Environment Canada
Water Science and Technology Directorate

Direction générale des sciences et de la technologie, eau
Environnement Canada

Regional groundwater assessment of the Grand River watershed

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98-260

MANAGEMENT PERSPECTIVE

Title:	Regional groundwater assessment of the Grand River watershed
Author(s):	**Piggott, A.R.**
NWRI Publication #:	98-260
Citation:	51st Canadian Geotechnical Conference
EC Priority/Issue:	This work contributes to Sub-objective 3.6 of the Great Lakes 2000 program, Prevent or Mitigate Climate Impacts. This work began in fiscal year 1994/1995 and will be completed in fiscal year 1999/2000. This paper is the second publication resulting from this collaborative research initiative.
Current Status:	The Grand River watershed is a large and nationally significant watershed and is situated in southwestern Ontario. Surface water drainage from the watershed enters Lake Erie at Port Maitland. The population of the watershed is located at some distance from the Great Lakes and is largely dependent on groundwater as a water supply relative to conditions elsewhere in southern Ontario. Shifting patterns of water availability due to climate change and variability, and rapid population growth, may impact the sustainable development of the groundwater resources of the watershed and the integrity of the Grand River ecosystem. Characterization and numerical modelling procedures are being developed to estimate the impacts of climate change on the groundwater resources of the watershed. These results will also be used to formulate a water management strategy that seeks an optimal balance of ground and surface water development subject to constraints on the maintenance of the aquatic ecosystem.
Next Steps:	Research will continue to focus on the characterization of the region and the integration of these results within regional scale groundwater modelling.

ABSTRACT

Climate change and variability are likely to have a pronounced impact on the hydrologic cycle. A research initiative has been established to determine the potential impacts of climate change on groundwater conditions within the Grand River watershed in southwestern Ontario. The approach that is being developed is to characterize the region from a groundwater perspective using meteorologic, hydrologic, and hydrogeologic data and to apply these results in conjunction with numerical modelling to estimate the impacts of climate change. Spatial characterization indicates the variation of groundwater conditions across the region while temporal analyses reveal relations among meteorologic, hydrologic, and hydrogeologic processes. Similarly, numerical modelling allows groundwater levels and discharge to surface water features to be determined in a spatial and temporal context as a function of net groundwater recharge.

REGIONAL GROUNDWATER ASSESSMENT OF THE GRAND RIVER WATERSHED

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ABSTRACT Climate change and variability are likely to have a pronounced impact on the hydrologic cycle. A research initiative has been established to determine the potential impacts of climate change on groundwater conditions within the Grand River watershed in southwestern Ontario. The approach that is being developed is to characterize the region from a groundwater perspective using meteorologic, hydrologic, and hydrogeologic data and to apply these results in conjunction with numerical modelling to estimate the impacts of climate change. Spatial characterization indicates the variation of groundwater conditions across the region while temporal analyses reveal relations among meteorologic, hydrologic, and hydrogeologic processes. Similarly, numerical modelling allows groundwater levels and discharge to surface water features to be determined in a spatial and temporal context as a function of net groundwater recharge.

RÉSUMÉ Les changements ainsi que les variations climatiques auront probablement des impacts importants sur le cycle hydrologique. Pour évaluer l'impact de ces variations climatiques sur l'eau souterraine du bassin de la rivière Grand au sud-ouest de l'Ontario, une initiative de recherche a été établie. Pour aborder la situation de la perspective des eaux souterraines, il est nécessaire de caractériser la région en utilisant des données météorologiques, hydrologiques, et hydrogéologiques et d'appliquer ces résultats en combinaison avec la modélisation numérique pour estimer l'impact de ces changements et variations climatiques. La caractérisation spatiale indique la variation des eaux souterraines à travers la région, tandis que les analyses temporelles révèlent les rapports entre les processus météorologiques, hydrologiques et hydrogéologiques. De plus, la modélisation numérique permet que le niveau d'eau souterraine et la décharge de la nappe souterraine aux eaux de surface soient déterminés dans un contexte spatial et temporel en fonction de l'alimentation nette de la nappe.

1. INTRODUCTION

The Grand River watershed is located in southwestern Ontario and extends approximately 155 km north to south from Dundalk to Port Maitland and 75 km east to west from Acton to Woodstock. The land area of the watershed is 6800 km^2 and the estimated annual discharge of the Grand River into Lake Erie at Port Maitland is 2.2x10^9 m^3. These values translate to an average annual runoff of 330 mm relative to an average of 950 mm of precipitation. The topography of the watershed is pronounced for southwestern Ontario with elevation varying from 171 m at Lake Erie to 521 m near Dundalk. The watershed is characterized by mixed land use and an increasingly urban population that is expected to exceed one million within 25 years.

Historically, the Grand River was known for flooding during the spring and for degraded water quality during the summer, the latter resulting from the combination of untreated waste water discharge and low surface water flow. The Grand River Conservation Authority was formed in 1938 in response to these issues and has since been responsible for the restoration of the Grand River ecosystem through the operation of reservoirs that both mitigate flooding and augment flow, and through the promotion of land and water conservation practices. Population growth and shifting patterns of water availability due to climate change are now regarded as challenges to the maintenance of the Grand River ecosystem and to sustainable development within the watershed. Southam et al. (1997) indicate that various projections of climate change and water use translate to severe impacts on surface water flows. The majority of the population of the watershed is located at some distance from the Great Lakes and therefore groundwater is widely developed as a water supply relative to other areas of southern Ontario. Despite the regional importance of groundwater as a water supply, there is limited knowledge of groundwater conditions, ground and surface water interaction, and the groundwater impacts that may develop due to climate change. McLaren and Sudicky (1993) indicate that the potential impacts of climate change on the groundwater resources of the Grand River watershed include a decline in groundwater levels and reduced groundwater discharge to surface water features. Lower groundwater levels may lead to diminished available drawdown and therefore to lower well yields. Reduced discharge may translate to a range of detrimental impacts on aquatic habitat and the capacity of rivers to assimilate waste water discharge, particularly during seasonal periods of low flow when a substantial portion of the flow in the lower Grand River is presently attributed to waste water discharge.

A research initiative focusing on the impacts of climate change and variability on the groundwater resources of the Grand River watershed has been formed among the

Water Issues Division and National Water Research Institute of Environment Canada, the Grand River Conservation Authority, and various stakeholder groups. Funding for the initiative is provided by Environment Canada through Sub-objective 3.6 of the Great Lakes 2000 program and through in-kind support from the participating agencies. The research approach that is being developed is based on the characterization of groundwater conditions and numerical modelling of groundwater flow and surface water interaction. This paper describes the progress that has been realized to date in the assembly of data and the characterization and modelling of groundwater conditions.

2. GROUNDWATER CHARACTERIZATION

Figure 1 illustrates the boundaries that are recognized in the groundwater study. The limits of the Grand River watershed are innermost and define the region where the determination of impacts is required. Unlike surface flow, groundwater flow is not fully constrained by topography and changes to groundwater conditions that occur outside of the watershed may result in impacts within the watershed. An extended study region with a land area of 27,600 km^2 that includes the counties of Brant, Dufferin, Elgin, Grey, Middlesex, Oxford, Perth, and Wellington and the regional municipalities of Haldimand-Norfolk, Halton, Hamilton-Wentworth, Niagara, and Waterloo is used to provide a buffer for the determination of impacts. Data collection within the outermost geographic boundaries links this study westward to an ongoing study of groundwater flow and transport in the counties of Essex, Kent, and Lambton and eastward to an emerging study that will include climate change impacts in Simcoe County; the regional municipalities of Durham, Peel, and York; and Metropolitan Toronto.

The data required to complete the characterization and modelling exercises are being extracted from various sources. The principal source of these data are water well construction records collected by the Ontario Ministry of the Environment (MOE). These records include a wide array of physiographic, geologic, hydrogeologic, and water supply and demand data. A total of 84,823 water well construction records spanning the period of 1908 to 1992 were obtained for the extended study region. Observation well data collected and published by the MOE during the period of 1974 to 1980 are available for 92 wells in the extended study region and include daily measurements of the depth to the static groundwater level. Meteorologic data were obtained from the Atmospheric Environment Service of Environment Canada for the period of 1970 to 1997 for 57 climate stations across southwestern Ontario. These data include daily measurements of temperature, precipitation, and evaporation and hourly measurements of radiation, illumination, humidity, and sunshine. Census of population and agriculture data for 168 census subdivisions for the period of 1951 to 1991 were collected from reports published by Statistics Canada. Hydrologic data including daily measurements of surface water flow were obtained from the Water Survey of Canada. Supporting data such as digital maps of bedrock and quaternary geology, terrain data, and digital topographic maps have also been assembled.

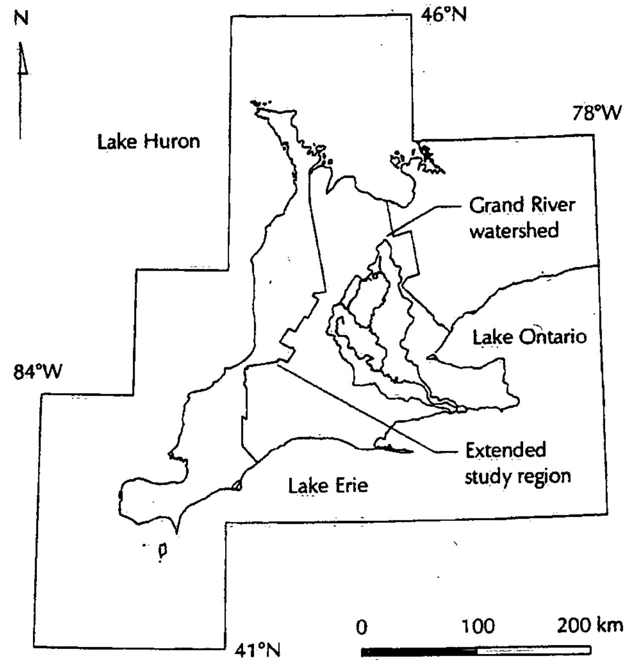


Figure 1. Locations of the Grand River watershed and extended study region.

Characterization of groundwater conditions is advancing in two areas. First, analyses are being conducted to determine the spatial variation of conditions across the region. Data is extracted from the database of water well construction records using queries that are designed to extract meaningful information while recognizing the uncertainty that is associated with the data. These parameters are then projected onto a uniform grid, or raster, using spatial interpolation. The multivariate statistical method of principal components analysis (PCA) is used to determine interdependence among the parameters where these relations reflect details of the hydrogeology of the region and the mechanics of the groundwater flow regime. The results of PCA are used to examine spatial patterns and perform classification and groundwater mapping. Figure 2 illustrates the results of a PCA where interdependence was detected among specific capacity and the fraction of permeable materials (i.e., sand and gravel) in the overburden, and among the depth to the static groundwater level and to bedrock. The two principal components, which are weighted measures of the depth and productivity of groundwater conditions, were classified within a GIS setting to form the four grouping shown in Figure 2. There is an obvious spatial pattern among the results that conforms to the known overburden and bedrock geologies of the region and to the distribution of topographic features such as river valleys and glacial landforms. PCA appears to be an effective method of data integration and continuing research will focus on the extension of the method to include meteorologic, water supply and demand, hydrologic, and remote sensing information.

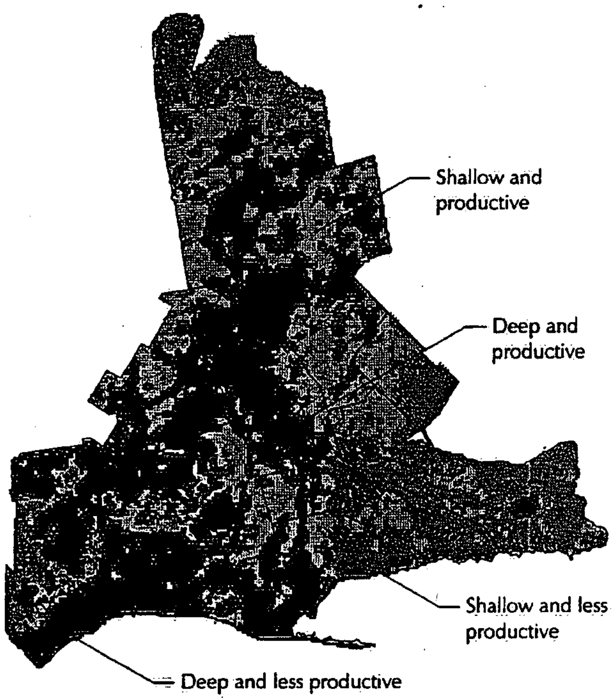


Figure 2. Spatial variation of groundwater conditions determined by PCA.

Important results are also being derived from the characterization of temporal relations among the observation well, meteorologic, and hydrologic data. Implementation of these data sets within a relational database allow the data to be aligned for plotting and time series analysis. Figure 3 shows the daily variation of the mean temperature and total precipitation, flow in the Grand River, and depth to the static groundwater level during 1980 for stations located north of Marsville. The piece-wise horizontal line across the precipitation data indicates monthly averages of daily values and suggests a relatively uniform distribution of precipitation throughout the year. The land area of the surface water catchment is 694 km^2. The observation well is situated at a depth of 10.7 m in a sand and clay aquifer and penetrates 6.1 m of gravely and sandy clay overburden. Seasonal fluctuations of groundwater levels and surface water flow are apparent. The decline of groundwater levels during the winter is the result of limited recharge coupled to groundwater discharge to the river, as indicated by the extended period of base flow. The gradual reduction in surface flow during the winter is evidence of diminishing groundwater discharge to the river due to the subsidence of groundwater levels in proportion to discharge. The most prominent recharge and surface runoff event occurred during the early spring and is coincident with the melting of snow accumulated during the winter. The steady decline of groundwater levels during the late spring, summer, and early fall is the result of a recharge deficit due to elevated evapotranspiration. Finally, recharge and increased surface flow during the late fall are the result of reduced evapotranspiration. Time series analysis and modelling of this form of data will yield an improved understanding of the temporal aspects of ground and surface water flow, and the manner in which the interdependence of these regimes can be best represented within the numerical modelling effort.

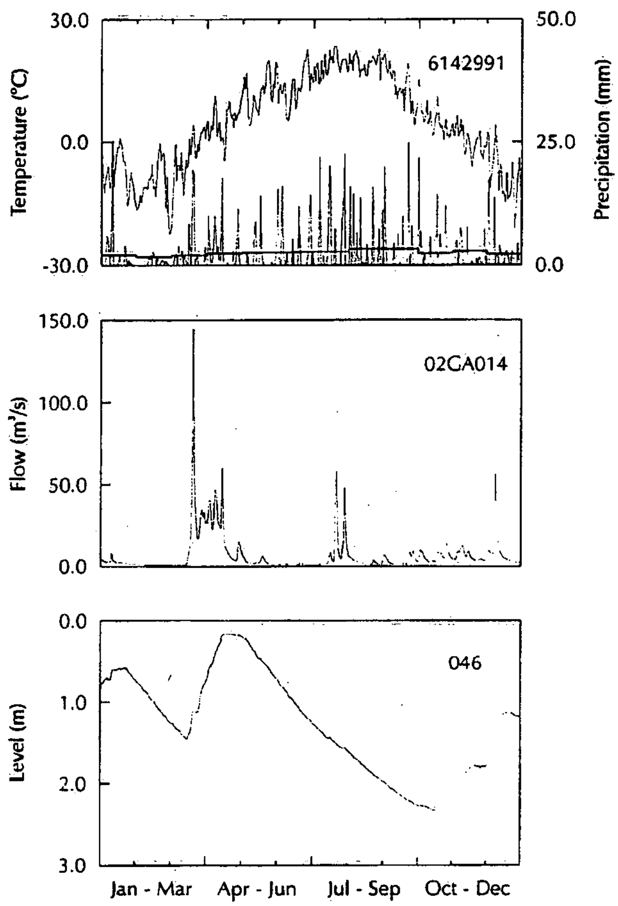


Figure 3. Daily variation of temperature, precipitation, stream flow, and groundwater levels.

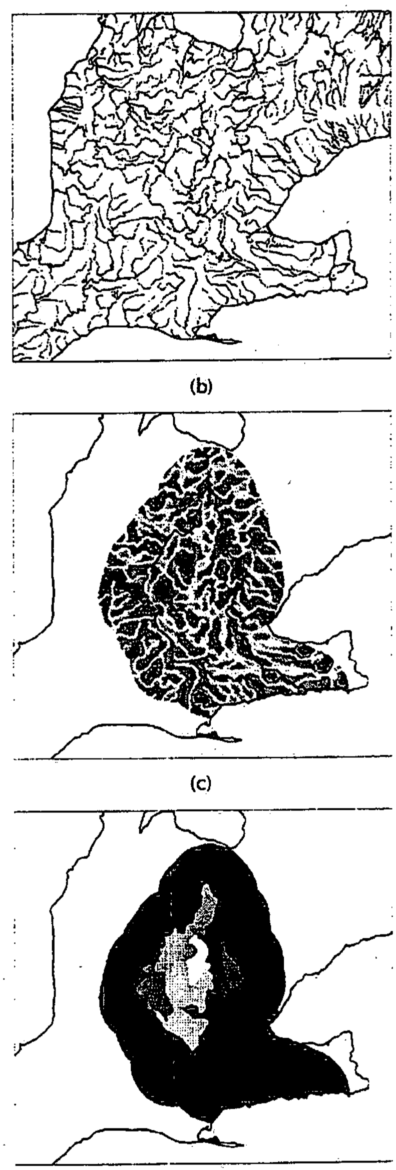
3. NUMERICAL MODELLING

Estimation of groundwater flow using numerical modelling forms a quantitative relation between net groundwater recharge, groundwater levels, and surface water flow where recharge is a function if meteorologic, hydrologic, and hydrogeologic conditions and water use. An algorithm for regional, two-dimensional, transient groundwater flow has been developed using a implicit finite difference formulation (Huyakorn and Pinder 1983). The algorithm is compatible with the GRASS GIS (USACERL 1993) in order to facilitate pre- and post-processing and visualization of the modelling data. A high performance solver from the SLATEC mathematical library is used to manage the large systems of equations that result from the spatial scale and resolution that are required to accurately represent the geometry of the region. The algorithm is referred to as RASTFDM in reference to the raster implementation of the finite difference method.

Figure 4 depicts a sequence of preliminary groundwater modelling results. Figure 4a shows the distribution of the larger surface water features of southwestern Ontario. The dimensions of the indicated region are 255 km from north to south and 275 km from east to west. Raster maps with a uniform spatial resolution of 250 m were prepared for input to RASTFDM. Arbitrary, unit values for transmissivity, storativity, and net groundwater recharge were assumed and hydraulic boundary conditions of zero induced hydraulic head were prescribed along each of the surface water features. The latter represents intimate connection of the ground and surface water flow regimes along the surface water features. Figure 4b shows the steady state distribution of groundwater levels determined for a 30 km buffer surrounding the watershed. The computed levels generally indicate flow toward the most proximal surface water feature. Figure 4c shows the distribution of groundwater catchments determined from the computed hydraulic head data for 12 stream gauges and for the outlet of the Grand River. These catchments were determined using a particle tracking procedure (Huyakorn and Pinder 1983) in which groundwater flow is traced from recharge at each pixel location to discharge at a surface water feature that is tributary to the gauge. This approach allows the results of groundwater modelling to be linked to surface water models that calculate flow at the gauges. In this simple scenario, the groundwater catchments are defined entirely by the pattern of surface water features and approximate the known surface catchments of the gauges. This result will vary as more plausible distributions of hydrogeologic properties and patterns of ground and surface water interaction are developed.

The temporal variation of groundwater discharge due to an instantaneous increase in aquifer recharge is indicated in Figure 5. This response illustrates the potential variation of the groundwater component of surface water flow resulting from a shift in recharge due to climate change or varying groundwater consumption; a decrease in recharge would result in a reduction in discharge with equivalent timing. Here, discharge is accumulated along the tributaries to stream gauges on the Grand River at Galt (02GA003), the Nith River at New Hamburg (02GA018) and the outlet of the Grand River at Port Maitland. Discharge is indicated in fractional form relative to the total, steady state change in discharge at the outlet. Time is measured relative to the applied change in recharge, and is expressed in pseudo-days as a result of the assumption of arbitrary values for transmissivity and storativity, both of which regulate the timing of discharge.

(a)



(b)

(c)

Figure 4. Selected modelling results illustrating steady state groundwater flow.

It is useful to estimate the actual timing of the response in order to predict the lag that may occur between a change in groundwater recharge and the corresponding change in discharge. A regional scale value for the transmissivity of the watershed may be estimated from the composition of the bedrock since the bedrock formations are likely to be significantly more conductive than the overburden deposits. Analyses of bedrock geology maps indicate that the watershed is predominantly underlain by the Guelph and Salina Formations, both of which have a transmissivity on the order of 10 m^2/day (Singer et al. 1997). A regional scale estimate of storativity of 0.01 is intermediate to confined and unconfined conditions. Figure 5 indicates that a fractional discharge of 0.5 at the outlet occurs at 2×10^6 pseudo-days. Scaling this result using the estimated values of transmissivity and storativity returns 2000 days as a metric of the actual response of groundwater discharge to a change in recharge. It is possible that refined estimates of this timing may differ by more than an order of magnitude. Regardless, this result suggests that the impacts of a change in recharge may develop over a period of months to decades, well within the scope of human recognition.

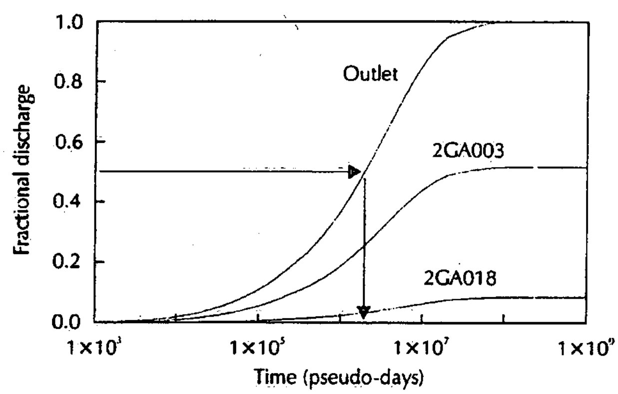


Figure 5. Computed groundwater discharge at three stream gauge locations.

4. CONCLUSIONS

There is a consensus that climate change and variability will result in significant impacts on the hydrologic cycle, including groundwater resources. Further, accurately responding to these impacts is thought to be critical to the successful adaptation of infrastructure and human behaviour to climate change. Within the Grand River watershed, these impacts are likely to be concurrent with population growth, urban development, and increased water consumption. This paper briefly described the progress that has been achieved in developing a regional model of groundwater conditions within the Grand River watershed in the context of estimating the impacts of climate change. Various sources of data and methods of analysis have been identified and a numerical model of groundwater flow and surface water interaction has been established.

Continuing research will focus on calibration of the numerical model relative to the data and emerging conceptual relations, and on post-processing of groundwater modelling results into a form that is appropriate for management of the water resources of the region using scenario optimization. The sustainable development and, in some cases, restoration of aquatic ecosystems requires a detailed understanding of the interaction of the components of the hydrologic cycle, and it is now recognized that the role of groundwater at regional scales is rather poorly understood. It is expected that the methods and results developed in this study will be applicable elsewhere in Ontario, and nationally, where similar forms of data are available.

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