REGIONAL GROUNDWATER MAPPING – AN ASSESSMENT TOOL FOR INCORPORATING GROUNDWATER INTO THE PLANNING PROCESS

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Abstract
Across much of southern Ontario there has been little work undertaken to understand groundwater movement on a regional or watershed scale. As a result there is very little in the way of maps or tools available to planners when making land use decisions that can impact groundwater resources. The Grand River Conservation Authority (GRCA) is in the midst of a study designed to fill this need and to lay the groundwork for future groundwater characterization within the watershed.

A regional mapping project was undertaken for the Grand River Watershed to more fully characterize the watershed's groundwater setting. The project involved the consolidation of existing Quaternary geological mapping, updating of the water well record database, and a mapping analysis to characterize the subsurface conditions across the watershed. A suite of colour contour maps that fall into three themes, physical geology, hydrogeology and resource protection, was produced that clearly display subsurface features within the watershed. The maps provide ideal decision support tools for integrated resource planning. The mapping methodology has implications for the future efficient characterization of Ontario's, and indeed Canada's subsurface environment.

1. Grand River Watershed

Together with its most significant tributaries, the Nith, the Conestogo, the Speed and Eramosa Rivers, the Grand River drains 6,965 square kilometres, and is one of the largest watersheds in southern Ontario. (Figure 1). The average width of the watershed is roughly 36 km with the Grand River itself having a length of about 290 km. The surface elevation within the watershed ranges from 535 mASL in the north to 173 mASL at the mouth of the Grand River at Port Maitland on Lake Erie. Major urban centres within the watershed include the tri-cities area of Waterloo, Cambridge and Kitchener, as well as the cities of Guelph and Brantford. In terms of municipalities, the watershed encompasses all of the Regional Municipality of Waterloo, almost all of Wellington and Brant Counties, parts of Hamilton-Wentworth and Halton Regions, and parts of Grey, Dufferin, Perth, and Oxford Counties (Figure 1).

The physiography or landscape of the Grand River Watershed has been shaped largely by the events of the last glaciation which in this part of Ontario came to an end about 10,000 years ago. Subsequent erosion has also played a role in the shaping of the Grand River landscape. In terms of overall physiography, the surficial overburden soils in the watershed can be divided into three general areas:

- the north parts of the watershed largely consist of lower permeability till plains showing varying relief;

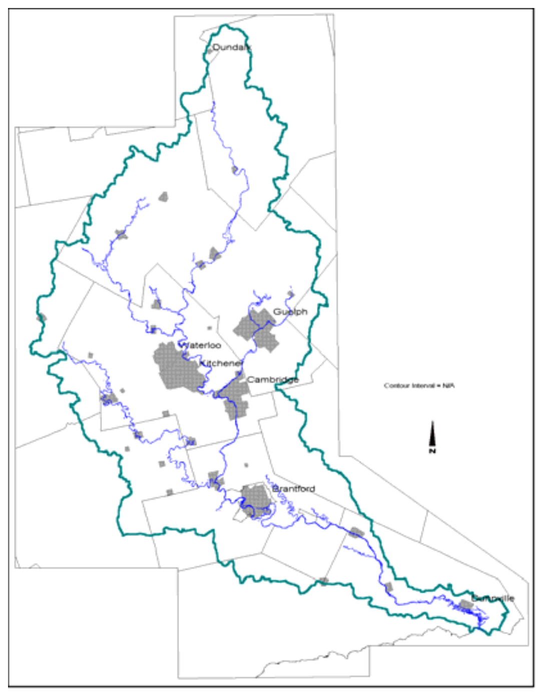

Figure 1. Setting of the Grand River Watershed.

- the central parts of the watershed are comprised of various higher permeability sand and gravel kame moraines with moderately high relief;
- the south part of the watershed is characterized by low relief, low permeability lacustrine clay plains.

It should be noted that many excellent studies have been prepared for areas within and adjacent to the Grand River Watershed. The reader is directed to an annotated bibliography of Grand River related studies prepared by Sam Singer (1995). This document briefly summarizes many of the key studies written on the physiography, geology, or hydrogeology of the Grand River Watershed.

With respect to land use, 78% of the watershed is in agricultural use, while 19% is covered with natural vegetation. The watershed is also home to some 750,000 residents, most of whom are located in the larger communities mentioned previously. Southern Ontario continues to experience an increase in population with new residents frequently migrating to the larger urban population centres. Consequently, there is increasing pressure for additional urban lands to accomodate these residents and planners are making land use change decisions that might be impacting the groundwater system.

2. Planning Frame Work

In Ontario the Ministry of Municipal Affairs and Housing, in 1994, released a "Comprehensive set of Policy Statements" which municipalities must have regard to when making land use change decisions. Under the Natural Heritage, Environmental Protection and Hazard Policies this document states

> *"Development may be permitted only if the quantity and quality of ground water and surface water are protected. Development that will negatively impact on ground water recharge areas, head waters and aquifers which have been identified as sensitive areas will not be permitted."*

This is all very well, however, in Ontario there has been very little effort put forth by the province to proactively map and delineate these sensitive ground water recharge areas, head water areas and aquifers. As a result, planners are reliant upon development proponents to carry out studies (usually incorporated into environmental impact statements or studies (EIS)) that will determine the sensitivity of the groundwater system to the proposed development. Best management techniques might be recommended as a part of an EIS study, but the municipality rarely has the resources available to ensure that these best management techniques are implemented at the development stage. Furthermore, there is very little (i.e. none) follow up monitoring to evaluate the success of implemented best management techniques or to quantify the actual impacts of urbanization on groundwater quality and groundwater levels.

It is within this planning context that the GRCA carried out a study to proactively characterize the geological and hydrogeological framework for the watershed. It is anticipated that the mapping techniques and the maps produced from this study will be of value to hydrogeologists and land use planners for many years to come.

3. Approach

Previous studies that have focussed on the hydrogeolgy of the entire Grand River Watershed have evaluated the watershed at a scale of 1:250,000. Whereas the maps resulting from these studies are useful for gaining an understanding of the overall regional hydrogeological picture within the watershed, it has been the experience of users that the maps are insufficient for guiding land use planning decisions. In addition, they often do not convey to the users detailed information that can be used to determine areas of particular significance in terms of linking groundwater/surface water systems (e.g. significant discharge areas).

Building on work that was being carried out at the Region of Halton (Holysh 1995, 1997) and on the Oak Ridges Moraine (Sharpe and Barnett, 1997), the GRCA began to assemble background geological and hydrogeological information in 1995. Through 1996 and 1997 the GRCA worked with the Ontario Geological Survey to prepare a seamless digital coverage of the Quaternary geology for the watershed. The Ministry of the Environment's water well record database was determined to be one of the most essential tools for characterizing the subsurface make up of the watershed.

In 1996, a memorandum of understanding was signed with the Ministry of the Environment to update the water well record database for the Grand River Watershed. All well records that were not previously in the database were located using a GPS system. In total, the GRCA added over 7,000 additional wells to the water well database. The Region of Waterloo (within the Grand River Watershed), undertaking a similar project, has added a further 1500 wells.

Given the requirement for meaningful mapping tools to be incorporated into the planning process, the current study focussed on mapping the watershed at a scale of 1:50,000, coinciding with the National Topographic Series (NTS) maps. The mapping relied extensively on the Ministry of the Environment's water well record database, the Ministry of Natural Resources' Ontario Base Mapping and the Ministry of

Northern Development and Mines Geology Mapping. Twelve NTS 1:50,000 maps cover the Grand River Watershed, and were used to provide the framework for this mapping exercise. In addition to the twelve individual map sheets, regional scale maps were also produced for the entire watershed. These regional maps convey an overall impression of the physical geological and hydrogeological conditions across the watershed.

Viewlog, a GIS based borehole editing software system was selected as the most appropriate tool for undertaking the study. Viewlog provides a "see through" link to Microsoft Access and allows for efficient visualization of data, both within the database itself, as well as on mapped surfaces. Viewlog also provides the ability to krige or contour surfaces using the well records, and allows for a geostatistical analysis of the resulting kriged surface. In addition, all layers created within Viewlog are suitable for transfer to Modflow for future modelling if required. Viewlog is particularly well suited for use on the water well record database given the known inaccuracies within the database. As various surfaces are kriged to a grid, anomalous results are easily observed. The wells centred on these anomalies can be easily selected and appropriate adjustments (either a correction or screening) made to the database.

For each of the 12 map sheets considered in the study, a 200 row by 150 column grid was generated. Each cell in the grid was 220 m by 220 m.

An initial task of the study was to screen out poor quality data from the database. Although the MOE took efforts to classify the reliability of the elevation and location columns in their database, errors were still found, such that the database required further screening. Final screening of the poor quality records from the database was undertaken by:

- screening out all wells with a UTM or elevation reliability code of six or greater;
- screening out wells that had good elevation reliability codes but no recorded elevation;
- comparing ground surface (from OBM data) to MOE estimated ground surface – wells with a difference greater than 10 m were screened from the database;
- remaining anomalies investigated individually to further screen poor quality wells from database.

Using the MOE classification criteria and removing all wells with either a UTM or elevation reliability code of 6 or greater, the database was reduced from the original 72,457 wells to 60,074 wells. The further screening carried out as part of the GRCA study removed a further 2,635 wells leaving 57,439 wells in the database for use in the study. Overall the screening of the database removed just over 15,000 wells or about 21% of the data. Once the database was screened, there were few problems associated with the remaining data. The most frequent problem encountered following the screening process was discovered when considering the static water levels in the database. Occasionally individual wells have a very low water level, which results in an anomalous low on a kriged water table surface. If no obvious hydrogeological reason was determined for the low static water level and nearby wells reflected a more consistent water table elevation, then the static water level was removed from the well and an appropriate flag added to the database.

It is important to note that of the wells for which corrections were made, none were removed from the database. To account for the poorer quality data found as part of the screening process, four columns were added to the main data table: three flagging columns (elevation, bedrock, and water level) and one comment column. The wells remain in the database and can be evaluated and corrected as new information becomes available.

4. Mapping Analysis

A series of map sheets was produced to convey relevant hydrogeological information for the Grand River Watershed. As was previously mentioned, maps were produced on a NTS map sheet basis. Once all map sheets were complete and the methodologies established, then the entire basin was also mapped at a watershed scale.

Maps that convey information pertaining to the physical structure of the watershed include:

- **Ground surface**
- **Bedrock surface**
- **Overburden thickness**
- **Sand and gravel thickness**

Maps that relate information pertaining to the hydrogeology and resource protection aspects of the watershed include:

- **Water table**
- **Potentiometric surface**
- **Vertical hydraulic gradient**
- **Potential Discharge areas**
- **Depth to water table**
- **Depth to 1st aquifer**
- **Areas vulnerable to contamination**

The remainder of the paper describes the map sheets individually describing the methodology used to construct the map, some highlights of the map and the usefulness of the maps within Ontario's planning framework.

4.1 Ground Surface

The ground surface map has been constructed by using elevation data from 1:10,000 Ontario Base Mapping across the watershed. Where this mapping was unavailable, elevation data from the 1:50,000 National Topographic Series (NTS) map sheets were used. The elevation contours and spot elevations were incorporated into a database that was kriged to the appropriate grid to obtain the ground surface mapping.

The map is useful for examining Quaternary geology features on the landscape. Moraines, former outwash channels, drumlin fields and other features are visible on the map sheet. The topographically high Waterloo Moraine and other adjacent moraines to the west are clearly visible as are the Paris, Galt and Moffat Moraines, especially in the southwest part of the watershed. Many of the quaternary features on the landscape are important in terms of controlling subsurface groundwater movement.

4.2 Bedrock Surface

The bedrock surface was constructed by kriging a surface from the wells that penetrated through the overburden soils to reach the bedrock surface. The bedrock surface map shows that the bedrock topography is highest in the north part of the watershed coincident with the "Dundalk Dome" one of the highest bedrock elevations in Southern Ontario. The bedrock surface drops uniformly towards Lake Erie in the south. The deep bedrock scour in the Dundas Valley along the east-side of the watershed is also prominent.

One important feature of the bedrock surface is the mapped bedrock lows or valleys. These valleys are important features of the Grand River Watershed. They are frequently partially filled with coarser grained sand and gravel materials, and may therefore serve as high yielding aquifers. Not only can they provide targets for future municipal well exploration, but they can also serve to conduct groundwater between subwatersheds. Understanding the function of these systems in terms of water transfers within the overall context of the Grand River is critical in terms of an overall water management strategy for the watershed. It is also important to note that the bedrock valleys may or may not be filled with permeable aquifer materials and therefore may or may not serve as high yield municipal aquifers. A bedrock valley thalweg was drawn through the centre of each interpreted bedrock depression or valley. Figure 2 shows the bedrock valley thalwegs across the watershed. The Figure shows four semi-parallel systems that extend in a south – southwest direction from the north part of the watershed. These systems extend nearly to Brantford where they join to form the deeply incised Dundas Valley that extends eastward towards Hamilton Harbour in Lake Ontario. It is likely that these bedrock valley systems are controlled by the underlying fracture pattern in the bedrock.

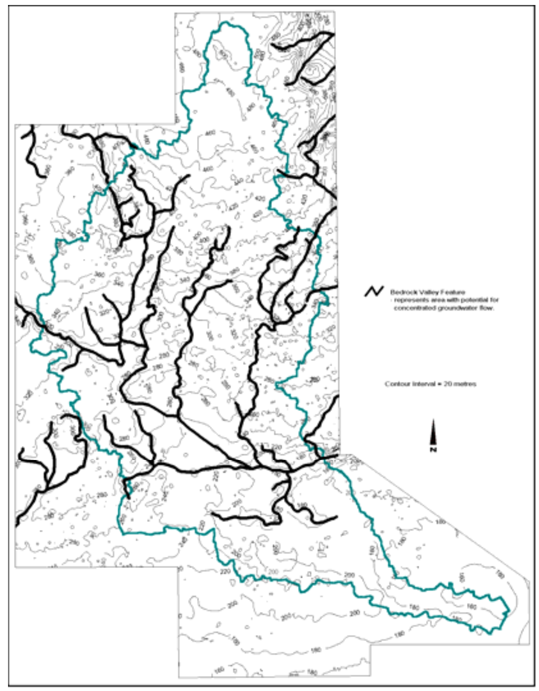

Figure 2. Bedrock Valleys of the Grand River Watershed.

Also noteworthy on the figure is the absence of notable bedrock valley features in the south part of the watershed, south of the Dundas Valley. This indicates that there were likely no significant north-south drainage systems extending to the Lake Erie basin prior to the formation of the Dundas Valley. It is uncertain as to whether these paleo-drainage features were all operational contemporaneously or whether they were active at different time periods.

4.3 Overburden Thickness

The overburden thickness was determined by subtracting the kriged bedrock surface from the kriged ground surface. Thick moraine sequences and valley fills are readily discernable on this map. The overburden thickness ranges from zero in many of the present-day river valleys and in bedrock plain areas where bedrock outcrops at surface, to over 130 m in areas where topographically high moraines overlie deep bedrock valley systems. The thickest overburden materials are found in the vicinity of Waterloo where the Waterloo Moraine sits atop one of the delineated bedrock valley features. When examined with the ground surface mapping, this map is useful to better delineate quaternary features within the watershed.

The overburden thickness map is also an important indicator of areas with high potential for contamination. Thin overburden may provide little or no protection to the underlying bedrock aquifer.

4.4 Sand and Gravel Thickness

The last map that addresses the physical subsurface materials is the sand and gravel thickness map. The map was produced by summing the total thickness of sand and/or gravel encountered when drilling each well in the watershed. The thickest sand and gravel accumulations tend to be associated with the moraines in the watershed.

The sand and gravel maps can be used by water managers in the watershed to focus attention on the more permeable aquifer materials that might be important in conveying groundwater through the subsurface. The areas of thicker sand and gravel accumulation could be important targets for municipal wells, or alternately they could be areas that have significant linkages with the surface water system. In any case the mapping of these aquifer systems is an important step in defining the groundwater regime of the watershed. The mapping of sand and gravel accumulations also has some use to the aggregate industry for locating potential aggregate targets.

4.5 Water Table

Having evaluated the physical composition of the subsurface materials, the study then focussed on evaluating the hydraulic conditions in the subsurface. Several maps were produced for this purpose. Groundwater flows in response to energy gradients, from areas where fluid potential energy is high to areas where the fluid potential energy is low. The static water level or hydraulic head in a well is a measure of the fluid potential at that location. Therefore, by contouring a map of the static water levels in wells across a region, one can determine the direction of groundwater movement in the subsurface. Groundwater will move perpendicular to contours of equal hydraulic head.

In this part of southern Ontario, topography is recognized as the major driving force behind shallow groundwater movement. Groundwater generally flows from areas where the topography is high to adjacent areas where the topography is lower. Because the topographical highs are generally subdued in southern Ontario (i.e. no mountains, etc.) there is no strong driving force that directs groundwater to great depths in the subsurface. For this reason the deeper bedrock groundwaters in the Grand River Watershed are generally of poor quality, having high concentrations of dissolved ions including chloride, sulphate, and sodium. The pore waters have been in the subsurface for extended periods of time (at least 10's of thousands of years) with no meteoric water influx to provide dilution. Over the years the waters in these deeper more stagnant systems have chemically reacted with the bedrock to produce the poor quality brine waters.

Difficulties arise when static water levels within different aquifer systems are plotted on the same map. If a particular aquifer has water levels that are influenced by some anomalous subsurface conditions then the resulting contour map of static water levels might convey incorrect information.

Because of the complexity within the overburden glacial materials, it is inappropriate, at the scale of the Grand River Watershed, to plot the hydraulic head configuration for specific aquifers. The overburden aquifers are simply too numerous and discontinuous to delineate at a regional scale. In the past hydrogeologists have frequently plotted the static water levels from all bedrock wells on one map and the static water levels from all overburden wells on a second map. It was felt that this was not entirely appropriate since:

- bedrock can occur either right at ground surface (in which case the static water levels in wells represent the water table); or
- bedrock can occur at some depth below a thick overburden package (in which case the water levels would reflect a deeper potentiometric surface).

By indiscriminately dividing the wells into bedrock versus overburden wells, the hydraulic head values between deeper and shallower systems were frequently confused using this approach.

Two surfaces of static water levels were produced for this study. All shallow wells (less than 25 m deep) were used to produce a map of the water table. The surface is believed to closely represent the true elevation of the unconfined water table. However, in some areas of the watershed there are thick till units at ground surface. Wells in these areas pass through the low permeability till to seek water in deeper permeable aquifers. In these locations the true water table might be located at a higher elevation within the surficial till unit. However, at a regional scale the mapped water table is believed to be fairly representative of the actual conditions. Groundwater in the shallow subsurface moves perpendicular to the contour lines shown on the water table map surface.

It should be pointed out that the water table map and the potentiometric surface map (as well as any maps produced by using these two surfaces) represent average conditions. The water table in southern Ontario is known to fluctuate considerably, both in response to seasonal climate changes and in response to longer term precipitation trends. The wells used to produce the maps have been drilled both during wet and dry years and at different times of the season. As a result, the derived elevation of the water table and of the potentiometric surface (discussed below) are representative of average conditions.

The water table map (and the associated potentiometric surface map (discussed below)) can be used by planners to gain an appreciation of groundwater flow directions. Proposed developments can be quickly assessed to determine upgradient and downgradient users of the groundwater resource. Upon review of an application, appropriate precautions can be implemented to protect downgradient groundwater users.

4.6 Potentiometric Surface

The second static water level surface was produced using the deeper wells in the watershed (greater than 40 m). The potentiometric surface map indicates that the deeper groundwaters generally move in a similar direction to the shallow groundwaters with the highest potentiometric elevations found in the north part of the watershed. Lower hydraulic head values are found in the south parts of the watershed. The major river systems and the Dundas Valley are also observed to influence groundwater movement in the deeper subsurface units within the watershed.

4.7 Vertical Gradients

Once the water table map and the potentiometric surface map were complete they were used to gain an insight into the likely areas of groundwater recharge and discharge. Groundwater not only moves laterally in response to differences in hydraulic head, but also moves vertically. Recharge areas are those areas where water is moving downwards from the ground surface to recharge the groundwater system. Alternatively, discharge areas are those areas where groundwater is moving from the deeper subsurface towards the ground surface to discharge to the surface environment. Since groundwater moves in response to energy gradients, the deep and the shallow hydraulic head values can be compared to see whether groundwater would have a tendency to move vertically upwards or downwards.

The potentiometric surface was subtracted from the water table map to produce a map of the difference in these two surfaces. Figure 3 shows those areas where the water table is found to be at a higher elevation than the potentiometric surface thus indicating those areas where there is a tendency for shallow groundwaters to move to depth; potential groundwater recharge areas.

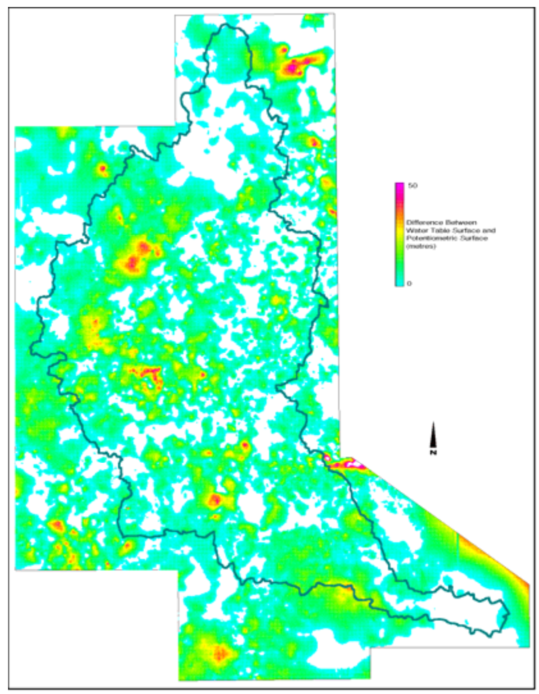

Figure 3. Areas showing downward hydraulic gradients

On the other hand, Figure 4 illustrates those areas where the water table is found to be at a lower elevation than the potentiometric surface, thus indicating those areas where there is a tendency for deeper groundwater to move upwards; potential discharge areas. Examination of these two figures indicates that there are only subtle differences in the elevations of these two surfaces. This is indicated by the low magnitude of the difference between the water table and potentiometric surface elevations. The higher moraine areas are associated with stronger downward gradients indicating a higher potential for groundwater recharge. Upward gradients are less prevalent across the watershed and are often found at the toe of moraines (e.g. the eastern toe of the Paris Moraine in the area to the east of Cambridge) or other topographic highs (e..g. adjacent to the Dundalk bedrock high to the north). Other areas of upward gradients correspond to topographically lower areas, often associated with wetlands (e.g. parts of the Beverly Swamp) or river valleys.

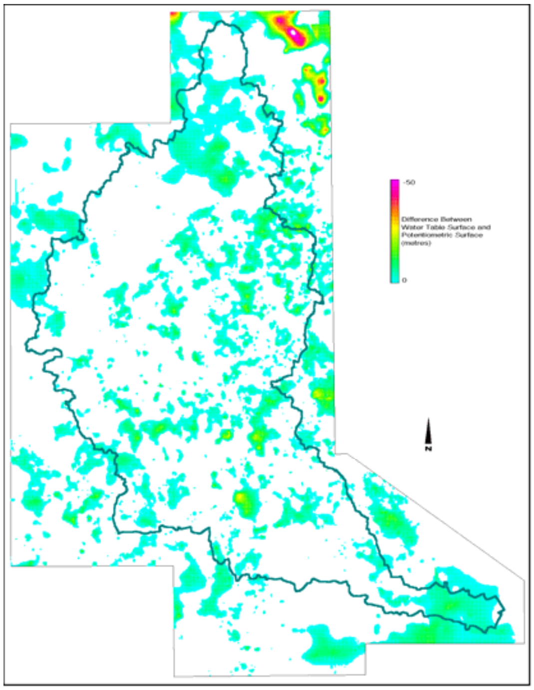

Figure 4. Areas showing an upward vertical gradient

Planners can use the vertical gradient mapping to identify particular recharge areas that require protection from development. Alternatively, best management practices can be required in these areas so that the recharge function of a particular property is maintained. The identified areas of upward gradients, which have the potential for cold water aquatic habitat, can also be identified in the planning process for protection.

4.8 Potential Discharge Areas

An additional methodology for delineating groundwater discharge areas was also used, whereby the kriged water table was compared to the ground surface to look for those areas where the water table was at a higher elevation than the ground surface. The derived map identifies specific reaches of stream corridors that appear to be more active discharge areas. The mapped areas are much more coincident with the stream corridors than the potential discharge areas delineated in Figure 4. The stream segments mapped through this second process have a strong potential for active cold water discharge and therefore have a similar sensitivity to the areas of upward vertical gradients (Figure 4).

4.9 Depth To Water Table; Depth to First Aquifer; Areas Vulnerable to Contamination

In assessing the vulnerability of a particular area to contamination, one readily available parameter is the depth to the water table. This can be obtained from the water well records. If the water table is at a very shallow depth below the ground surface then any contaminant spilled or applied at the surface can very quickly move to degrade groundwater quality. On the other hand a deeper water table provides a greater unsaturated thickness above the water table. This would allow for aerobic degradation and attenuation of contaminants prior to their arrival at the water table surface. This longer period in the unsaturated zone also would provide additional time for action to be taken to cleanup a known spill before groundwater degradation occurs.

The depth to the water table was calculated by subtracting the constructed water table surface from the OBM ground surface. In general, those areas of high moraines (north and west areas) have a greater depth to the water table than do the areas associated with clay or bedrock plains (south and east areas).

The second parameter that was used to determine the vulnerability of the groundwater system to contamination was the depth to the first aquifer. For the purpose of constructing the map an aquifer was considered to be: i) a sand or gravel unit greater than 3 m in thickness; or ii) one of the bedrock units (excluding shale). The depth to the uppermost aquifer was determined for each well in the water well record database. This depth was then kriged to construct the surface. Where the uppermost aquifer is at a shallow depth, contaminants can quickly move from the ground surface into the aquifer.

The two previous parameters were combined to delineate those areas where the groundwater was deemed more vulnerable to surficial contamination. The depth to the first aquifer was added to the depth to the water table. Figure 5 shows all of those areas where the combined value is less than 10. In these areas the water table and the uppermost aquifer are generally within 5 m of the ground surface.

This map can be used by planners in assessing development applications. High-risk land uses can be dissuaded from establishing in these more sensitive areas. Policies can be developed requiring the locating of high risk land uses into areas where the groundwater sensitivity is particularly low.

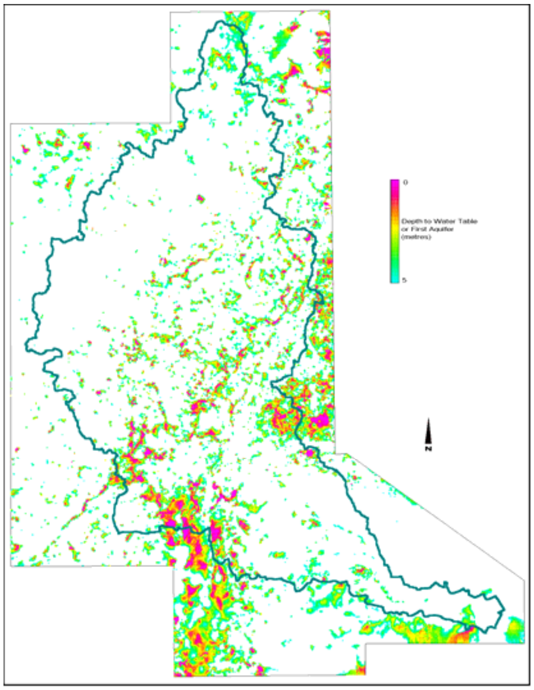

Figure 5. Areas vulnerable to contamination

5. Conclusions

To date, hydrogeologists have largely been ineffective in conveying clear concise groundwater related information to land-use decision makers. As a direct result, groundwater has not been properly considered when land use decisions are made. The Grand River Hydrogeological study is an example of a regional study that can be used to readily incorporate groundwater into a planning framework. The maps produced as a result of the study clearly convey information pertaining to both the physical make-up of the subsurface, as well as to the groundwater hydrodynamics of the watershed.

Specific examples of some of the results of the study include the mapped bedrock valley features, which might be significant corridors for conducting groundwater within the watershed. Maps showing areas vulnerable to contamination can be used to assess future land development applications. Sand and gravel thickness mapping can be used to identify aquifers within the Grand River basin. The vertical gradient mapping can be used to identify significant recharge areas in need of protection. Groundwater discharge maps can focus cold water fisheries managers to locations for habitat preservation.

The present planning climate in Ontario has seen a shift in responsibility for land use decisions away from the provincial level of government to the local level. Given the inability of local planners to rely on provincial experts, there is a greater need for planners to have readily available groundwater mapping that can be used to guide decisions that must be made in a timely manner. In the past, hydrogeological studies have been carried out in a reactionary approach, by the proponent when development applications are submitted. There is very little information to guide the requirements of the requested study. The Grand River study has proactively mapped the groundwater water regime of the basin and can now be used by planners at all levels to guide future land use decisions.