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Regional groundwater modeling within the Grand River Watershed

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MANAGEMENT PERSPECTIVE

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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 third 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: Continuing research will focus on the determination of climate and water use impacts on groundwater flow and discharge within the watershed.

ABSTRACT

A model of regional scale groundwater flow is being developed for the Grand River watershed in west-central Ontario. This model is one component of a larger effort to determine the potential impacts of climate change on the groundwater resources of the watershed. The central feature of the model is a numerical solution for groundwater flow that is based on a finite difference formulation and is implemented within a raster GIS setting. Modelling results are used to delineate groundwater catchments, and to determine response functions that may be combined with a time series of groundwater recharge to estimate the variation of groundwater levels and discharge. Preliminary modelling results are presented for the upper Grand River and demonstrate reasonable correspondence with in situ measurements.

Regional Groundwater Modelling Within the Grand River Watershed

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Abstract

A model of regional scale groundwater flow is being developed for the Grand River watershed in west-central Ontario. This model is one component of a larger effort to determine the potential impacts of climate change on the groundwater resources of the watershed. The central feature of the model is a numerical solution for groundwater flow that is based on a finite difference formulation and is implemented within a raster GIS setting. Modelling results are used to delineate groundwater catchments, and to determine response functions that may be combined with a time series of groundwater recharge to estimate the variation of groundwater levels and discharge. Preliminary modelling results are presented for the upper Grand River and demonstrate reasonable correspondence with in situ measurements.

Introduction

The Grand River watershed has an area of 6800 km^2 and is situated in west-central Ontario, extending from north to south from Dundalk to Lake Erie at Port Maitland and from east to west from Acton to Woodstock. The watershed is characterized by an expanding urban population that is largely dependent on groundwater as a water supply. Figure 1a indicates the location of the watershed within southwestern Ontario. The topography of the region is illustrated in Figure 1b and is dominated by the abrupt relief of the Niagara Escarpment, which extends from Lake Ontario to Georgian Bay, and by the Oak Ridges Moraine, which extends westward south of Lake Simcoe. The bedrock and quaternary geologies of the region are characterized by carbonate and shale formations and a highly varied distribution of glacial and post-glacial deposits

Southam et al. (1997) determined that various climate change scenarios translate to detrimental impacts on the surface water resources of the Grand River watershed. Similar impacts on groundwater resources have also been forecast (McLaren and Sudicky, 1993). In response to these concerns, Environment Canada is conducting a research study focusing on the potential impacts of climate change on the groundwater resources of the watershed. This paper briefly describes the progress that has been realized in preparing a regional scale groundwater model to support this study. The modelling exercise is being conducted over the study region indicated in Figure 1a, which includes a 10 km buffer zone surrounding the watershed. The objective of the exercise is to relate varying groundwater recharge to groundwater levels and discharge, both of which are indicators of the sustainability of groundwater resources relative to climate change and shifting patterns of groundwater consumption due to population and industrial growth.

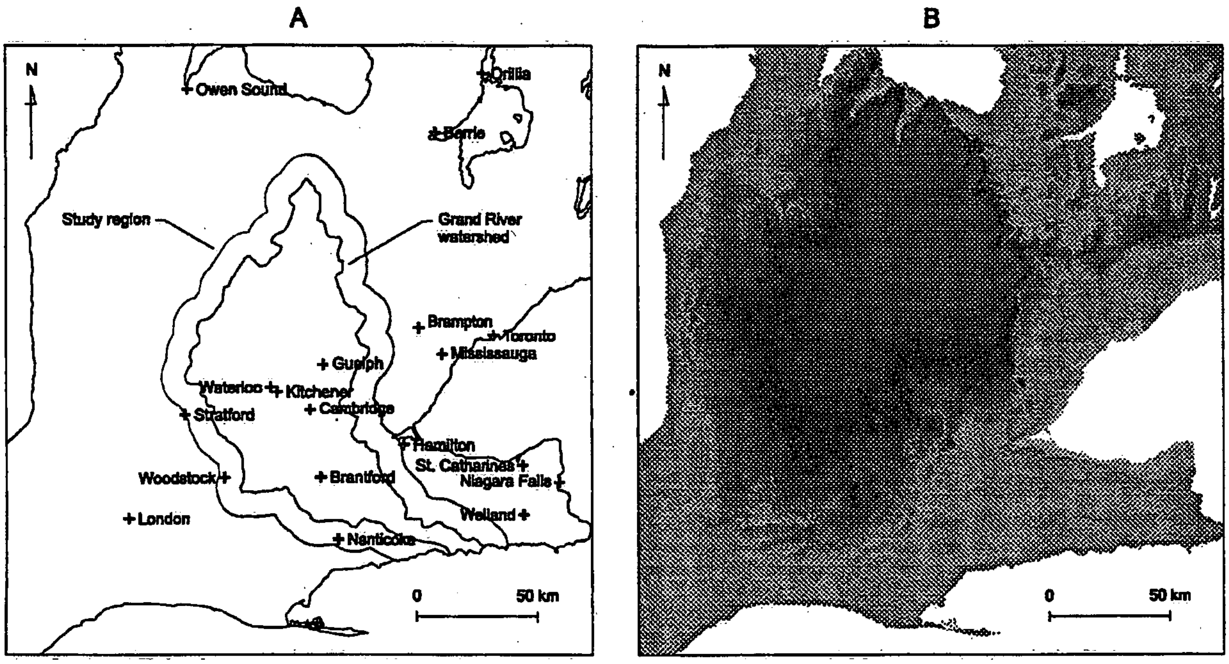

Figure 1. Location of the Grand River watershed and study region (A) and topography of southwestern Ontario (B).

Description and Implementation of the Numerical Solution

The numerical solution for groundwater flow is based on a two-dimensional, transient, implicit finite difference approach (e.g., Huyakorn and Pinder, 1983) and has the mathematical form

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

where **q** and **h** are vectors of groundwater discharge and hydraulic head, **K** and **S** are conductance and storage matrices, and the subscripts indicate results for times, t_i and t_{i+1}. Time stepping is performed using the standard approach

$$t_{i+1} = t_i + \Delta t_{i+1} \qquad [2]$$

in which the sequence of time step magnitudes are determined using

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

with $\alpha \geq 1$. This allows time step magnitudes, increase with time, maintaining numerical accuracy and minimizing the number of steps required to span a prescribed period. Varying the time step magnitude requires re-evaluation of the storage matrix for each time step using the relation

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

The numerical solution has been implemented in FORTRAN using SSDGC, a diagonally scaled, conjugate gradient solver for sparse systems of linear equations, which is included in the publicly accessible SLATEC library of mathematical subroutines. The resulting algorithm is implemented within the Geographic Resources Analysis Support System (GRASS) geographic information system (GIS) developed by the United States Army Corps of Engineers Construction Engineering Research Laboratories (USACERL, 1993). Implementation of the solution within a GIS setting facilitates pre- and post-processing of modelling results. Further, the raster processing facilities of the GRASS are well suited to the management of finite difference results defined on a uniform and rectangular grid. The principal output from the numerical solution are groundwater levels and discharge, both summarized for each time step in raster and database format.

Preliminary Modelling Results

Development of the groundwater model for the study region is ongoing; the following paragraphs describe preliminary results for only a portion of the domain. It is expected that the methodology that will ultimately be applied will be to decompose the region into a series of component groundwater flow regimes, determine groundwater responses at this component scale, and then assemble the component results into regional values. This allows groundwater conditions to be represented with the spatial resolution of the components, and will facilitate the integration of the results of this study with other aspects of the larger Grand River groundwater study.

The first step in the modelling procedure is the determination of the distribution of static groundwater levels across the region in a seamless manner. The objective of this component of the procedure is to relate recharge to groundwater levels and discharge in a generic manner and thus the input parameters applied at this stage are entirely arbitrary. A spatial resolution of 100 m was selected and a uniform, unit transmissivity was assigned to each of the 1,158,693 nodes that form the study region. Boundary conditions of constant hydraulic head were applied to each of the 63,944 nodes that are coincident with surface water features identified on digital 1:250,000 scale maps drawn from the National Topographic Database (NTDB). Boundary conditions of uniform, unit groundwater recharge were applied to the remaining 1,094,749 nodes. The distribution of hydraulic head determined using the numerical solution is shown in Figure 2a. Here, shading indicates the magnitude of groundwater mounding and illustrates groundwater discharge to the surface water features, which are most lightly shaded.

The NTDB map of surface water features was then labelled relative to 12 stream gauges and the outlet of the Grand River to Lake Erie. These 13 locations allow the subsequent modelling results to be linked to surface water flow models being developed for the locations. Methods of particle tracking (e.g., Huyakorn and Pinder, 1983) were applied to the computed hydraulic head data and used to trace flow from recharge to capture along one of the surface water features. Upon capture, the label applied to the surface water feature was assigned to the location of the particle at recharge. The resulting raster is shown in Figure 2b. Each of the 13 areas correspond to a component groundwater flow regime, or catchment, where recharge within the catchment is first detected as discharge at the corresponding stream gauge location. The limits of these catchments are no-flow boundaries and therefore it is possible to complete subsequent modelling by catchment, significantly reducing the computational burden of the analyses.

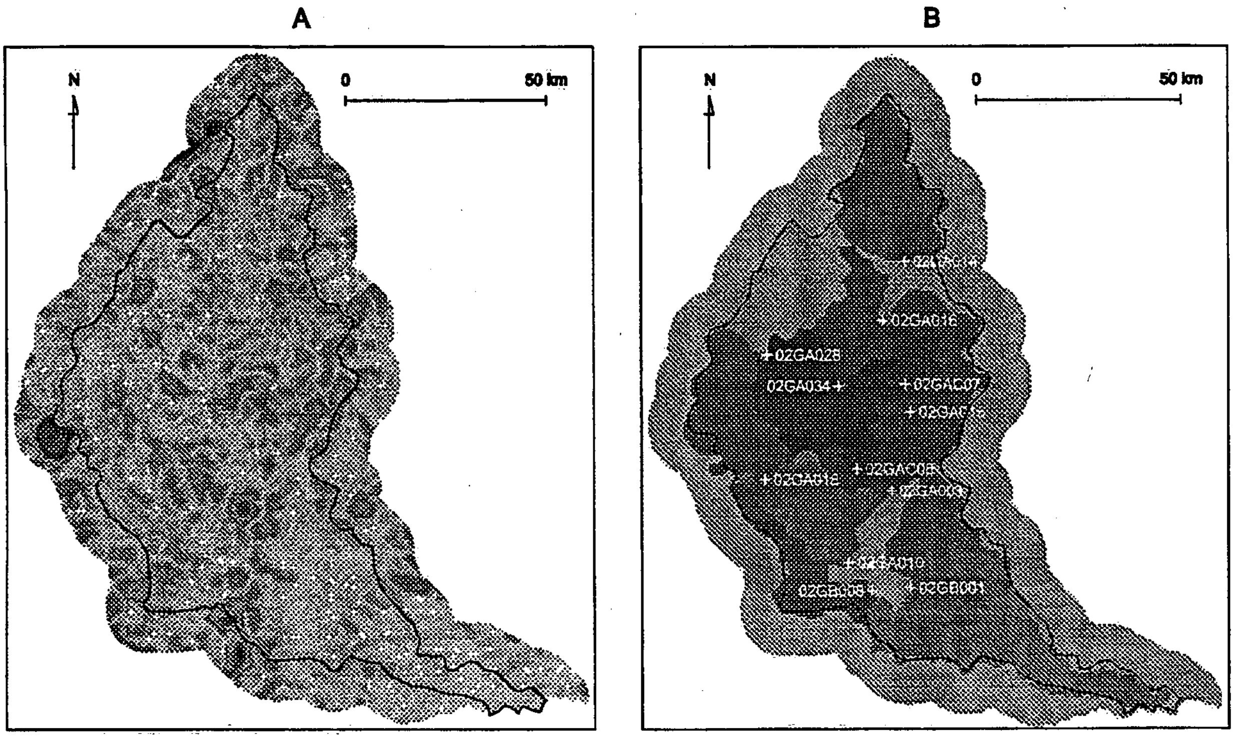

Figure 2. Calculated distribution of groundwater levels (A) and catchments corresponding to the indicated stream gauge locations (B).

Figure 3 is a detailed view of the groundwater catchment determined for Water Survey of Canada stream gauge 02GA014, which is located on the Grand River near Marsville. Figure 3 also shows the associated surface water features, the location of Ontario Ministry of the Environment observation well 46, and the location of Environment Canada climate station 6142991.

Next, the numerical solution was used to calculate transient groundwater flow within the catchment for stream gauge 02GA014, assigning a uniform, unit value of storativity to each of the 68,230 nodes within the catchment. Groundwater levels were averaged over the catchment and discharge was totalled for each time step. Both sets of results were then output in database format. These results are based on the assumption of uniform, continuous recharge. A derivative set of results for a finite recharge event were determined using

$$h_j = h(t_j) - h(t_j - \Delta t) \qquad [5]$$

and

$$q_j = q(t_j) - q(t_j - \Delta t) \qquad [6]$$

where $h(t)$ and $q(t)$ are the results for continuous recharge and Δt is the duration of the recharge event. These increments form response functions for groundwater levels and discharge that may be used to compute the variation of levels and discharge due to an arbitrary time series of recharge. The use of arbitrary values for recharge, transmissivity, and storativity allow the computed responses to be determined in dimensionless form where dimensional values may be readily obtained from the dimensionless results using scaling relations. For example, estimates of the transmissivity and storativity of the catchment of 1×10^{-4} m^2/s and 1×10^{-2}, respectively, were used to select a dimensionless value for Δt that conforms to a recharge event duration of Δt = 1 day. Superposition of a time series of recharge is performed using

$$H_i = \sum_{j=1}^{i} r_{i-j+1}\, h_j \qquad [7]$$

and

$$Q_i = \sum_{j=1}^{i} r_{i-j+1}\, q_j \qquad [8]$$

where H_i and Q_i are the present groundwater level and discharge, r_{i-j+1} is the magnitude of a previous recharge event, and h_j and q_j are the responses computed using Equations (5) and (6).

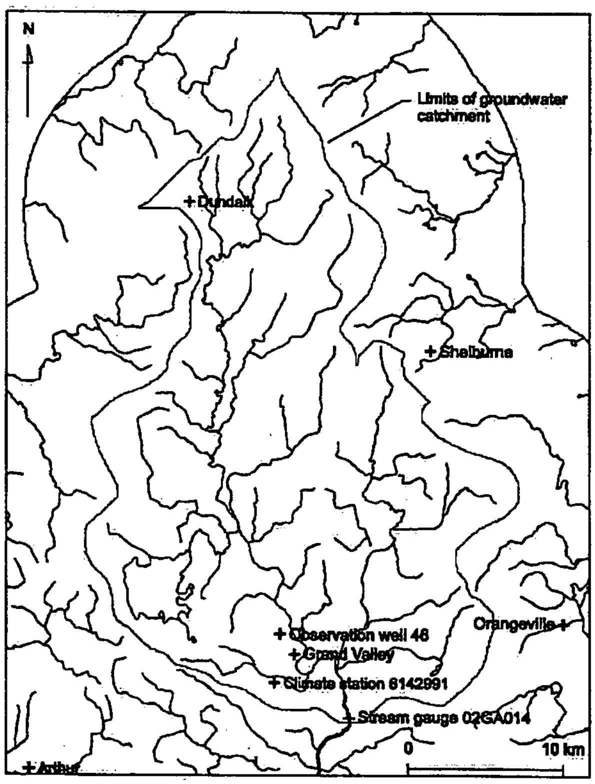

Figure 3. Computed groundwater catchment for stream gauge 02GA014.

A daily time series of groundwater recharge was synthesised for the period of October 1, 1974 to December 31, 1987 using meteorological data from climate station 6142991 and stream flow data from stream gauge 02GA014. Rainfall and snowfall were determined directly from the meteorological data while snow accumulation and melting were computed using the degree-day method (Gray, 1970). Annual evapotranspiration was estimated by calculating annual rainfall and snow melting and deducting the corresponding annual stream flow. These annual totals were then distributed on a daily basis using the degree-day method in proportion to maximum daily temperatures in excess of 0 °C. Finally, recharge was estimated by deducting daily water loss from the input and scaling the difference by 0.25, a preliminary estimate of the deregulated base flow index of the catchment. The resulting average annual groundwater recharge is 98 mm.

Groundwater levels and discharge were calculated using Equations (7) and (8). The time series of recharge was repeated to form a 39 year series where two repetitions of the series were used to equilibrate the convolution and the results obtained for the third repetition were retained as output. It was observed that the estimated time series of recharge resulted in spurious functions in the computed results and therefore the series was filtered using a 30 day moving average. Figure 4 illustrates the initial and filtered estimates of recharge for 1980. The filtered variation indicates neutral groundwater recharge conditions during January, February, and early March and again during late May, June, and early July. Recharge to the groundwater flow system occurs at varying rates during late March through mid May, July and August, and September though December. Episodes of a net loss of groundwater occur during May through September.

Figure 4 also compares estimated variations of the depth to the groundwater level to the data available for observation well 46. Two modelling cases are presented. Case 1 is based on the estimates of transmissivity and storativity cited previously while Case 2 is based on a ten fold increase in the diffusivity of the groundwater flow regime relative to Case 1. Both cases have been translated and scaled to match the statistics of the measured data where these transformations are required to represent the in situ topography and transmissivity of the catchment. There is generally favourable correspondence between the estimated and measured variations, although Case 2 is characterized by a more rapid response than the measured data. Further, the estimated results indicate an increase in groundwater levels during mid July through mid September that is not consistent with the measured data. The recharge that is estimated for this period may be the result of relatively intense, convective storm events that may yield limited recharge, and therefore actual recharge during this period is likely to differ from the estimated variation.

The final set of results shown in Figure 4 is a comparison of the estimated groundwater discharge for gauge 02GA014 and the measured stream flow at the gauge location. It should be noted that the measured data includes both direct surface runoff and groundwater discharge and therefore the results are not entirely comparable. It is expected that the base flow component of the measured flow occurs during the winter and at the various minima of the total flow. Luther Marsh is located upstream of the gauge and is used to augment stream flow during seasonal periods of low flow. Records of water releases from Luther Marsh indicate that the effects of augmentation are most significant during January, February, and early March and again during July, August, and September. Case 1 follows the trends apparent in the measured data but consistently and substantially underestimates the variability of the data. Case 2 similarly follows the trends in the measured data but more accurately reflects the variability of the data. Matching even the trends in the measured data is regarded as an encouraging result at this stage in the modelling effort.

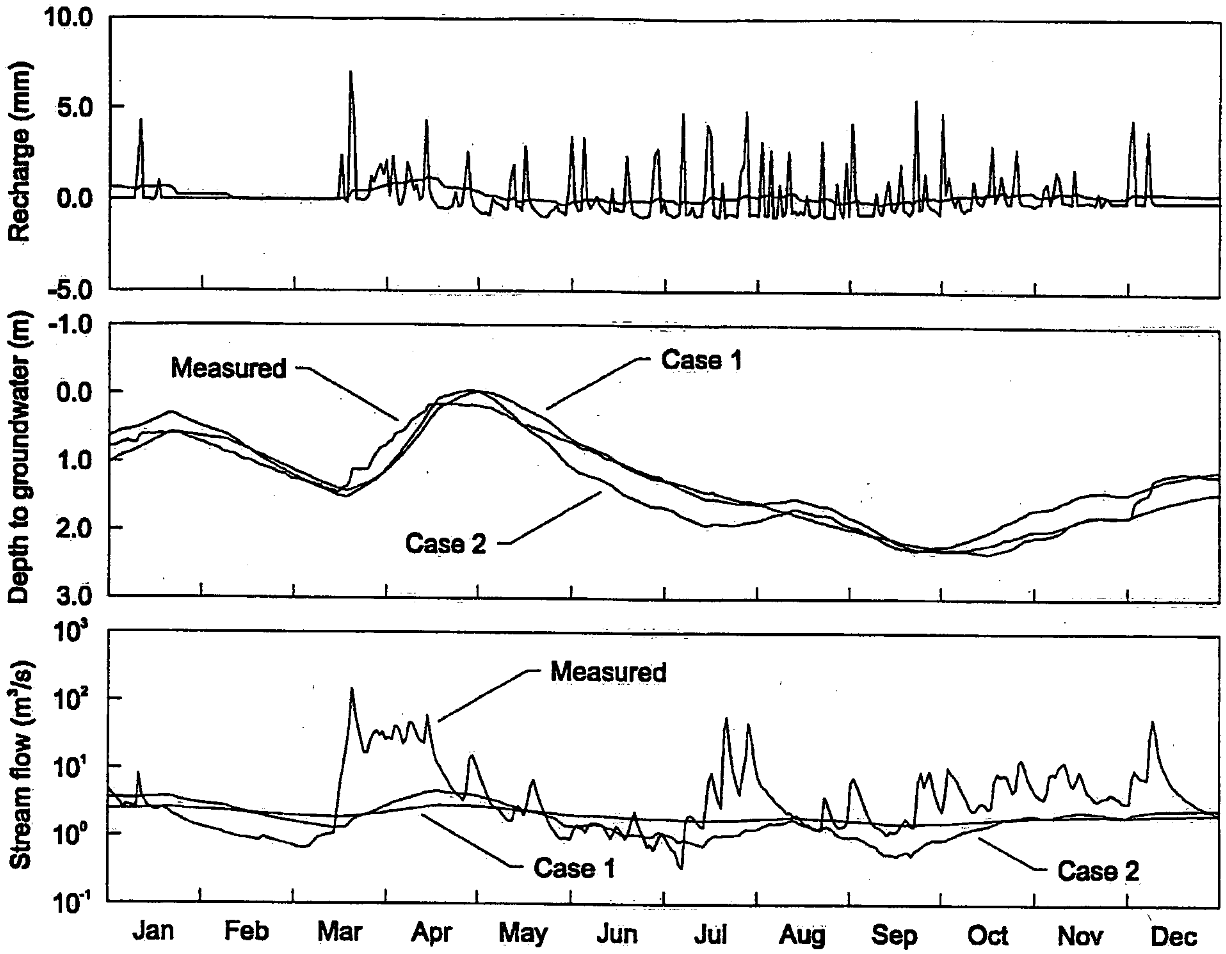

Figure 4. Estimated groundwater recharge and measured and calculated groundwater levels and discharge.

Discussion and Conclusions

The proposed modelling procedure allows groundwater levels and discharge within component flow regimes to be determined as function of hydrogeologic parameters and time series of recharge. Component results may be assembled to form a regional result. This procedure allows the computationally intensive aspects of the simulation of groundwater flow to be completed prior to the application of the time series, significantly improving the efficiency of the exercise.

Groundwater recharge is regulated by meteorological conditions and by the rate of groundwater consumption, and therefore changes in these conditions may be related to varying levels and discharge in a quantitative manner. This relation provides a mechanism for determining the potential impacts of climate change on groundwater resources, and the sustainability of concurrent population and industrial growth. Computed results are determined on a daily basis and consequently impacts may be summarized on an annual, seasonal, or monthly basis.

It is suggested that the approach developed in this paper represents a compromise among the conflicting requirements of hydrogeologic detail and operational simplicity, and the limitations of the data that are available to substantiate the model. Databases of supporting information such as groundwater characterization results have been compiled and are used to refine the conceptual model where deficiencies are detected. The objectives of the study require a consistent and seamless regional model. Similar studies conducted at a local scale access more detailed hydrogeologic knowledge and therefore may be used to produce a more detailed description of groundwater flow. In these cases, the value of the regional model may be to provide linkage of local results through the provision of a consistent set of boundary conditions.

Finally, representing groundwater levels and discharge as the product of a time series and response function using the mathematical formality of the convolution integral may allow components of the modelling exercise to be completed using spectral techniques and other methods of time series analysis. Implementation of the numerical solution for groundwater flow within a GIS setting and the manipulation of computed results using analogues to database management have proven to be critical to the formulation of the regional model.

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