Thoughts on groundwater level variations in Southern Ontario

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ABSTRACT
An analysis of the measured depth to static water level data found within Ontario's Water Well Information System (WWIS) was undertaken to determine if the data could be used to better understand groundwater level fluctuations across Ontario over time. The study has found that the data can be successfully used to highlight areas where groundwater levels have changed over time, although caution must be taken in any interpretation of the data. Many factors can contribute to interpretations made on the spatially and temporally aggregated WWIS data. The study found that well depth in particular, corresponds with the depth to static water level measurements, and is an important factor that must be considered when using this WWIS data. Across Ontario there has been a tendency for well depth to increase over time, perhaps related to improvements in well drilling technology. Climatic and seasonal variability, groundwater pumping, land use changes and geological variability are all factors that can affect measured static water level depths.

RÉSUMÉ
Une analyse de la profondeur mesurée du niveau d'eau statique obtenue dans le système d'information de forages d'eau de l'Ontario (WWIS) a été entreprise pour déterminer si les données pouvaient être employées pour mieux comprendre les fluctuations du niveau de l'eau souterraine en Ontario au fil du temps. L'étude a constaté que les données peuvent être employées avec succès pour identifier des secteurs où les niveaux d'eau souterraine ont changé au fil du temps. Beaucoup de facteurs peuvent contribuer aux interprétations faites sur des données du WWIS agrégées dans l'espace et dans le temps. La profondeur des puits en particulier, correspond à la profondeur du niveau d'eau statique mesuré, et est un facteur important à considérer dans l'utilisation des données du WWIS. À travers l'Ontario il y a eu une tendance pour que la profondeur de puits augmente au fil du temps, peut-être reliée aux améliorations des technologies de forage de puits. Les changements climatiques et saisonniers, le pompage des eaux souterraines, les changements de l'utilisation du territoire, et la variabilité géologique sont tous des facteurs qui peuvent affecter le niveau d'eau statique.

1 INTRODUCTION

Since 1946, the Ministry of the Environment (MOE) has been collecting information on new water supply wells as they are drilled. Upon well completion, well drillers are required to submit to the MOE, a well record form which contains location, geology, well depth and other installation details along with the depth to water level as measured after the well has been completed and the water level has stabilized. Over 600,000 records now exist for the province and they are maintained within the Ministry's Water Well Information System (WWIS).

It has been recognized that with such a wealth of data that now resides within the WWIS, there are opportunities to use the data to gain an improved understanding of Ontario's groundwater resources. The main objective of this study is to use the static water level information retained in the WWIS to attain a general understanding of when, where and by how much groundwater levels have fluctuated over the past six decades. This study uses both graphical and mapping analyses to investigate longer term trends that may lie hidden within the reported water level data.

An appreciation for groundwater level fluctuations over time can be important since areas of low groundwater levels, resulting from drought for example, may pose severe difficulties if they occur in areas with insufficient reserves of stored water, and where surface water sources are economically unavailable.

The study area is shown in Figure 1. Over the years the authors have been working with the WWIS for many different activities related to groundwater management. One result from this work was an extensive GIS analysis undertaken across Ontario to investigate long term water level trends (Haile-Meskale, 2012). This study explored how static water level depths may have changed over time. Final maps (for both glacial overburden sediments and for the bedrock) are shown in Figure 2 and indicate changes to the measured static water level depths between 1948 and 2011. In order to better understand the map, factors affecting measured water levels are discussed further.

It is recognized that the study is a very broad based review of a provincial data set. None-the-less owing to very broad differing geological conditions, notably: i) less glacial overburden sediment in the eastern vs. the western parts of the province (Singer, et.al, 1997); and ii), bedrock units in the west are generally more shaley in nature, are part of the Michigan Basin and have a westerly dip vs. the more silicic rocks in the east that are part of the Appalachian Basin and have an easterly dip. Some of the following discussions are divided between the south-eastern/central parts of the province versus the south-western parts. Although perhaps not ideal, the boundary between the two areas is coincident with the provincial administrative line that runs northwards from Lake Ontario near Oshawa.

Future studies could further refine the well populations presented here to better take account of the unique geological features especially in the western part of the province (e.g. divide wells between those that lie above and below the Niagara Escarpment, consider grouping wells that are found in or beneath thick packages of glacial sediment as found in the Laurentian Valley or in the Oak Ridges Moraine, etc.).

Figure 1. Location of the study areas

2 METHODOLOGY

A number of tasks were required in order to prepare the data within the WWIS for this study. These included:

- all measurements within the WWIS were converted to a consistent set of metric units and geographic coordinates were converted from UTM to Latitude/Longitude;
- various methods of cross validation techniques were employed to correct the data and remove outliers and incomplete records (e.g. no drill date specified, no static water level recorded, etc.);
- using a set of queries, the database has been segregated according to wells drilled within the different zones (wells completed within bedrock vs those completed either in the overburden or at the interface between the bedrock and the overburden).

3 RESULTS AND DISCUSSION

3.1 Aggregating WWIS static water level measurements - GIS analyses

The maps produced in Figure 2 are the compilation of analyses on Ontario's long term static water levels reported within the WWIS and segregated or grouped based on climatic variations over time. To produce the maps in Figure 2, climatic variation (1948 to 2008) in Ontario was initially studied independently (Haile - Meskale, 2012). The study evaluated both seasonal and annual climatic conditions with a focus on temperature and precipitation. Over this 43 year period, the study determined both wet vs dry years as well as hot vs cool years (Haile-Meskale, 2012). When the analysis of temperature and precipitation for Southern Ontario was combined, the following broad climatic periods were derived:

- 1948 to 1966 (not characterized although early 1960s recorded a significant drought);
- 1966 to 1989 (mostly variable precipitation and cold to mild temperature);
- 1990 to 1996 (mostly wet precipitation and mild temperature);
- 1997 to 2002 (mostly dry precipitation and mild to hot temperature);
- 2003 to 2008 (mostly moderate precipitation and hot temperature).

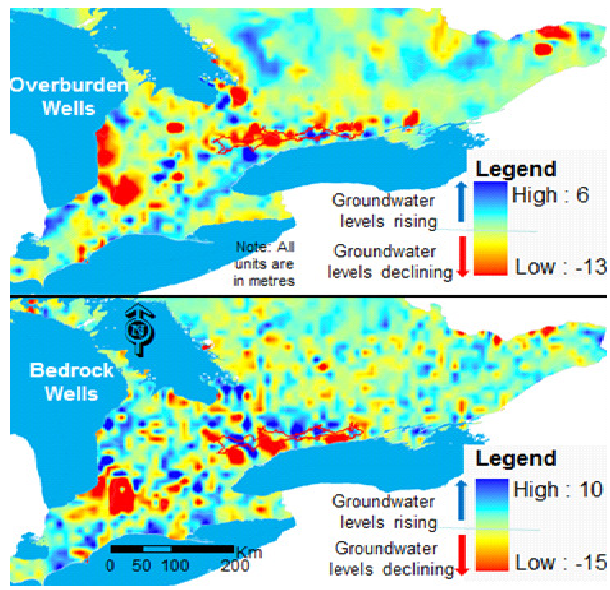


Figure 2. The integrated (average) measured depth to water levels from 1948 to 2010

Ten raster maps were constructed representing the measured static water level depths in the overburden and bedrock for each of the above mentioned time intervals. To investigate the change in static water level depth measurements over the indicated time intervals, each raster map produced from the static water level measurements of wells drilled within one climatic period was compared to the one before. This resulted in a set of four "difference" maps for the bedrock and four "difference" maps for the overburden/ interface. The difference between subsequent raster maps was then integrated (averaged) to arrive at the final maps shown in Figure 2.

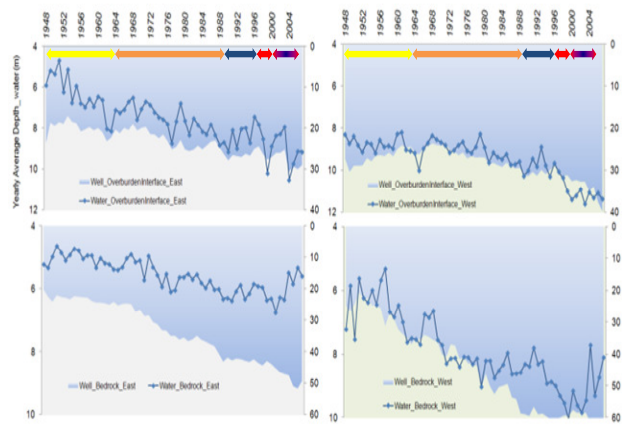
The methodology has tried to evaluate the long term change in the measured static water level depth as a potential indicator of changes in the overall groundwater system. The map in Figure 2 shows spatial variability of the measured depth to static water level changes over time. In particular, the map indicates general areas where the measured static water level depth decline/increase has been persistent throughout the last sixty years. These areas can be selected for further more localized investigation.

For both the overburden (upper map) and bedrock (lower map), the red coloured regions on Figure 2 show areas where the measured static water level depths have persistently declined from 1948 to 2010, whereas the blue coloured regions on Figure 2 show areas where the measured static water level depths have increased from 1948 to 2010. From the frequency analysis within the ArcGIS platform, it has been observed that few areas of known high groundwater extraction were observed to have long-term water level declines of on the order of 10 m or more, whereas fluctuations of +/- 2 m were more typically observed where groundwater use is low. Thus, depending on distinctions between rural and urban areas alone, it may be possible to identify some parts of the maps that may reflect more of the influence of climate than anthropogenic effects.

As will be discussed below, it is important to note at this time that the maps do not necessarily indicate that the static water level for any one individual well is declining/increasing or that the overall groundwater system in any particular area is naturally declining/increasing. This is certainly a possibility; however other causes (e.g. long term excessive pumping in populated areas) can cause depressed groundwater. It can also be pointed out that any of the red areas on the map are not necessarily vulnerable to drying up during drought periods. Several factors that are indicative of well vulnerability (e.g. minimal available drawdown, shallow well depths, low aquifer transmissivity, etc.) are discussed in more detail by Haile-Maskale (2012).

3.2 Aggregating WWIS static water level measurements –Time series analyses

In order to investigate changes both in the measured well depth and in the depth to static water level measurements over time, several time series graphs were plotted for different areas. For the graphs (Figure 3), wells drilled in the South-eastern/central (right side of Figure 3) and wells drilled in the South-western (left side of Figure 3) parts of the province were grouped. These wells were then segregated according to those that tap bedrock aquifers (bottom of Figure 3) vs. those that are completed in the overburden/interface (top of Figure 3). The graphs show the average annual well depth and the average annual measured static water level depth for each of the four categories of wells. The coloured bar at the top of the figures reflects the various climate intervals that were mentioned in Section 2. Although it is recognized that many processes potentially affecting static water level depth measurements have been grossly aggregated into such plots, several observations can be made. First, it can be observed that regardless of which plot is examined, there is a tendency to an increase in the well depth over time, coupled with an increase in the measured static water level depth (this is discussed further below).



Years groups with similar trend	South Eastern and South Central Ontario		South Western Ontario	
	Overburden	Bedrock	Overburden	Bedrock
1948 - 1965	6.44	5.06	8.85	6.65
	-1.19	-0.55	-0.26	-1.45
1966- 1989	7.63	5.61	9.11	8.10
	-0.71	-0.53	-0.61	-0.41
1990 - 1996	8.34	6.13	9.72	8.51
	-0.34	-0.13	-1.12	-1.08
1997 - 2002	8.68	6.26	10.84	9.59
	-0.61	0.54	-0.46	0.93
2003 - 2008	9.29	5.72	11.30	8.66

Legend: -1.19 Difference in groundwater levels between the averages of the two consecutive year intervals

Figure 3. Mean yearly depth to water and well depth variations for the different aquifers and for the different areas (upper figure) and breakdown of the variation (table)

The table in the lower part of Figure 3 summarizes some of the observed changes in the measured static water level depths over the identified climate intervals. The table does not take into account well depth variation. For each climate interval, the table shows the average measured static water level depth for each of the four well categories (values in black). The table also shows the difference in this average value between each climate interval (values in red). For example, the lowering of average depth to static water level between the 1948/1966 climate period vs. the 1966/1989 period was -1.19 m. In general, the table reflects an overall trend towards a decline in the average static water level depth between successive climate intervals for both the bedrock and overburden wells in the east and the west. The one exception is a more recent increase in the measured static water level depth for the bedrock aquifers wells in both the east and west.

Figure 3 also reflects some observed water level differences tied to known differences in geology. For example, most wells within the west grouping are deeper, particularly in more recent years. Given the greater depth in glacial overburden sediment in the west (e.g. greater than 100 m on the Oak Ridges Moraine and in the Laurentian Valley) (Singer, et al 1997) it is likely that these wells penetrate more different aquifers with greater variability in the hydrogeologic characteristics than do wells in the east, where the glacial sediment is generally less than 30 m. This geological variability may be reflected in the greater variability in the average annual depth to static water level observed in the bedrock and overburden wells in the west vs. the reduced variability in the east.

3.3 Factors affecting long term water levels

In order to effectively tease out any overall trends in groundwater levels from the WWIS database, it is important to recognize factors that, over time, may influence the static water levels measurements reported in the WWIS: including well depth, degree of saturation (seasonality), water use and land use. These factors are discussed in further detail below.

Factors influenced by geological variables, such as the degree of confinement, permeability, etc. are not considered to have changed since water levels measurements began in the middle of the last century, and therefore are not considered to be factors affecting long term water level trends. However it should be noted that the spatial differences in geology would have significant affect on static water level measurements spatially. The WWIS is also known to house erroneous measurements, including those for static water level, owing to any number of possible sources (e.g. transcription error, water level not equilibrated when static measurement taken, etc.). Improper construction, for example where seals are improperly set, can also affect static water level measurements. However, an assumption has been made in the paper that human errors are more or less random and have not systematically changed (improved or decreased) over time. Therefore any observed trends in water levels through time would not be attributable to errors in measurements.

3.3.1 Well depth

In typical groundwater flow systems water levels are known to change with well depth. In groundwater recharge areas, where the vertical hydraulic gradient is downwards, the measured static water level in a shallow well would be higher (i.e. found at a higher elevation) than the static water level of a deeper well drilled at the same location. Conversely, in a groundwater discharge area, where the vertical hydraulic gradient is upwards, the static water level in a deeper well would be higher (i.e. found at a higher elevation) than the static level in a shallow well drilled at the same location.

Well depth variations in time were investigated using the WWIS data from the Southern Ontario (Figure 4a). This figure shows the annual average well depth from 1948 through to 2010. The figure also shows that, starting in 1970 and continuing through to 2006, the average well depth across the province increased from about 25 m to about 45 m.

To further investigate reasons for this increase in well depth, well construction methodologies across the whole Ontario were examined. Figure 4b shows the number of wells drilled by different drilling methods. This Figure shows that since record keeping began, the greatest number of wells was constructed using cable tool drilling technology. This was especially true in the earlier years (1948 to 1970) when nearly all wells were drilled using cable tool rigs. Since 1989, more and more wells have been drilled using rotary rigs. The figure also show the total number of wells drilled per year (shown in grey). The Figure indicates that the greatest number of wells was drilled in 1989 when almost 17,000 wells were drilled. Incidentally, the total number of wells drilled reflects the overall economy, which showed a peak in Canadian housing starts in the late 1980s.

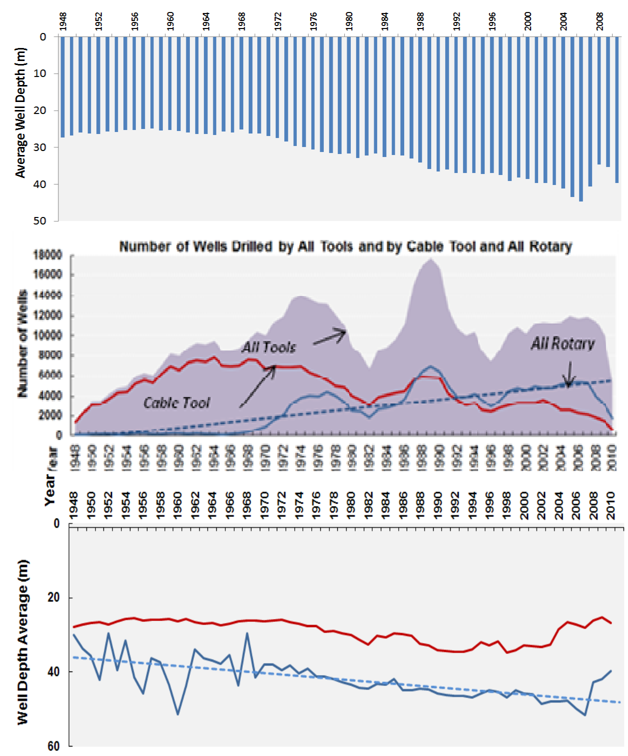


Figure 4. a) Average annual well depth variations for Southern Ontario 1948 to 2010 (upper figure); b) Number of wells drilled and drill method of all Ontario (middle figure); and c) Comparison of well depth over time for cable tool and rotary drilled wells of all Ontario (lower figure)

Figure 4c shows that, particularly for the rotary drilled wells, there has been a trend to increasing well depths over time. In general, several factors can contribute to the final total depth of any individual well including:

- the availability of groundwater in the subsurface sediments and rocks;
- the amount of water required (e.g the database contains wells drilled for various purposes (e.g. municipal, domestic, industrial, etc.);
- the cost of drilling;
- the desire of well owners for wells that tap into more deeper, more protected aquifers;
- a decline in overall groundwater levels.

The fact that the depth of cable tool drilled wells has remained relatively constant over the years suggests the onset of rotary drilling technology in the 1970s may be the main reason for increasing well depths. This newer technology allowed drillers to more cost effectively drill to deeper more protected and possibly more productive aquifers.

Figure 5 has been prepared to further investigate the relationship between the well depth and the depth to the static water level. For the Figure, wells were segregated into those that tap aquifers in the glacial sediment and interface zone versus those that tap into bedrock aquifers. Furthermore, the wells in eastern and central Ontario have been separated from those drilled in the western part of the province. For each aquifer, the average well depth has been plotted against the average depth to static water level.

Considering all wells, the positive and strong correlation (>0.5) shown in Figure 5 confirms that deeper wells have deeper static groundwater levels. This is to be expected since most wells tend to be drilled outside of river valleys (i.e. outside of discharge areas). Ontario's planning policies largely restrict development in these low lying environmentally sensitive areas. With the majority of wells being drilled in recharge areas, the tendency for static water levels to decline with increasing well depth is not unanticipated. The flatter curves for the bedrock wells (lower part of Figure 5) is attributed to the fact that most of the bedrock wells (98.5%) do not have screens set within them. Rather, they are open across the entire bedrock interval and the static water levels therefore reflect the hydraulic head from many different bedrock units. This would tend to dampen the increase in water level with depth. Of course this trend to deeper water levels with increasing depth does not always hold true and there are cases where some deeper wells may have higher groundwater levels due to confined aquifer conditions.

It can also be seen from the Figure 5a (top part) that the overburden wells drilled in the western part of the province are generally deeper than those drilled in east/central Ontario. Figure 5b (lower part) suggests that for bedrock wells of similar depth, the depth to static water is greater in the west vs. east/central Ontario.

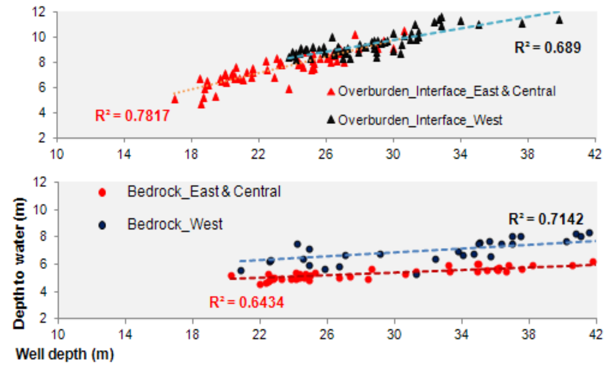


Figure 5. Relation between mean yearly well depth and depth to static water level, a) overburden (glacial sediment) and interface wells; b) bedrock wells

3.3.2 Climate/Seasonality

Groundwater levels would be expected to be higher during wetter periods (e.g. spring, fall and/or wet years) and lower during dry periods (e.g. late summer/early fall and/or drought years).

Figure 6 has been prepared using all wells in Southern Ontario (both east and west) to examine how static water level depths may vary through the year owing to Ontario's climate variability. The figure also reflects wells of various depths to investigate whether deep wells also reflect climate variability. Based on well depth, the wells were classified into the following quartiles: i) equal or less than 16 metres; ii) between 16 and 26 metres; iii) between 26 and 46 metres; and iv) greater than 46 metres). For each category, the average annual static water level depth was calculated and shown on the Figure. The graphs on the left are the mean yearly variation (1948 to 2010), whereas those on the right indicate the overall monthly static water level depth variations for the indicated depth intervals. The coloured bar at the top of the figure reflects the various climate intervals that were mentioned in Section 2.

What can be noticed readily from the graphs is that water depth progressively increases as well depths increases. This is similar to what was observed above (Figure 5). Also, regardless of well depth, all four groups of wells reflect a similar average static water level depth trend over time. The average static water level depths are observed to decline during the early 1960s, coincident with a well documented drought period in the Great Lakes basin. Water level depths then generally rise through to the early 1980s before flattening out through to about 2000. In general, the measured water level depths show an increasing trend from 2000 through to 2008 (see also Figure 3). The significant drought of the early 1960's, which appears to have influenced water levels right to depths, regardless of well depths, as well as the short dry hot period from 1997 to 2002 (which is again reflected right to depth) are both reflected in Figure 6. The intervening periods of cooler temperatures coupled with either higher or variable precipitation, are times when the static water level depths generally show an increase.

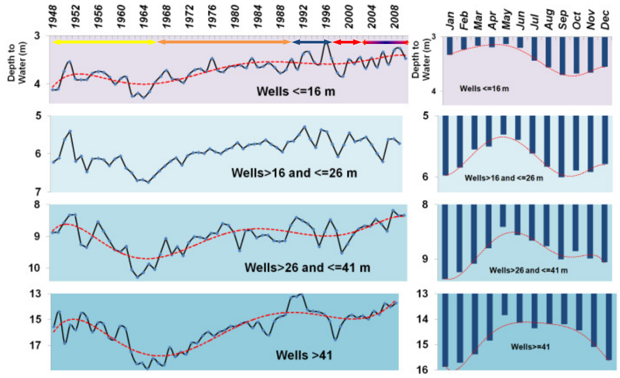


Figure 6. Mean annual depth to static water level variations for various well depths from 1948 to 2010 and the corresponding mean monthly variations

Another observation from Figure 6 is that the overall fluctuation is greater for the deeper wells than for the shallow wells. For the wells less than 16 m in depth for example, the variability in the measured static water level depth is generally on the order of one meter over the period of record. In contrast, the wells that are deeper than 41 m tend to show variability in the measured static water level depth of on the order of 3 to 5 m. This perhaps is attributed to the ability of the deeper wells to better reflect dryer conditions given that they have a larger available drawdown.

At an annual scale, Ontario has four distinct seasons with summers being warm, hot and humid, and winters being quite the opposite (cold and dry). Fall and spring represent more transitional periods between the two more extreme seasons. Actual evapotranspiration (AET) which generally correlates inversely with shallow groundwater levels, is found to be generally negligible through the winter months (December through March) and picks up with the onset of warmer weather in April and then increases considerably with the start of the vegetation growing season in May. AET remains high through the summer months and then trails off in the fall with vegetation dye-off prior to the onset of winter (LSRCA, 2011).

This annual climatic variability is reflected in the graphs on the right side of Figure 6, which show a noticeable difference in the average monthly measured static water level variations with well depth. The shallowest wells tend to better reflect seasonal climate with the deepest static water levels being measured through the summer months and the shallowest water levels measured in the spring. For the wells greater than 41 m in depth, there is a lag in the static water levels of the deepest water levels, which are observed to be measured in the winter months of December and January.

Figure 6 demonstrates that climatic shifts, both those that occur on an annual basis from summer to winter, as well as those that are longer term in magnitude are reflected in the measured static groundwater depths across southern Ontario. The magnitude of the water level change appears to be influenced by well depth and, although not examined within this paper, is also likely to be affected by the geological setting.

3.3.3 Water use

One additional factor that can affect longer term water level measurements, albeit on a more localized basis, is the pumping or withdrawal of water from the groundwater system (e.g. to support the drinking water needs of communities) which would tend to cause groundwater levels to decline. Conversely, in areas where long term pumping ceases the static groundwater levels would be expected to recover.

Figure 7 presents hourly (top) and daily (bottom) groundwater level hydrographs from three conventional monitoring wells from different communities outside of Toronto: Newmarket (well is 137 m deep), Stouffville (well is 109 m deep), and Orono (well is 14 m deep) (see Figure 1 - lower part for location map). The communities are all dependent to some degree upon groundwater withdrawals to service the every day needs of residents and they vary in size with Orono having the smallest population (least groundwater withdrawal) and Newmarket the largest population (greatest groundwater withdrawals). The wells are actual monitoring wells located nearby pumping wells, and as such, the water levels reflect the cycle of continual pumping and recovery as pumps are turned on and off to service the community.

For the deep Newmarket and Stouffville wells, the seasonal water levels (between the dry summer months and wetter spring months) varied between about 3 and 4 metres, whereas the hourly water levels (between intervals when the pump was running and the pump was shut off) varied between about 0.6 and 0.7 metre. The seasonal influence, which is linked to greater groundwater withdrawals in the summer season for lawn watering, etc., is much more pronounced in the Newmarket well hydrographs (top 2 charts) vs. the Stouffville or Orono hydrographs. At the Orono location the hydrograph also reflects shorter term hourly trends that are pumping related

At the New Newmarket and Stouffville wells, overprinted on top of both of these shorter term patterns is a longer term change in water level, which reflects groundwater pumping. In the case of both Newmarket (1992 to 2009) and Stouffville (2001 to 2009) a long term decline of about 10 m is reflected in longer term water levels shown in Figure 7. Given the depth of the wells and the available drawdown, this magnitude of drawdown is considered to be reasonable. Water levels in Stouffville started to show a longer term recovery starting after about 2006. For the Newmarket well, the more recent rebound in the static water levels observed in 2008 and 2009 is attributed to a decrease in pumping within the community as surface sources are now being used to supplement groundwater supplies, in particular for new growth in the community. The Orono well reflects a longer term increase in static water level of about 2 m over a 4 year period from 2005 to 2009.

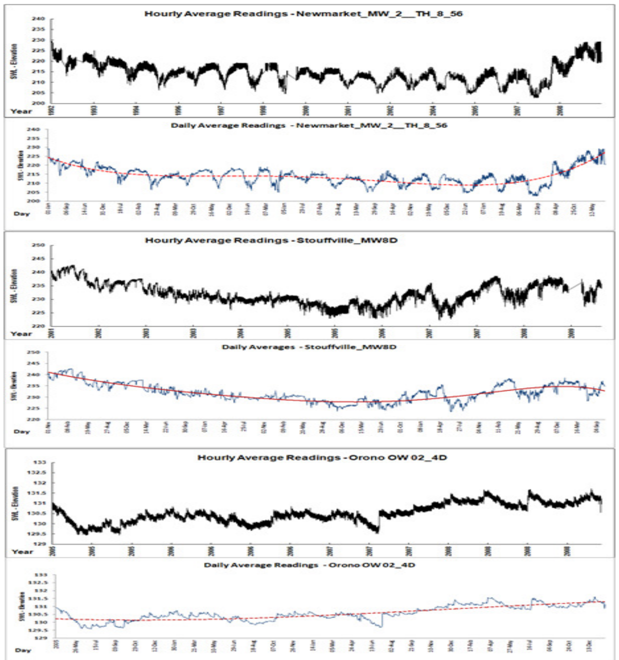


Figure 7. Hourly (top) followed by daily (bottom) groundwater level hydrographs from monitoring wells in Newmarket (top 2 charts), Stouffville (middle 2 charts) and Orono (bottom 2 charts)

It is worth noting that in Figure 2, both the Newmarket and Stouffville wells are located in the bright red zones indicating that static water level depths have declined in these areas. For these areas, the aggregated static water level depth map shown in Figure 2 was successful in highlighting these as areas of actual declining groundwater levels.

3.3.4 Other factors affecting water levels

The three major factors discussed above can certainly cause changes to the static water level measurements taken through time. Beyond these three factors, it should also be noted that the geological setting can also affect water level measurements in various ways. Even though the geology remains static through the short time intervals being discussed here, wells that are drilled in close proximity can show very different static water levels based on the subsurface or the vertical variability of geological conditions encountered when drilling (e.g. permeability distribution, inter-connectedness of aquifers, degree of confinement, etc.).

Also not addressed in this paper is the possibility for changes in land use to affect groundwater levels. For example in urban areas where recharge to the groundwater system has been diverted to surface runoff, groundwater levels could be anticipated to decline over time.

4. CONCLUSIONS

This paper has presented and discussed a methodology for evaluating the measured static water levels collected by drillers and assembled by MOE staff for some sixty years. The aggregated map presented in Figure 2 is considered to reasonably reflect those parts of the province where the potential exists for groundwater levels to be changing (declining or increasing) over the long term. The Figure shows that the magnitude in the change in the measured static water level depth over time can range to as high as +/- 10 m in places.

Several factors have been discussed as possibly contributing to these long term static water level depth changes. These include: i) well depth variation; ii) long and short term climatic variability; iii) changes in land use and groundwater use; and iv) different wells encountering different geological conditions. Given that climatic conditions would be similar over short spatial distances, it is likely that this factor may not be as significant as the other factors, in areas where decline/increase occur close together in Figure 2. The study has clearly shown that both well depth and long term water use can affect the aggregated long term measured static water level depths reflected in Figure 2.

For any particular area in Figure 2, additional investigation is required to determine the root cause for the change noted in the depth in the measured static water levels. In general, it is likely that the integrated effects of natural (e.g. seasonality/climate, geological variability) and anthropogenic (e.g. change in well depth or pumping) phenomenon contribute to the results shown in Figure 2.

Given the close association between well depth and the depth to the measured static water levels, perhaps the most effective way of screening for longer term groundwater level trends is to group wells based on the depth of the well regardless of whether wells are completed in bedrock or overburden/interface zones. Figure 6 in particular, is believed to best reflect the most representative long term trend in Ontario's groundwater levels over time. The figure shows that the greatest change to the measured static water level depths over time occurred during the early 1960s, a documented period of drought in the Great Lakes basin.

Even though deeper wells would be more resilient during dryer climatic periods, Figure 6 also suggests that it is the deeper wells that tend to show greater fluctuations in the measured depth to static water level. This is perhaps owing to the fact that deeper wells may better reflect dryer conditions due to their greater available drawdown. Figure 6 also indicates that annual, as well as longer term, seasonality is reflected more quickly in shallow wells vs in deep wells.

The study has also pointed out a significant trend in Ontario over the past sixty years, that is the trend to drill wells deeper. The reasons for the increase in well depth are not fully known although it appears to be related to improvements in drilling technology (e.g. rotary drilling replacing cable tool drilling). A significant result of this increase in well depth is an accompanying increase in the depth to the measured static water levels.

Researchers and groundwater managers must take note of this trend when evaluating water level measurements aggregated from many wells over larger geographic areas.

This study has shown that the depth to the static water levels as obtained from the WWIS, can indeed be used to investigate the possible influences of future climate change on Ontario's groundwater system. It should also be pointed out that this paper has not exhausted all spatial and temporal variables that affect measured static water level depths. The factors discussed in some detail here (well depth, climate/seasonality, and pumping) along with other factors, such as land use change, geology and well construction may all contribute to variability in measured static water level depths. All of these factors should all be considered when trying to determine the cause of declining or increasing static water level depths in any localized areas investigated in the future.

Future work can be focused on those red/blue areas in Figure 2 that indicate the possibility for long term water level changes. Localized hydrogeological studies within these areas may yield interesting results as the cause of the measured static water level depths in any particular area is more fully characterized.

5. ACKNOWLEDGEMENTS

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