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Prediction of climate and water use impacts on Groundwater resources

By:

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MANAGEMENT PERSPECTIVE

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EC Priority/Issue:	This research contributes to the *Nature* business line with the outcome *Conservation of biodiversity in healthy ecosystems* and result *Priority ecosystems are conserved and restored.* The sub-result of this research is support of the Great Lakes 2000 program, sub-objective 3.6, prevent or mitigate climate impacts. This research began in the fiscal year 1994/1995 and will be completed in the fiscal year 1999/2000. Continuation and elaboration of this line of research over an extended study region is probable, beginning in the fiscal year 1999/2000 and potentially using resources from the Climate Change Action Fund. This paper is the fifth publication resulting from this collaborative research initiative.
Current Status:	The Grand River watershed is a nationally significant watershed that discharges into Lake Erie at Port Maitland. The population of the watershed 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, population growth, and evolution of the agricultural and industrial sectors may impact the sustainable development of the groundwater resources of the watershed and the integrity of the Grand River ecosystem. Numerical modelling procedures are being developed to estimate the impacts of climate change and water use on the groundwater resources of the watershed. These results will also be used to formulate an integrated water resources management strategy that optimally balances ground and surface water development subject to constraints on the maintenance of the aquatic ecosystem.
Next Steps:	Continuing research will focus on the application of the modelling procedure to the analysis of climate and water use scenarios.

PREDICTION OF CLIMATE AND WATER USE IMPACTS ON GROUNDWATER RESOURCES

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ABSTRACT A numerical modelling procedure that estimates the response of groundwater resources to climate and water use is introduced. The procedure is based on temporal and spatial superposition of response functions that relate groundwater recharge within an array of source areas to groundwater levels and discharge within an array of destination areas. The design of the modelling procedure and formulation of spatial textures for the source and destination areas are described. Selected modelling results are presented and illustrate the performance of the procedure.

RÉSUMÉ Un procédé de modelant numérique qui estime la réponse des ressources d'eaux souterraines au climat et à l'utilisation de l'eau est présenté. Le procédé est basé sur la superposition temporelle et spatiale des fonctions de réponse qui associent la recharge d'eaux souterraines dans un choix de zones de source aux niveaux d'eaux souterraines et la déchargent dans un choix de zones de destination. Le dessein du procédé et de la formulation modelants des textures spatiales pour la source et les zones de destination sont décrites. Choisi modelant des résultats sont présentés et illustrent l'exécution du procédé.

1. INTRODUCTION

Groundwater is an important water supply across Canada and, as an element of the hydrologic cycle, is responsive to climate change (Hofmann et al. 1998). For example, the combination of below normal precipitation and above normal temperatures persisted across southern Ontario from mid 1997 through, at least, the spring of 1999 and resulted in widespread reports of diminished groundwater levels and base flow in rivers. Thus, there is tangible evidence of the interaction of climate and groundwater resources where pronounced ecosystem, societal, and economic implications are manifest during prolonged periods of reduced water availability. While the response of regional climatic conditions to factors such as increased concentrations of green house gases and aerosols is not yet known with certainty, climate models indicate that the response may include a shift in the occurrence of episodes of reduced water availability. Further, the consumptive use of groundwater as a municipal, industrial, and agricultural water supply similarly impacts groundwater conditions, will increase in proportion to growth in these sectors, and may also expand in response to climate change.

This paper outlines the progress that has been achieved in developing a modelling procedure that represents the interaction of groundwater resources, climate, and water use. The procedure uses a groundwater flow model to predict groundwater levels and discharge as a function of groundwater recharge. Recharge is distributed using a composite of municipal and geologic spatial textures. Output groundwater levels and discharge are summarized using municipal and hydrologic textures. Development of the modelling procedure is one component of an effort to estimate the impacts of climate change on the groundwater resources of the Grand River watershed. It is expected that the procedure, and selected results, will be applicable elsewhere in Canada, and internationally.

Figure 1 indicates the location of the study region within southern Ontario. The region of interest is shaded and extends 145 km from west to east and 170 km from south to north over an area of 24,650 km^2. The Grand River is located at the centre of the indicated region. Ground and surface water discharge from the 6,770 km^2 drainage area of the watershed enter Lake Erie at Port Maitland at a spatially and annually averaged rate of 0.33 m/year in response to similarly averaged precipitation of 0.95 m/year. Modelling results are required only where variations in recharge influence hydrologic conditions within the Grand River. Preliminary modelling results (Piggott 1998) indicate that the areas where groundwater recharge contributes discharge to the Grand River are contained within a region that includes the watershed and a 10 km buffer zone, as shown in Figure 1. Subsequent calculations are restricted to this region, which has an area of 11,590 km^2.

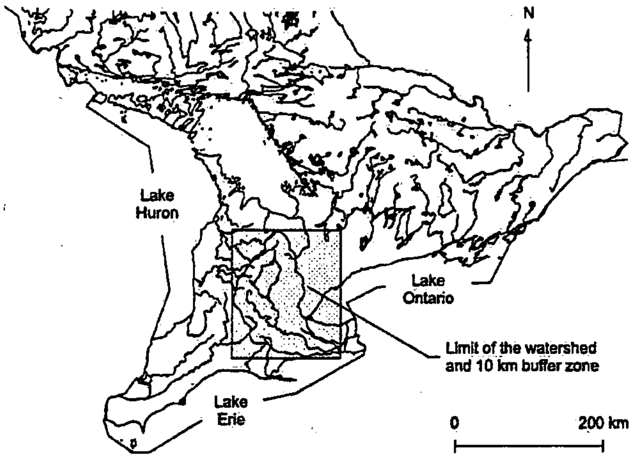

Figure 1. Location of the study region.

2. FORMULATION OF THE MODELLING PROCEDURE

Evolution of the modelling procedure has been guided by the large extent and considerable geographic and geologic complexity of the region, the need to link the procedure to existing representations of surface water flow and water use, and the goal of implementing the procedure as a method of integrated water resource management. The degree of abstraction that is required to achieve these objectives is a recognized limitation. Regardless, the procedure that is outlined in this paper provides a novel, if somewhat pedagogic, mechanism for regional modelling of coupled hydrologic and hydrogeologic processes.

Two-dimensional, transient, confined groundwater flow is presently assumed across the study region where the flow regime is hydraulically connected to all of the surface water features that are indicated on 1:250,000 scale topographic maps of the region. Figure 2a indicates the distribution of these features. It is expected that delineation of the features at this scale is an indicator of the persistence of flow within the features and of the incision of the features into the terrain, thereby establishing a hydraulic connection to the groundwater flow regime. This conceptual model ensures that the response of the groundwater flow regime is linear with respect to the input hydrogeologic parameters and distribution of recharge and therefore enables the use of scaling relations and methods of superposition.

Figure 2b indicates 14 tributary areas for surface flow that correspond to the 12 stream gauge locations shown in the figure, the outlet of the Grand River to Lake Erie, and surface water features that occur within the buffer zone but do not discharge to the Grand River. Groundwater discharge to surface water features is integrated using this hydrologic texture, thereby allowing discharge to be indexed relative to the stream gauges and providing the required linkage to surface water flow. Figure 2c illustrates the prominent terrain features of the region, including the Oak Ridges Moraine, which roughly parallels the northern shore of Lake Ontario, the Dundalk Upland, which forms the headwaters of the Grand River, and the Niagara Escarpment, which occurs along the eastern limit of the modelled region. The incision of the Grand River into the terrain of the region is particularly apparent in the lower portion of the watershed.

The groundwater flow model is used to relate the net rate of groundwater recharge to groundwater levels and discharge where net recharge is defined as infiltration minus the rates of evapotranspiration and groundwater withdrawal. This relation is expressed in a quantitative manner using a series of response functions where these functions are determined by serially modelling a finite recharge event within each of an array of source areas and aggregating the computed response within each of an array of destination areas. The cumulative response within a prescribed destination due to a time series of recharge events within a prescribed source is determined by temporal superposition, or convolution, of the time series and associated response function. Similarly, the cumulative response due to spatially distributed recharge is determined by superposition of the convoluted responses for each source. This process is summarized in the deceptively simple form

$$[1] \qquad F_i(t) = \sum_{j=1}^{n} \int_{0}^{t} r_j(\lambda)\, f_{i,j}(t-\lambda)\, d\lambda$$

where $F_i(t)$ is the variation of either groundwater levels or discharge within destination i, $r_j(\lambda)$ is the time dependent rate of recharge within source j, $f_{i,j}(t-\lambda)$ is the computed response function relating the source and destination, λ is an integration parameter, and n is the number of sources. .

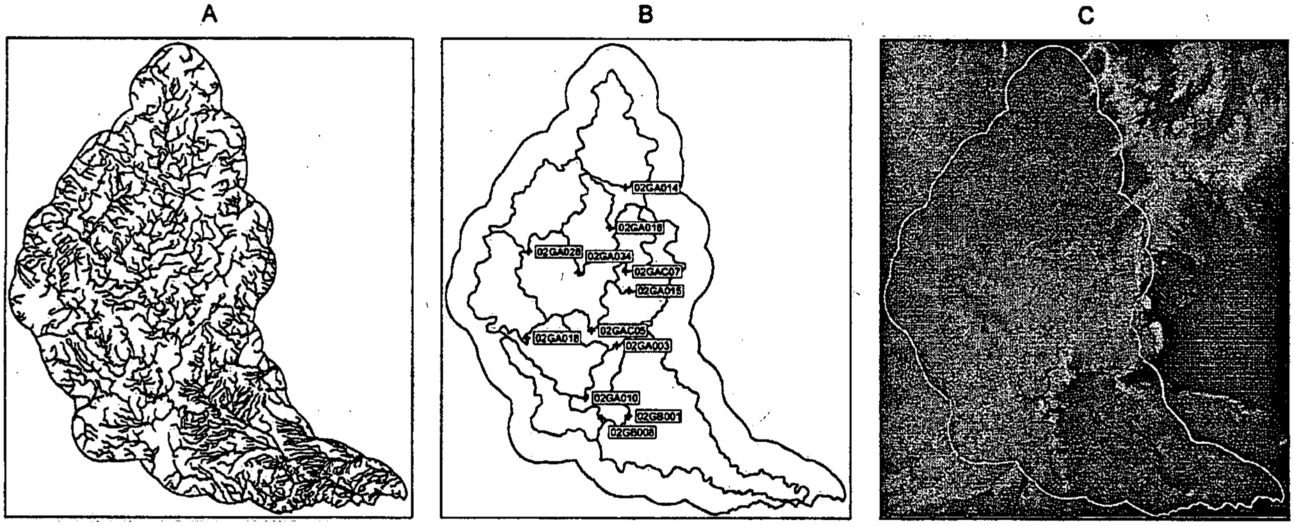

Figure 2. Illustration of the surface hydrology and terrain of the study region.

An implicit finite difference formulation (e.g., Huyakorn and Pinder 1983) with the form

$$[2] \qquad \mathbf{q}_{i+1} = \mathbf{K}\,\mathbf{h}_{i+1} + \mathbf{S}_{i+1}(\mathbf{h}_{i+1} - \mathbf{h}_i)$$

is used to model groundwater flow. Here, **q** and **h** are global vectors of nodal discharge and hydraulic head, **K** and **S** are global conductance and storage matrices, and the subscripts i and i+1 indicate calculated results for the previous and current time steps. The conductance and storage matrices are a function of the geometry of the finite difference grid, the parameters of the time stepping schedule, and the transmissivity and storativity of the flow regime. Both of these matrices are sparsely populated and symmetric and therefore the vectors of hydraulic head and discharge are determined using an iterative, preconditioned conjugate gradient solver for sparse systems of linear equations. The combination of this solver technology and careful implementation of the finite difference formulation allows analyses consisting of more than one million nodes to be determined using desktop computing facilities.

The duration of the various response functions is regulated by fluid diffusion from recharge to the proximal surface water features. The time scales of the functions vary widely and are difficult to estimate a priori. Time stepping is therefore performed using the non-standard approach

$$[3] \qquad t_{i+1} = \alpha\, t_i$$

and

$$[4] \qquad \mathbf{S}_{i+1} = \alpha^{-1}\,\mathbf{S}_i$$

where $\alpha > 1$. This results in time steps that are uniformly distributed in a logarithmic sense. The response functions reported in this paper were computed using a uniform schedule of 332 time steps with $t_1 = 10$ and $\alpha = 1.05$. Results determined using the finite difference formulation were compared to analytic solutions derived using an analogy to heat conduction. This comparison confirmed that the time stepping scheme allows the finite difference formulation to rapidly and accurately proceed across a broad range of time scales.

Nodal hydraulic heads are determined relative to the elevation of the ground and surface water interface along the surface water features shown in Figure 2a. A hydraulic head boundary condition of 0 m is applied to the nodes that occur at the interface. This isolates recharge regulated groundwater flow where flow proceeds from recharge to discharge along adjacent surface water features. Computed groundwater levels therefore most closely approximate levels that are measured relative to local ground surface elevation. For economic reasons, wells are generally constructed to the minimum depth that is required to obtain a reliable water supply, and thus the computed levels are a useful proxy for in situ conditions.

Estimation of regional scale values for the transmissivity and storativity of the groundwater flow regime is a difficult task that has not yet been resolved. As a result, response functions are computed using an arbitrary, spatially uniform distribution of transmissivity and storativity with $T_1 = 1$ and $S_1 = 1$. Scaling relations allow the functions to be transformed to match any other combination of these parameters, T_2 and S_2. These scaling relations are

$$[5] \qquad f_2\left(\frac{T_1}{T_2}\frac{S_2}{S_1}t_1\right) = \frac{S_1}{S_2}f_1(t_1)$$

and

$$[6] \qquad f_2\left(\frac{T_1}{T_2}\frac{S_2}{S_1}t_1\right) = \frac{S_1}{S_2}\frac{T_2}{T_1}f_1(t_1)$$

for groundwater levels and discharge, respectively. The principal advantage of this approach is that the response functions are calculated once using a consistent set of hydrogeologic parameters and a common time stepping schedule. Response functions for any other combination of the input hydrogeologic parameters can then be calculated with greatly reduced computational effort using the scaling relations. Calculation of the response functions requires approximately 100 hours of dedicated computational time and thus significant efficiencies are achieved by scaling the response functions to match differing hydrogeologic scenarios. The principal disadvantage of the approach is that it is not possible to rigorously represent the spatial variation of transmissivity and storativity. A lesser disadvantage is that a fixed temporal resolution represents both slowly and rapidly fluctuating response functions.

3. SPATIAL VARIATION OF RECHARGE

The output of the groundwater flow model is a function of the distribution of surface water features, the transmissivity and storativity of the flow regime, and the net rate of recharge. Application of convolution and superposition allows recharge to vary both temporally and spatially.

Rates of groundwater withdrawal can be estimated on a municipal basis using census, water taking permit, and well construction data (Schellenberg and Piggott 1998). While this approach does not accurately locate punctual withdrawals of groundwater that may have a significant local impact, the methodology is robust and portable and has proven to be adequate for regional studies. Figure 3a indicates the 91 municipalities that are distributed across the modelled region. This municipal texture includes a total of 49 townships, 6 Indian Reserves, 9 villages, 18 towns, and 9 cities with an average area of 135 km^2.

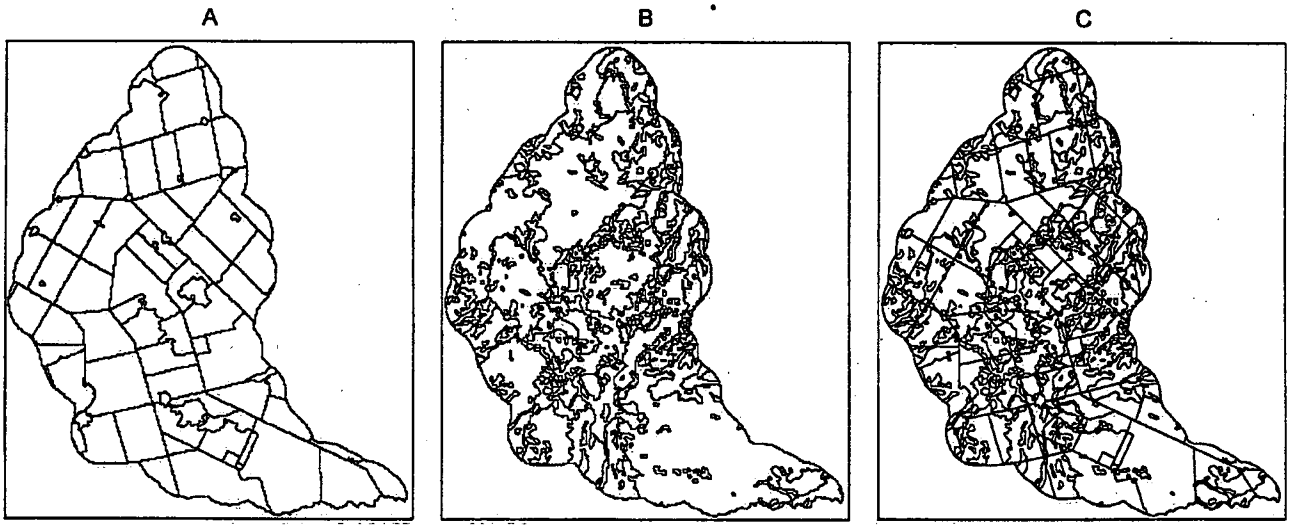

Figure 3. Illustration of the municipal, geologic, and composite spatial textures of the study region.

Base flow mapping is presently being conducted within the region (Moin et al. 1998). Preliminary results indicate a pronounced correlation of base flow, and therefore average rates of groundwater recharge, to the composition of the overburden measured in terms of proportions of permeable and less permeable sediments. The Quaternary geology of the region illustrated in Figure 3b is used to represent this geologic texture. The geology of the region is complex and consists of a mix of organic, fluvial, glacio-lacustrine, glacio-fluvial, and ice contact deposits and a range of glacial tills of varying composition. Bedrock is exposed over two percent of the region. Less than one percent of the region is covered by water bodies and is unmapped. A total of 20 Quaternary geology units occur within the modelled region where these units have an average area of 608 km^2.

The climate of the region is less variable than the municipal or geological textures. Average temperatures during May through September regulate total annual evapotranspiration and increase toward Lakes Erie and Ontario. Precipitation increases toward Lake Huron, presumably in response to lake effects. Finally, the General Circulation Model (GCM) data that is used to estimate climate change is determined with a grid spacing of several degrees of longitude and latitude. As a result, the variation of climate across the region is not explicitly represented as a spatial texture.

If uniform rates of groundwater withdrawal and recharge (i.e., infiltration minus evapotranspiration) are assumed for each unit within the municipal and geologic textures, respectively, then the net rate of groundwater recharge (i.e., recharge minus withdrawal) will be uniform within each of the areas defined by the intersection of the municipal and geologic textures. The resulting composite texture is shown in Figure 3c and consists of 358 unique parcels with an average area of 32 km^2. Each of these areas are assumed to be a distinct source of recharge where net recharge is determined using the corresponding municipal rate of groundwater withdrawal and geologic rate of recharge. Again, net recharge is assumed to be spatially uniform and temporally variable within each source. A unit value of recharge is assigned in determining the response functions and the groundwater flow model is programmed to output a differential result. Multiplication of the response functions and rate of recharge, as indicated in Eq. 1, represents the influence of the in situ value of recharge.

The influence of recharge within each source is measured in terms of two response types; namely, hydraulic head and discharge. The groundwater flow model determines these responses for each node and time step. In the present application, this translates to 1.4×10^{11} values. It is therefore necessary to aggregate the nodal data by type and destination in order to manage and implement the modelling results. Groundwater levels (or Type 1 data) are a proxy for water levels in wells and concerns regarding low or high groundwater levels are most often reported on a municipal basis. Type 1 data are therefore averaged over the 91 municipalities shown in Figure 3a. Groundwater discharge (or Type 2 data) is aggregated by integrating the nodal data over the hydrologic texture shown in Figure 2b.

4. IMPLEMENTATION OF THE MODELLING PROCEDURE

The modelling procedure is implemented using an embedded programming approach that combines the groundwater flow model, GRASS geographic information system (GIS), and POSTGRESQL relational database management system (RDBMS). The GRASS and POSTGRESQL are publicly accessible via the Internet at www.baylor.edu/~grass and postgresql.nextpath.com. The groundwater flow model is programmed in FORTRAN using the SLATEC library of mathematical subroutines and is compiled using G77. The SLATEC library and G77 compiler are publicly accessible via www.netlib.org/slatec and egcs.cygnus.com. Finally, analyses are performed using an

Intel-based personal computer and the publicly accessible Linux operating system.

Two forms of data are output. The first form are nodal values of hydraulic head and discharge recorded in a raster format; that is, as an array of rows and columns of nodal values. Separate raster images are output for each application of the groundwater flow model, type of data, and time step. These images are numerous and large and are required only to visualize the modelling results in a spatial sense. As a result, output of this form of data is suppressed in most applications. The second form of output are the aggregated values of hydraulic head and discharge data. This output is recorded in a database format where each record consists of fields indicating the input hydrogeologic and recharge scenarios and the current source, type of data, destination, time, and value of the response function This format can be input into RDBMS software, which then enables interaction with the data.

Spatial analyses are performed over the rectangular region shown in Figure 1 using the UTM projection and NAD 83 datum. Raster analyses, including the determination of groundwater flow, are performed using uniform resolution of 100 m. This results in an array of 1700 rows and 1450 columns of elements. Groundwater flow, and many other spatial results, are calculated within a subset of this array that is defined using a masking approach. For example, a mask consisting of the Grand River watershed and the 10 km buffer zone surrounding the watershed is widely used to limit the extent of calculations. This mask restricts the determination of groundwater flow to 1,158,693 nodes.

The groundwater flow model is able to compute hydraulic head and discharge over the full modelled region. However, this is a demanding task, particularly in the case of transient flow, that can be minimized using GIS and RDBMS support and a localized masking procedure. The masking procedure is illustrated in Figure 4 for source area 169 from the composite texture, which is formed by the intersection of the Town of Ingersoll from the municipal texture and the Tavistock Till from the geologic texture. The intersection of these two textures is shown in Figure 4a. A mask for the calculation of steady groundwater flow due to recharge with source 169 flow is constructed using a database query to determine the municipality containing the source and the GIS to extend a 50 km buffer zone around the municipality, as shown in Figure 4b. The groundwater flow model is then used to calculate the influence of steady flow due to recharge within source 169 on each of the destination areas defined in the municipal and hydrologic textures. The procedure is repeated for each source and the resulting output is used to form a database of response functions for steady flow.

In the case of source 169, a hydraulic head response was detected within 10 of the municipalities surrounding the source. The limits of these 10 municipalities, and the extent of induced distribution of hydraulic head, are shown in Figure 4c. Analyses were subsequently conducted to confirm that the 50 km buffer used to form the mask for each source did not over-constrain the calculated results.

A database of response functions for transient flow was assembled following a similar approach. In this case, the mask generated for each source was limited to municipalities where a steady flow was detected, again as shown in Figure 4c. The input data for the steady and transient series of analyses were specified such that the single value of the response function for each source, type, and destination indicated in the database for steady flow should, in theory, be equal to the integral of the corresponding transient response function. Each response function within the database for transient flow was numerically integrated and compared to the corresponding entry in the database for steady flow. The two sets of values were found to be in close agreement, confirming the adequacy of the time stepping schedule and masking approach used to determine the transient results. A total of 2523 Type 1 response functions and 1095 Type 2 response functions are defined. Thus, on average, each source influences 7 municipalities and 3 stream gauges.

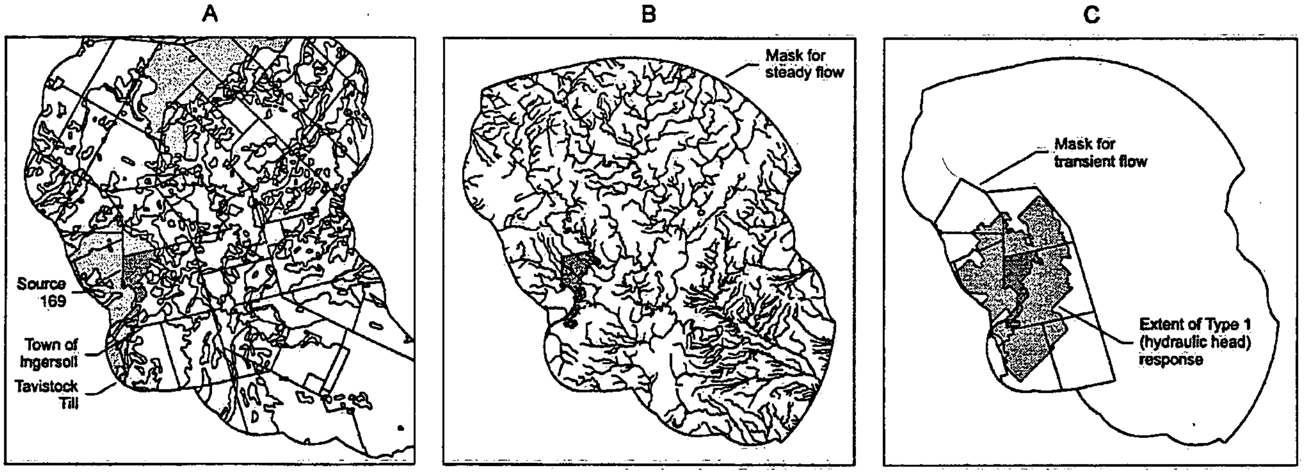

Figure 4. Definition of source area 169 and masking of groundwater flow.

5. SELECTED MODELLING RESULTS

Figure 5 depicts the variation of hydraulic head determined for the full modelled region for steady flow and uniform distributions of transmissivity and recharge. The shading of the image indicates the progression of groundwater levels from zero along each of the surface water features (shown in white) to locally maximum values between the features (shown varying from black to white). The image clearly illustrates the relation of the surface water features to the output of the groundwater flow model and the complex flow regime that results from the distribution of the features.

Figure 6 illustrates a selection of Type 1 and 2 response functions extracted from the database for transient flow. Each plot consists of a total of ten response functions arranged in two sets; namely, the 5 functions with the largest peak magnitudes where the peak occurs at the first time step, and the 5 functions with the largest peak magnitudes where the peak does not occur at the first time step. The second set of Type 2 response functions have peak values that are typically two orders of magnitude smaller than the first set of functions and therefore are plotted relative to a secondary axis. Inspection of Figure 6 reveals several important characteristics of the response functions. First, the functions vary over time scales that span several orders of magnitude. Thus, if the influence of a recharge event is evident in the days following the event, this influence may persist for months, or even years. The peak values of the response functions generally decrease as the time at which the peak occurs increases. Thus, the most rapid portion of the response to a recharge event is likely to have the greatest influence on the overall magnitude of the response. Finally, the response functions have variably complex forms which, in some cases, differ substantially from the simple relations that are traditionally used to describe groundwater recession.

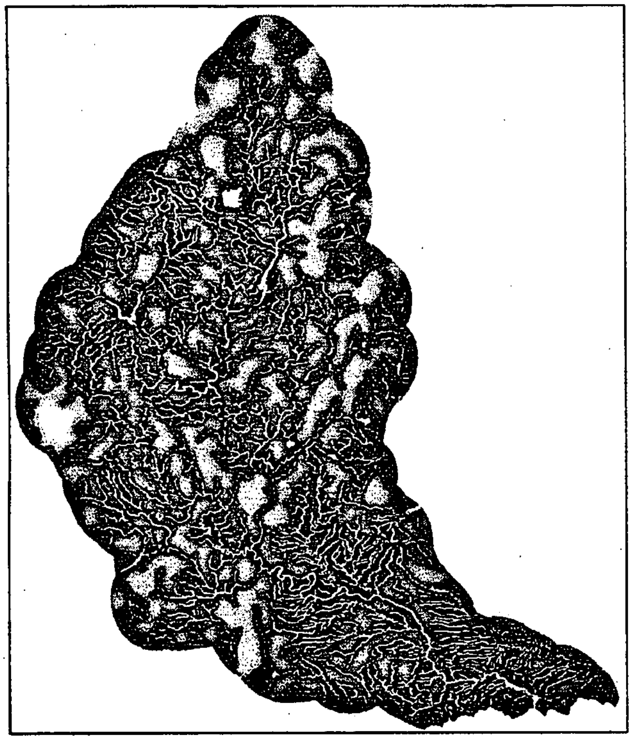

Figure 5. Steady variation of hydraulic head.

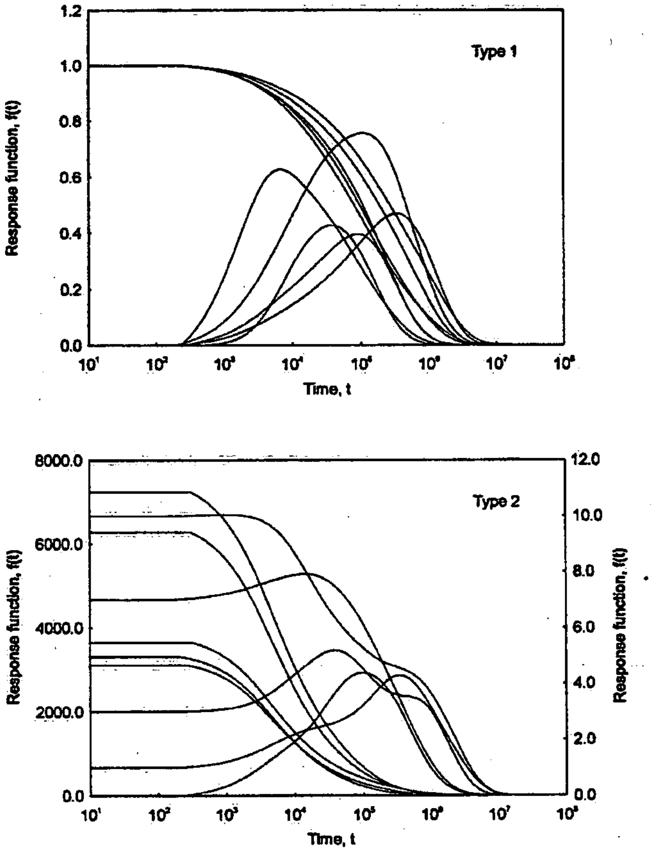

Figure 6. Selected response functions.

Analytic Type 1 and 2 response functions for one-dimensional, transient, confined groundwater flow have been derived using an analogy to one-dimensional heat conduction. These relations were used to verify the finite difference formation and time stepping scheme and to further examine the temporal characteristics of response functions. For example, the analytic relations indicate that the source areas corresponding to response functions with a peak magnitude at $t = 0$ (i.e., at $t = t_1$ in the case of the finite difference results) are in direct contact with the destination area. Where this is the case, Type 1 response functions approach limiting values that are independent of the geometry of the flow regime. This behaviour is apparent in the first set of response functions shown in Figure 6. The analytic relations also indicate that, when a source and destination are in direct contact, Type 2 response functions are singular at $t = 0$ (i.e., $f(t) \rightarrow \infty$ as $t \rightarrow 0$). This behaviour is not apparent in the results shown in Figure 6 due to the finite precision of the calculations.

6. DESCRIPTION OF CONTINUING RESEARCH

Additional research and development is required prior to applying the modelling procedure to the analysis of climate and water use scenarios. It is presently expected that these analyses will be conducted with a daily resolution for the period of 1900 to 2100. Estimates of the in situ variation of transmissivity and storativity for regional scale flow are required in order to transform the computed response functions to match this time scale. Formulation of the input time series is also ongoing. Estimates of water use are being prepared using projections of population growth and of change and growth in the industrial and agricultural sectors. Rates of groundwater recharge corresponding to historic climatic and water use conditions are being determined using base flow analysis. These rates will be projected into time series by correlating historic conditions to climate scenarios. Finally, additional formulation of methods of manipulating, summarizing, and visualizing the large quantities of input and output data are required.

7. SUMMARY AND CONCLUSIONS

This paper outlines a quantitative procedure that relates climate and water use to groundwater conditions. A finite difference approximation for two-dimensional, transient, confined groundwater flow is used to determine response functions that relate groundwater recharge to groundwater levels and discharge across the Grand River watershed.

The net rate of groundwater recharge is assumed to be a function of climate and water use and is distributed using a composite of municipal and geologic spatial textures. Computed, nodal values of hydraulic head and discharge are aggregated using municipal and hydrologic textures, respectively. Aggregation reduces the quantity of output data to manageable levels and to a spatial basis that is useful in the context of regional scale groundwater management. While the development of the modelling procedure is not yet complete, it is apparent that the effective use of embedded GIS and RDBMS technologies in conjunction with numerical modelling is critical to the performance of the proposed procedure.

A total of 3618 response functions are defined by the source and destination textures and have been computed for both steady and transient flow. The peak magnitude and duration of the functions vary over many orders of magnitude for even a uniform distribution of transmissivity and storativity. Scaling relations allow response functions determined for arbitrary distributions of transmissivity and storativity to be transformed to match spatially varying, in situ estimates of these parameters.

8. ACKNOWLEDGEMENTS

This paper is a product of a collaborative and ongoing research initiative addressing the hydrologic impacts of climate change within the Grand River watershed. The participants in this initiative include Shirley Schellenberg and Ghosh Bobba of the National Water Research Institute; Doug Brown, Syed Moin, and Chuck Southam of the Water Issues Division of Environment Canada; Brian Mills and Linda Mortsch of the Environmental Adaptation Research Group of Environment Canada; and Dwight Boyd of the Grand River Conservation Authority. Funding for this initiative is provided, in part, by Great Lakes 2000.

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