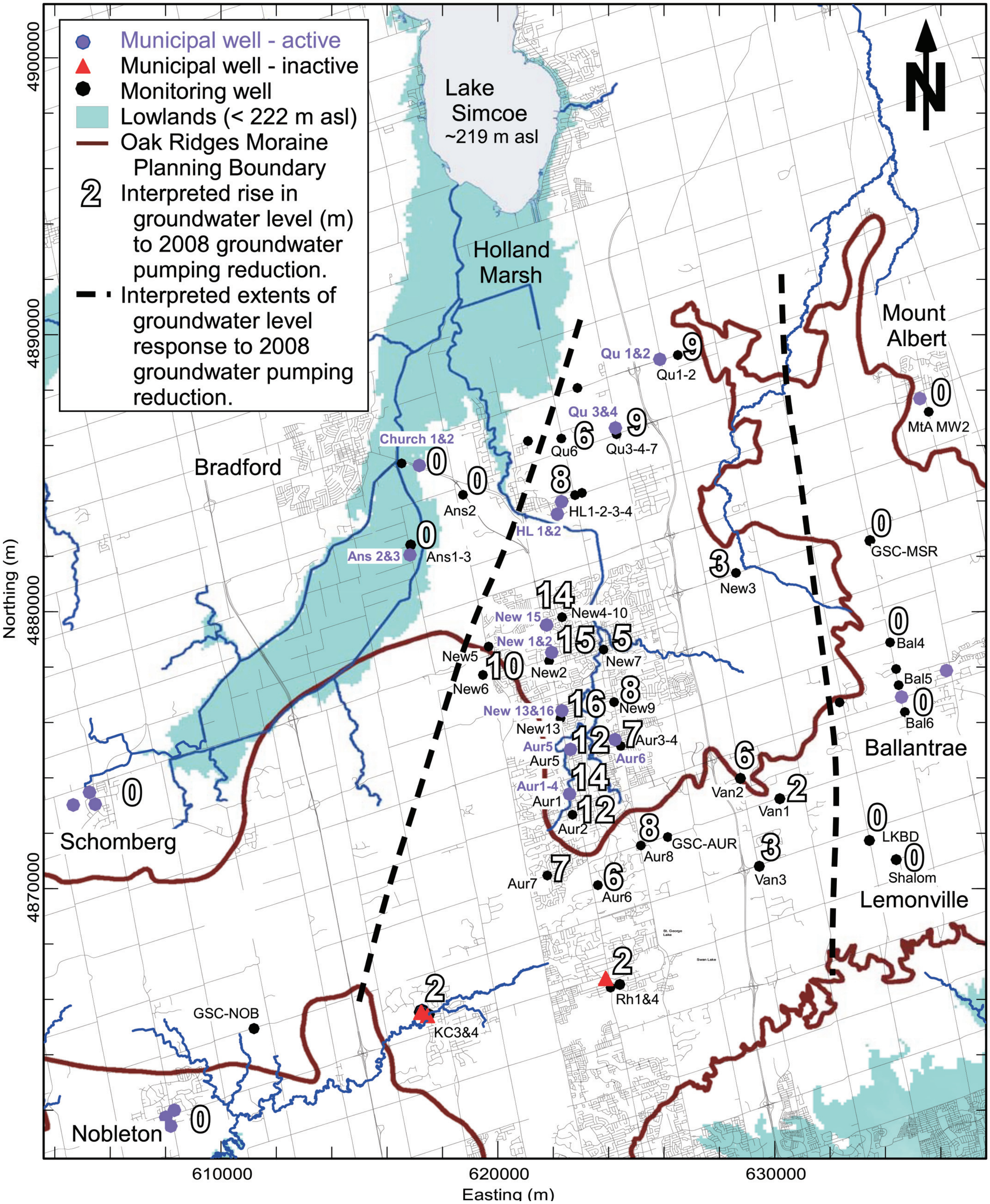
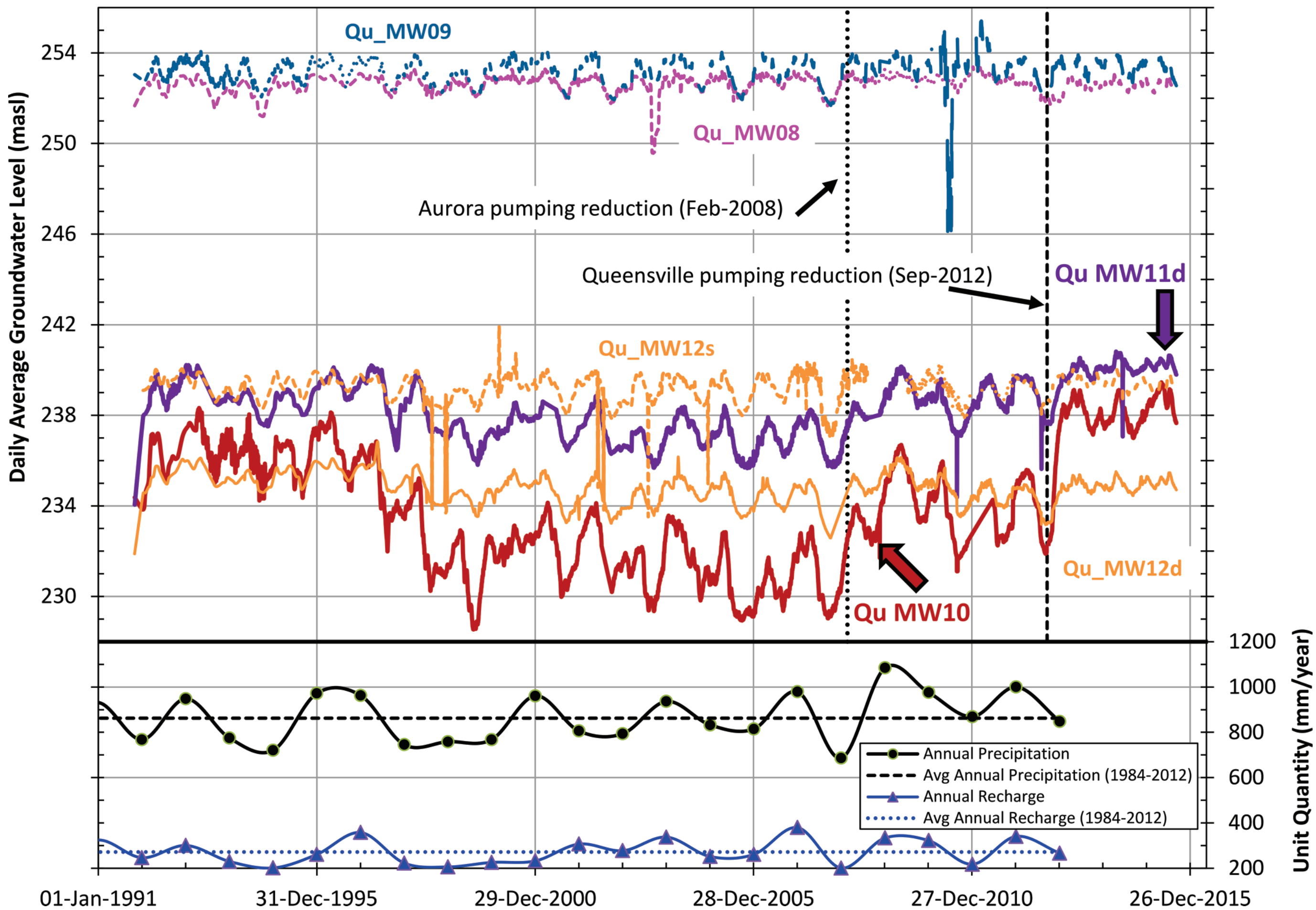


**Fig. 21.** Queensville shallow flow system groundwater monitor daily average groundwater level hydrographs. Monitor locations shown on Fig. 4. Recharge estimates from a GSFLOW model developed by Earthfx Inc. (2014) utilizing daily input data for the period October 1984 to September 2009. Model simulations have been extended to September 2013 for this figure. Recharge estimates are for the 20 km × 30 km area outlined on Fig. 4.






pattern also appears to be reflected in the Thorncliffe Formation regionally, in areas south of the ORM. For example, an esker – subaqueous fan setting has been interpreted in Thorncliffe Formation sediments near Markham (Sharpe et al. 2011) where pumping test response in a similar aquifer system extending from Markham northeast to Stouffville, illustrate high-yield hydraulic connection of approximately 1–10 km under heavy pumping (peak pumping rates of approximately 21 000 $m^3$/day; Inspec-Sol/Conestoga-Rovers & Associates 2009). Similar Thorncliffe Formation deposition is also inferred further downflow, south along Duffins Creek and likely to the Scarborough Bluffs. Further afield, a possible example includes confined aquifers stratigraphically beneath the Catfish Creek Till aquitard (coeval with the Newmarket Till) west of the Niagara Escarpment, which form important sources of municipal water supply. The Greenbrook confined aquifer (Waterloo Moraine, Bajc et al. 2014*a*), as one example, is in a similar geologic setting as the YSA.

***Strip aquifer***

The YSA is primarily visualized as a Thorncliffe channel, or strip aquifer. It is situated adjacent to, and in places possibly hydraulically connected to, horizontally layered, inter-channel Lower sediments (pre-Newmarket Till in age; Figs. 2, 3, and 9). Given this geological complexity, Table 6 was prepared to investigate whether the available hydraulic data could be used to further support the interpretation of the YSA being a channelized or strip aquifer versus a sheet aquifer. Making the assumption of the YSA as a sheet aquifer, the table summarizes the maximum (2005) estimated drawdown at Oak Ridges (Richmond Hill MW01), Aurora, and Newmarket for various estimates of aquifer transmissivity. From Fig. 15, the maximum observed drawdown at Aurora and Newmarket was approximately 35 m in 2005, coinciding with the period of maximum YSA pumping. The magnitude of the drawdown at Queensville is estimated at approximately 30–35 m based on reported static water levels (~240–245 m asl) from the MOECC water well record database in this area prior to 1960. This estimate is also consistent with pre-municipal pumping static groundwater levels in the area of approximately 245 m asl (International Water Consultants Ltd. 1977; Vallery et al. 1982). The onset of YSA pumping in Aurora in the late 1950s would have affected any initial static water levels measured in this part of the YSA when the Queensville wells were drilled several decades later.

Examination of Table 6 shows that the magnitude of the observed drawdown is not possible within a sheet aquifer system given the estimated YSA transmissivity values from pumping tests (Table 4). Rather, the high YSA pumping test transmissivity estimates, along with the observed drawdown, both in terms of its magnitude and extent, are consistent with the Yonge Street aquifer being a strip aquifer, and consistent with observations presented for the Estevan Valley Aquifer in Saskatchewan and the theoretical semiconfined channel or strip versus sheet aquifer comparison presented in van der Kamp and Maathuis (2012). Although the YSA width is difficult to fully constrain with the existing

**Table 6.** Estimated values of steady-state drawdown in a semiconfined sheet aquifer.

| Monitoring locations (Fig. 4): | | Richmond Hill MW01, $r$ = 7140 m | Aurora MW01, $r$ = 37 m | Newmarket MW04, $r$ = 6392 m |
|---|---|---|---|---|
| Observed max. drawdown (m) (see Fig. 15): | | 5.0 | 36.2 | 33.0 |
| | | Estimated[a] max. drawdown (m) | | |
| Transmissivity (m²/day) | Hydraulic conductivity (m/s) | Richmond Hill MW01 | Aurora MW01 | Newmarket MW04 |
| 22 | 1.0E–05 | 5.9 | >55[b] | >70[b] |
| 500 | 2.3E–04 | 7.1 | 30.8 | 17.4 |
| 1000 | 4.6E–04 | 5.1 | 17.4 | 10.8 |
| 1500 | 6.9E–04 | 4.1 | 12.5 | 8.1 |
| 2000 | 9.3E–04 | 3.5 | 9.8 | 6.5 |
| 2500 | 1.2E–03 | 3.1 | 8.1 | 5.5 |
| 3000 | 1.4E–03 | 2.7 | 7.0 | 4.8 |
| 3500 | 1.6E–03 | 2.5 | 6.1 | 4.2 |
| 4000 | 1.9E–03 | 2.3 | 5.5 | 3.8 |
| 4500 | 2.1E–03 | 2.1 | 5.0 | 3.5 |

**Note:** Overlying aquitard: $K_v'$ (m/s) = $1 \times 10^{-9}$ m/s; $b'$ = 30 m; Aquifer $b$ = 25 m. $r$ = distance in metres from Aurora PW1 to PW4 pumping centre. Drawdown estimated utilizing superposition within AQTESOLV (Duffield 2007) for the nine active Yonge Street Aquifer pumping centres using 2005 pumping rates (Fig. 14*b*).

[a]Estimated using the methods of Hantush and Jacob (1955) and Hantush (1964) with no aquitard storage. Estimates considered approximate and not accurate to the degree shown.

[b]Estimate larger than available drawdown in nearby pumping well (Earthfx Inc. 2014).

data distribution, Butler and Liu (1991) conclude that drawdown is less sensitive to strip aquifer width than it is to strip aquifer transmissivity. A detailed water budget analysis was conducted for the study area by Earthfx Inc. and Gerber Geosciences Inc. (2008) utilizing a three-dimensional numerical groundwater flow model. The YSA wells are situated within the East Holland and Maskinonge River watersheds with drainage areas of 244.1 and 68.4 km², respectively (312.5 km² total). Simulated vertical flux to the deep aquifer system within the Lower sediment (i.e., downward through overlying Newmarket Till/Thorncliffe mud aquitard) averages approximately 100 mm/year based on 2002 YSA municipal pumping rates, which averaged approximately 50 mm/year over the two watersheds. The interpreted extents of the groundwater level rise to the 2008 YSA groundwater pumping reduction within the deep flow system (Lower sediment) is shown on Fig. 20. This interpreted response area is approximately 323 km². The most recent groundwater flow model (Earthfx Inc. 2014) estimates the average downward groundwater flow to the Lower sediments within this area as approximately 100 mm/year (2007 pumping rates), similar to the earlier model version estimates (Earthfx Inc. and Gerber Geosciences Inc. 2008). The maximum YSA municipal pumping rate was approximately 16 million m³/year (Fig. 14*a*) in the 2005–2007 period. This quantity averages approximately 50 mm/year over the "response" area shown on Fig. 20. Groundwater levels within the YSA also seemed to stabilize during this time period suggesting that some state of quasi-equilibrium was being approached (Fig. 15). Although the detailed YSA channel width (Thorncliffe channel) remains unknown, the above areas are provided to give an indication of the extent over which vertical groundwater flow to the YSA (Thorncliffe channel) and inter-channel areas (Lower sediment) is interpreted to occur to support peak YSA pumping rates. From geological information, the minimum YSA Thorncliffe channel area is estimated at 40 km² (20 km long × 2 km wide). Groundwater in all Lower sediment is replenished by vertical downward groundwater flow. The YSA channel is interpreted to be replenished by vertical groundwater flow through the overlying aquitard, and also by lateral flow from the inter-channel areas, which are also replenished by vertical groundwater flow through the overlying Newmarket Till aquitard and also through ORM channel silt and sand where these occur (e.g., Vandorf, Figs. 8*c* and 11).

***Aquitard considerations***

Based on the available detailed geological data, the YSA channel lacks the presence of any internal aquitard layers. This is supported by the hydraulic data which reveals that no vertical hydraulic gradient ($i_v$) is found within the YSA. In contrast, in the inter-channel areas, the groundwater monitoring data reflect a difference in groundwater levels of up to tens of metres between vertically separated Lower sediment aquifers (see Earthfx Inc. 2006, 2014).

The subaqueous fan gravel–sand–mud, fining-upward facies succession provides a thick Thorncliffe post-channel mud capping aquitard to the YSA. When combined with the overlying Newmarket Till, the collective aquitard can reach between 30 and 80 m in thickness (Fig. 8). This provides considerable protection to the YSA from any surface anthropogenic influences. Although there is a paucity of shallow monitors with suitable groundwater level records, there is likely to be little direct hydraulic connection across this thick aquitard between shallow wells and the deep YSA flow system. Evidence of a muted shallow system hydraulic response is observed in some, but not all, monitors at the north end of the YSA in Queensville. Also, the shallow system response to reduction in YSA pumping observed in the Vandorf and Ballantrae areas (Van MW01i, Van MW02i, Fig. 19), can possibly be attributed to the presence of ORM channels that have cut through (Pugin et al. 1999) the thick aquitard to possibly connect the shallow and deeper parts of the flow system in this area (e.g., Vandorf, Fig. 8*c*).

## Regional prospecting implications

The acquired knowledge of the YSA within the north–south axis of the Aurora basin (Figs. 5 and 8) allows for aquifer assessment within an expected stratigraphic framework, from site to regional scales. This serves as a guide for prospecting similar settings in adjacent areas. The Thorncliffe Formation channel–esker–fan depositional model occurs within a well-constrained framework (Fig. 9). The orientation, geometry, sedimentary architecture, and composition of the YSA channel aquifer, as depicted (Fig. 9), should occur elsewhere in a similar arrangement, below Newmarket Till and within incised older Lower sediments, in places to bedrock.

Channel features were not controlled directly by bedrock topography, as previously thought (e.g., AECOM Canada Ltd. 2014); however, topography played a role as the Laurentian trough collected glacial meltwater. This ponded water trapped thick sediments, in particular Thorncliffe Formation sediment, prior to the deposition of the Newmarket Till. In contrast, as bedrock rises eastward in the area, Thorncliffe Formation and older sediments pinch out beyond the basin (Fig. 11).

At the site scale, detailed understanding of the key YSA depositional setting allows for length-scale sediment and hydrofacies predictions (Fig. 10). This subaqueous fan process understanding illustrates the organized arrangement of sediment and hydrofacies related to a high-energy influx of water and sediment into a basin with standing water. Sediment deposited parallel to flow grades from coarse to fine grain sizes over distances up to kilometres downflow, depending on discharge position in the basin, and proximity to, or distance from, the subglacial influx point. Coarse-to-fine grading in grain sizes also occurs upward in this deep-water-basin sequence on a scale of 10–100 m. Perpendicular to approximate north–south paleoflow trends of the YSA, grain sizes grade rapidly on a scale of 10–100 m. The directional grain-size attributes of the subaqueous fan sediment relate directly to the hydrogeological properties of their associated hydrofacies (Fig. 10).

In addition, the YSA has regional significance. The YSA Thorncliffe channel incised pre-existing Thorncliffe Formation and older sediment (Fig. 9). Channels likely formed subglacially (e.g., Burke et al. 2008, 2012; Perkins et al. 2016) and the hydraulic gradient of the ice sheet might have created multiple meltwater–sediment influx points (piezometric flow paths), in addition to the YSA. Hence, other identified Thorncliffe channels across the region are likely part of a network of north–south to northeast—southwest-trending channel–esker–fan systems (Table 3; Schomberg, Nobleton, 15th Ave., 16th Ave., and at Holt on the eastern flank of the YSA). The inferred array of fans has a likely spacing of 5–15 km (e.g., Sharpe et al. 2017), which effectively drained excess water from the ice sheet (Lelandais et al. 2016). This estimate of esker–fan spacing is based on an exposed network of eskers in treeless terrain of northern Canada (Aylsworth et al. 2012). Here, esker ridges were mapped 5–15 km apart, with most eskers set within a channel corridor, eroded approximately 1–3 km wide (Sharpe et al. 2017). The above scenario provides a regional prospecting understanding for Thorncliffe Formation aquifers across the area of thick basin sediments, such as the Laurentian trough (Sharpe et al. 2018). Channels incised into Lower sediment were rapidly filled with a gravel–sand–mud fining-upward sequence. This characteristic sediment sequence can help with locating north–south influx corridors and channels along with their related sediment facies and hydrofacies (directional hydraulic attributes; Fig. 10). This understanding allows us to describe the YSA as a north to south trending semiconfined (Fig. 8) linear (strip) aquifer where high permeability sediments are embedded within and surrounded by a matrix of lower permeability sediment within inter-channel areas. Variable lateral (west–east) permeability may occur where the channel–esker expands to a subaqueous fan setting (Figs. 9 and 10), and perhaps where inter-channel sediment allows, or intersection with an adjacent channel system occurs.

Buried valley aquifers are common in glaciated terrains and provide a typical case of a strip aquifer (Russell et al. 2004; van der Kamp and Maathuis 2012). Case studies of strip aquifers (Butler and Liu 1991; van der Kamp and Maathuis 2012) suggest that drawdown observed near and remote from pumping centers (along the length of the aquifer) are much greater (can be at least an order of magnitude greater) than would be expected in a typical sheet aquifer with similar transmissivity and storage coefficient. Sheet aquifers are assumed to extend infinitely in every direction with radially symmetric flow; however, strip aquifer flow is influenced by boundaries and radially symmetric flow induced by pumping only occurs near the pumping well. Water then moves to the well preferentially along the longitudinal axis of the strip aquifer. The YSA performs as a semiconfined strip aquifer extending at least from Aurora north to Queensville. A summary of the conceptual model for the YSA is presented in Fig. 11 and shows how channels relate to other components of the YSA aquifer system (i.e., inter-channel areas; overlying aquitard), including recharge from the ORM. For example, hydraulic properties of the flow system on the west side of the cross-section (ORM channel along Holland Marsh) differ from the properties of the flow system on the east side of the cross-section (inter-channel sequence) because of geological differences. South of Aurora the YSA grades into a setting more like a sheet aquifer as the observed hydraulic response broadens laterally in response to the transition from channel to fan setting (Figs. 9 and 10).

## Conclusions

Since 1941, the YSA has continuously been one of the most prolific municipal water supply aquifers in southern Ontario. A synthesis of municipal technical reports along with geological studies has allowed for a conceptual framework to be developed for the geology and hydrogeology of the aquifer. This framework provides a context for which to review the hydraulic data that are available for the aquifer, only previously accessible in technical reports. The current conceptual model provides a framework for future aquifer management, and for prospecting elsewhere in the area.

The YSA is located within a thick Quaternary succession (greater than 200 m) within the eastern margin of a large bedrock low (Laurentian trough) that extends from Georgian Bay to Lake Ontario. The lower part of the Quaternary succession (mainly less than 100 m asl) consists of deposits of the Scarborough, Sunnybrook, and Thorncliffe formations (Lower sediment) that were likely deposited within a large lacustrine–glaciolacustrine basin. Detailed geologic analysis utilizing seismic reflection data and continuously cored boreholes, coupled with accompanying hydrogeological data, has led to the interpretation of channelized structures that were filled with up to 100 m of fining-upward channel–esker–fan sequences consisting of basal gravel overlain by sand and capped by silt–clay rhythmites. The YSA is protected by an overlying leaky aquitard of Newmarket Till and lacustrine mud that is locally breached by ORM-age channel erosion and fill.

YSA geological and hydrogeological data maps out an elongated north–south aquifer geometry. Aquifer heterogeneity is controlled by primary depositional trends of sediments that fine downflow from north to south over a longitudinal distance of approximately 20 km. Sediments also fine in a lateral direction away from the channel (approximately 1–3 km) as well as vertically (about 100 m) as channel sedimentation waned within the basin. Hydraulic properties relate to proximal-distal facies changes and specific locations within the vertical channel infill succession. High hydraulic conductivity (*K*) zones are related to channelized gravel deposition.

Two ages of approximately north to south channelization occurred (Figs. 2 and 11). The oldest channels are late-Thorncliffe Formation age (greater than approximately 20 ka) before deposition of Newmarket Till. Younger channels also exist (e.g., Ballantrae, Bradford) within the study area and are of similar age to the ORM (less than approximately 14 ka) that have eroded to various depths within the Quaternary succession. The two ages of channels may intersect where the younger channels (ORM channels) have eroded to significant depths, and where they coincide with deeper (and older) Thorncliffe channels (Fig. 11). At such locations, the regional Newmarket Till aquitard would be absent and greater hydraulic connection between the shallow and deep parts of the flow system would be possible. ORM channels are visible north of the ORM as long, broad, north–south trending river valleys (Russell et al. 2003*b*; Brennand et al. 2006). Sediment facies differences between channel sediments and pre-existing Quaternary successions (inter-channel areas) are shown with continuous cores to be abrupt; however, lateral hydraulic connection is observed between coarser-grained channel sediments (sand and gravel) and inter-channel sediment. The YSA is not directly controlled by a bedrock trough, rather it occurs within a Thorncliffe-aged channel that formed late in Thorncliffe sedimentation.

This study integrates high-quality geological and geophysical data with hydraulic analysis to advance the understanding of the controls on YSA three-dimensional architecture and hydraulic properties (conceptual model). The study highlights the value of such data to support aquifer studies and the need for multi-agency and multi-disciplinary collaboration to address groundwater supply issues. In the absence of such high quality data, no amount of re-analysis of water well data and other low quality data sets having high uncertainty will advance aquifer knowledge. The refined YSA synthesis presented here is based on process sedimentological and geological understanding along with hydrogeological knowledge, and provides a framework and example that can be applied to other aquifer settings in the GTA that may be similar to the YSA (e.g., Markham, Holt).

A key refinement to the conceptual model presented here is the presence of late Thorncliffe Formation age north to south trending high permeability gravel channels (Thorncliffe channel) that produce significant groundwater yields within Quaternary successions (greater than 20 ka) of southern Ontario. It is anticipated that this conceptual model may guide groundwater exploration and development activities for channel aquifers that exist within thick Quaternary succession glaciated terrains. The key to robust conceptual models is ongoing testing and refinement as new high-quality sediment coring, seismic data, and hydraulic information becomes available. Future work can be focused on more detailed statistical and numerical analysis of groundwater level and groundwater pumping trends, analysis of shallow system response to better determine properties of the intervening Newmarket Till – Thorncliffe mud aquitard, and detailed analysis of groundwater chemical and isotopic evolution. Finally, refinement of existing numerical groundwater flow models is necessary to better incorporate the three-dimensional YSA geologic architecture and process models, particularly inclusion of the Thorncliffe age channels, and to refine (steady-state and transient) the calibration to the entire historical record of groundwater level measurements.

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