THE ANALYSIS OF SEASONALLY VARYING FLOW IN A CRYSTALLINE ROCK WATERSHED USING AN INTEGRATED SURFACE WATER AND GROUNDWATER MODEL

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ABSTRACT

The surface water and groundwater flow in a small watershed are investigated using the fully coupled groundwater/surface water model HydroGeoSphere. The watershed has an area of 6.92 square kilometers and contains multiple lakes, including Bass Lake (the largest lake) with a surface area of 0.94 square kilometers and a maximum depth of 9.0 meters. The surface water drainage system includes wetlands, small streams, and beaver dams while the topographic relief has a range of 50 meters. The overburden is thin with granite bedrock outcrops occurring at numerous locations throughout the basin. Hydrologic data for the basin includes 2 rain gauges and a continuous water level recorder for Bass Lake. Additional climate data were obtained from nearby meteorological stations. The HydroGeoSphere model was used to investigate and calibrate the parameters for groundwater and surface water flow in the basin for a spring to fall time period. Modeled surface water depths and locations of water accumulation are consistent with known and collected field data. Low overland friction values produced the most accurate Bass Lake elevations.

1 INTRODUCTION

The District of Muskoka in Ontario (Figure 1) is located on the Canadian Shield and is characterized by forests, multiple lakes, and minimally impacted natural settings. Due to its status as a popular vacation destination, the quality and quantity of both surface water and groundwater in the Muskoka district are of major concern for area communities. The application of an integrated surface water-groundwater model to a crystalline rock environment (as is consistent with Canadian Shield settings) would offer insights and information that could help examine the existing water quality, water quantity, and provide interpretations of human impact. To accomplish this, a physically-based, integrated surface water-groundwater numerical model HydroGeoSphere (Therrien et al., 2005) was used to analyze the Bass Lake watershed, located within the Muskoka district. To support the modeling analysis, a large climatological and physical property database for the Bass Lake watershed and surrounding model domain was compiled.

2 HYDROGEOSPHERE

HydroGeoSphere (Therrien et al., 2005) is a Frac3DVS based integrated surface water – groundwater flow simulation model formulated from the work by VanderKwaak (1999) with attributes of MODHMS (HydroGeoLogic, 2005). HydroGeoSphere can use both an integrated finite difference or an integrated finite element approach and is capable of modelling the interactions between surface water, groundwater, and channel flow domains. HydroGeoSphere also offers the option of dual continua (fractured flow) groundwater flow simulation. In the HydroGeoSphere model, the variably saturated groundwater component, for a single continuum subsurface (porous medium), is described by a modified version of the three-dimensional Richards equation:

$$-\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z} + \Gamma_0 \pm Q = S_w S_s \frac{\partial \psi}{\partial t} + \theta_s \frac{\partial S_w}{\partial t} \qquad (1)$$

where the fluid flux components (L T^{-1}) q_i are defined by

$$q_i = -K_{ij} \cdot k_r \frac{\partial(\psi + z)}{\partial x_i} \qquad (2)$$

in which K_{ij} is the hydraulic conductivity (L T^{-1}), k_r is the relative permeability of the medium (-), Ψ is the pressure head (L), z is the elevation head (L), θ_s is the saturated water content (-), S_w is the water saturation (-), and S_s is the specific storage coefficient of the porous medium (L^{-1}). $\Sigma\Gamma_0$ is the fluid exchange flux (L^3 L^{-3} T^{-1}) between the surface and subsurface flow regimes, where a positive value represents a flow into the subsurface. Q is defined as a source (+ve) or a sink (-ve) flux within the subsurface.

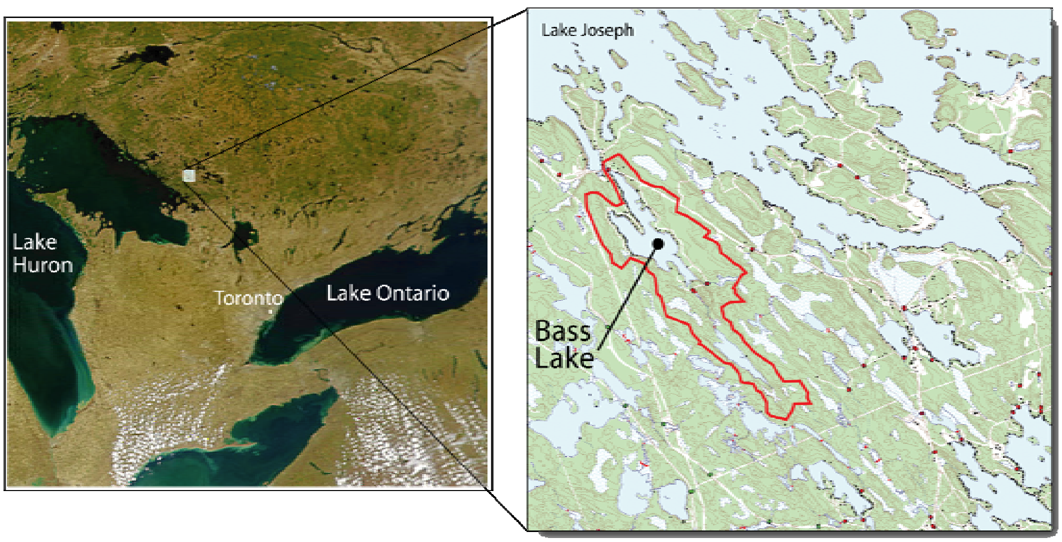

FIGURE 1. Bass Lake Location (from NASA, 2004)

The surface water component of HydroGeoSphere is calculated with a two-dimensional diffusion wave approximation of the St. Venant equations. This approximation makes several assumptions originating from the St. Venant equations: inertial terms are neglected, depth-averaged flow velocities are used, the vertical pressure distribution is hydrostatic, only mild slopes are considered, and bottom shear stresses are dominant (Therrien et al., 2005). The resulting diffusion wave approximation solved by HydroGeoSphere is expressed as:

$$\frac{\partial \phi_o h_o}{\partial t} - \frac{\partial}{\partial x} \; d_o K_{ox} \frac{\partial h_o}{\partial x} \; - \frac{\partial}{\partial y} \; d_o K_{oy} \frac{\partial h_o}{\partial y} \; + d_o \Gamma_o \pm Q_o = 0 \qquad (3)$$

where d_o is the depth of surface water flow (L), h_o is the water surface elevation (where $h_o = z_o + d_o$) (L), z_o is the ground surface elevation (L), Q_o is a volumetric flow rate per unit area representing external sources and sinks (L T^{-1}), ϕ_o is a surface flow domain porosity equal to unity over flat surfaces and varying from zero to unity over uneven surfaces, and Γ_o is the fluid flow from the subsurface to the surface system. The surface conductances K_{ox} and K_{oy} (L T^{-1}), using the Manning equation, are defined by:

$$K_{ox} = \frac{d_o^{2/3}}{n_x} \frac{1}{[\partial h_o / \partial s]^{1/2}} \text{ and } K_{oy} = \frac{d_o^{2/3}}{n_y} \frac{1}{[\partial h_o / \partial s]^{1/2}} \quad (4)$$

where the slope, s, is the direction of maximum slope (-) while n_x and n_y are the Manning roughness coefficients in the x- and y- directions ($L^{-1/3}$ T).

The subsurface of the Bass Lake domain is modelled using an assumed equivalent porous medium without considering additional major fractures, macropores, or injection/extraction wells. The single continuum surface – subsurface linkage term is:

$$d_o \Gamma_o = k_{ro} K_{so} (h - h_o) \quad (5)$$

where d_o and Γ_o are defined in the surface water flow equations, k_{ro} accounts for the rill storage effects (-), K_{so} is the leakance factor across the thin porous medium layer (T^{-1}), h is the subsurface head (L), and h_o is the surface head (L). The leakance factor, K_{so}, can be further defined as $K_{so} = K / \Delta T$ where K is the hydraulic conductivity of the thin porous medium (L T^{-1}) and ΔT is the thickness through which the fluid flux occurs (L).

The evapotranspiration component of HydroGeoSphere is simulated using the "bucket model" as detailed by Panday and Huyakorn (2004). The bucket model functions such that any precipitation in excess of interception storage and evaporation from interception reaches the ground surface. Parameters in the model include the interception storage capacity which is a function of the vegetation type and the growth stage of the vegetation defined in terms of a canopy storage parameter and a leaf area index. The evapotranspiration is modelled with evaporation and transpiration components affecting surface and subsurface nodes. All vegetative transpiration occurs from the ground surface to the maximum vegetative root depth and can encompass multiple subsurface layers. Parameters of the model include the moisture contents at the wilting point, field capacity, oxic limit, and anoxic limits, the effective root length and a depth varying root extraction function.

3 BASS LAKE DATA BASE

The Bass Lake watershed was delineated using Ontario Base Maps (OBMs) at a scale of 1:10000. The watershed has a surface area of 6.92 km^2 with two major lakes, Bass Lake (0.94 km^2) and Long Lake (0.23 km^2; also know as Concession Lake). The relief of the watershed varies widely from a minimum elevation of 216.5 m to a maximum elevation of 265.0 m. A bathymetric survey of the Bass Lake was completed for this study and revealed a mean water depth of 4.5 meters and a maximum depth of 9.0 meters. The outflow from Bass Lake is controlled by a natural rock weir. The resulting outflows can vary from high early spring thaw flow rates to zero outflow conditions during hot and dry summer conditions.

Conventional approaches to groundwater modeling use the outer watershed boundary as the maximum extent of the modeled domain. This model boundary definition assumes that the groundwater catchment boundaries directly coincide with the surface water catchment area. In the case of the Bass Lake study, the frequency of fractures and major geologic contacts did not support the conceptual construction that the surface water and groundwater catchments coincided. As such, the modeling domain was extended to account for these discontinuities resulting in a domain surface area of 17.7 km^2 (Figure 2). The increased domain size allows for groundwater table highs to migrate as dictated by the transient flow conditions.

To create an accurate estimate of surface elevations across the model domain, a digital elevation model (DEM) was created. It was created using digital versions of OBMs. The surface contours (5 m contour interval) were used to create a surface TIN for the elevations.

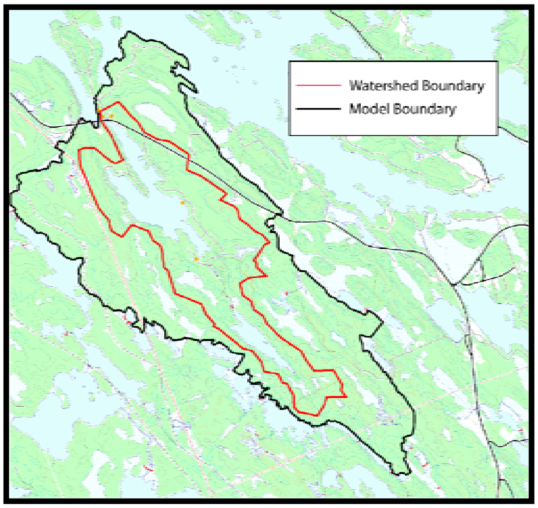

FIGURE 2. Bass Lake Watershed and Model Boundaries

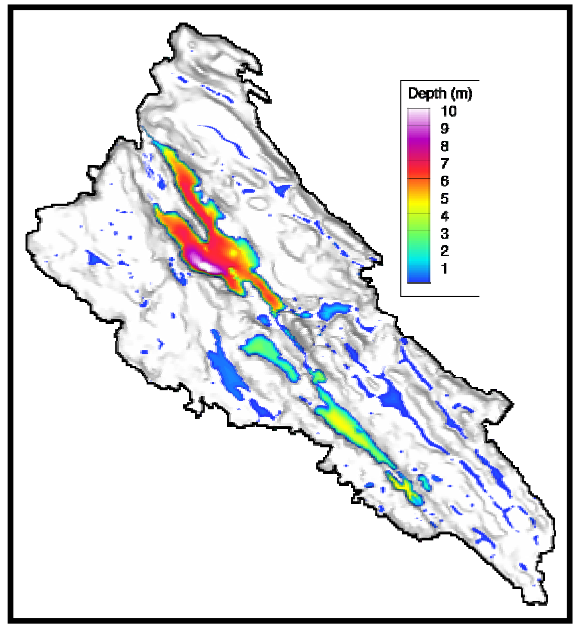

FIGURE 3. Surface Water Depths (t = 10 d)

The natural rock weir located at the north end of Bass Lake provides hydraulic control for surface water outflow from the watershed. As a result, an accurate cross-sectional survey was completed to determine the elevations across the weir.

Minimal surficial soil cover exists in and surrounding the Bass Lake watershed. To determine the surficial soil properties within the model domain, soil samples were taken at locations across the watershed. Grain size distribution analyses were performed on the soil samples. From these results, it was determined that the surficial soil is a silty sand.

To record the precipitation within the Bass Lake model domain, two rain gauges were setup in the watershed. The collected precipitation data sets were supplemented with additional climate data obtained from the Canadian Ministry of Natural Resources for three weather stations within a 38 km radius of Bass Lake. These data sets include, but are not limited to, air temperature, relative humidity, wind speed, percentage cloud cover, and atmospheric pressure. An inverse squared distance weighting approach was used to determine the values within the watershed.

To facilitate model calibration, a lake level sampling program was designed for Bass Lake. A pressure transducer was installed approximately 1.2 m below the water surface of a dock on the north-east bank of Bass Lake. Lake levels were sampled on 15 minute intervals from May 2nd to November 26th, 2004. The collected data was processed and the pressure reading converted to an equivalent depth of water, which was in turn referenced to survey data to yield the lake level elevations with respect to meters above sea level (masl).

The land class (LC) designation is used in the elemental allocation of surface flow and evapotranspiration properties across the model domain. The LC data was acquired through the Minstry of Natural Resources Canada's GeoGratis website. The Ontario Land Cover map (1:250,000 scale) was incorporated with existing ArcView data and revealed four land cover categories for the model domain: surface water, dense deciduous forest, mixed forest, and sparse forest.

4 CONCEPTUAL MODEL

The completed two-dimensional quadrilateral element mesh contains 48693 nodes and 47761 elements. Topographic contour lines from the digital Ontario Base Maps were used to create an initial DEM. Results of visual field inspections and the Bass Lake bathymetric survey were added to the DEM to compliment the existing topographic data and to create realistic bathymetry for all water bodies within the watershed.

The thin surface sediment layer combined with exposed fractured bedrock offers preferential pathways for the fluid flow between the groundwater and surface water flow regimes. The thickness of the surface sediments are variable across the watershed with the metamorphosed bedrock outcropping throughout. Site investigations yielded a maximum surface sediment depth of approximately 5.0 meters and a mean surface sediment depth of approximately 0.5 meters. The location and extent of these outcrops are themselves quite variable, although they are influenced by topography and occur more frequently on peaks of hills rather than in valley bottoms. This topographic influence was the basis for the randomly generated surface thicknesses.

A Fast-Fourrier Transform (FFT) random field generator was used to generate random fields across the watershed. Based on observation during site visits and due to the surface soil variability across the watershed, a correlation length of 30 meters was used. This correlation length implies that the surface sediments in one location are independent of those 30 or more meters away. To include the topographic influence, a surface smoothing function was created to determine convex and concave surface topography. The function calculates the average grid cell elevation for a 201 x 201 grid area, centered on the cell of interest. The average cell value was then compared to the center cell value. A negative difference between the center cell and average values corresponds with a concave condition (valley) while a positive difference corresponds with a convex condition (hill). The smoothed surfaces were then normalized to yield maximum and minimum values of +1 and -1 respectively. Any values along the margins that could not be calculated were assigned a normalized value of 0. The FFT and normalized smoothed surface values were determined at each node location and combined to produce the surface sediment locations and depths. The FFT values were initially found to follow a normal distribution; however, they were transformed to follow a log-normal distribution to ensure non-negative surface depths. The resulting surface thickness has a maximum value of 4.81 meters, a minimum value of 0.00 meters, a median value of 0.39 meters, and an average value of 0.43 meters.

The subsurface consists of three layers of fractured bedrock: weathered bedrock, shallow bedrock, and deep bedrock. The weathered bedrock is directly below the surface sediments, and in some locations, is expressed as exposed bedrock. The bedrock within this layer is influenced by weathering and erosion processes. The main effect of these processes is increased hydraulic conductivities resulting from fracture propagation induced by numerous freeze-thaw cycles. The weathered bedrock extends from the bottom of the surface sediments to a depth of 4 meters below surface.

The shallow bedrock is assumed to be largely unaffected by weathering; however, its hydraulic conductivity is higher than that of the deep bedrock. This layer extends from 4 meters below surface to 14 meters below surface. The deep bedrock is the least hydraulically conductive layer and extends from 14 meters below surface to 26.5 meters below surface. The properties of the equivalent porous media fractured bedrock layers are: hydraulic conductivity varies from 5.0×10^{-6} to 7.0×10^{-8} m/s, porosity is 2.0×10^{-3} and specific storage is 2.2×10^{-7} m^{-1}. To facilitate the variably saturated flow conditions, the discretization of the subsurface begins with small element thicknesses near surface, with element thicknesses increasing with depth.

The overland flow parameters were assigned based on the land cover designation. The parameters were assigned to the surface faces of the elements based on the location of the element centroid. Due to similar surface covers within the three forest land covers, all non-water body elements were assigned equal overland flow parameters. The friction factors, rill storage heights, and bottom leakance factors for the land covers are shown in Table 1.

TABLE 1. Overland Flow Parameters

	Friction Factor ($s/m^{(1/3)}$)	**Rill Storage Height (m)**	**Bottom Leakance Factor (s^{-1})**
Mixed Forest	0.03 to 0.06 (x- & y-)	0.0001	0.02
Sparse Forest	0.03 to 0.06 (x- & y-)	0.0001	0.02
Dense Deciduous Forest	0.03 to 0.06 (x- & y-)	0.0001	0.02
Water Body	0.025 to 0.05 (x- & y-)	-	0.05

As the model domain was extended to the next adjacent water body or topographic low, Dirichlet boundary conditions were used along the outer model boundary to allow the exit of excess groundwater from the model. Any outer boundary node located adjacent to a water body was assigned a constant head boundary condition equal to the surface elevation of that node.

The watershed maximum evaporation values are required input parameters for the evapotranspiration component of HydroGeoSphere. The weighted historical climate data was used for the Bass Lake maximum evaporation calculations. The surface water temperature was set to equal the daily air temperature. The water temperature used in the evaporation calculations is that of a thin film at the water surface. Given this information and with minimal available data, the use of this assumption is reasonable given that Bass Lake is relatively shallow.

The evapotranspiration properties determined for the model domain are fairly similar in nature, differing only slightly between land cover classes. Surface element faces defined as surface water were assigned a leaf area index (LAI) of 0 and a root depth of 0 m. The mixed forest, sparse forest, and dense deciduous forest land covers were assigned maximum LAIs varying from 2.58 to 3.605 and root depths of 2.0 m.

The evapotranspiration input requires soil properties for the surficial layers of soil from which the vegetation roots draw their water. A wilting point of 0.06 (vol/vol) and field capacity of 0.015 (vol/vol) was used.

5 RESULTS AND DISCUSSION

The Bass Lake model domain groundwater heads follow a general trend of decreasing overall head toward the Bass Lake watershed rock weir outlet to Lake Joseph. Decreased groundwater head occurs in regions of decreased topographic elevation and is consistent with the expected groundwater flow patterns. The local groundwater highs also mimic the previously delineated watershed divide boundaries. The calculated groundwater flow vector field generally mimics topography. The subsurface saturation levels show decreased values within the forested land cover areas across the domain as compared to the other areas. These decreased values appear as expected and show that the evapotranspiration component is depleting the subsurface saturation levels. Observed and modelled locations of fully saturated conditions (i.e. surface water bodies) correspond very closely, providing qualitative validity to the modelled results.

The surface water results for the Bass Lake domain simulations were compared to observed Bass Lake water elevation response data.

The surface water depths are presented in Figure 3. Only surface water depths greater than 0.001 m have been shown to illustrate areas of surface water accumulation. These surface water depths are consistent with the bathymetric survey results. Across the model domain, the locations of surface water accumulation are consistent with the air photos, digital Ontario Base Maps, and field observations.

For surface water flow maximum velocities of 1.4 m/s were simulated. The surface water flows within the watershed boundaries are moving towards Bass Lake; conversely, surface water flows outside of the watershed are flowing away from Bass Lake towards the model domain boundary. Water flow within Bass Lake is moving towards the north end and the watershed outflow.

An 85-day simulation was performed to capture the Bass Lake response to seasonally varying flow. These simulations include the evapotranspiration component. The results of two simulations are presented on Figure 4: the first using a high overland n while the second uses a low overland n.

The simulated responses to precipitation events show similar water levels throughout the 85-day simulation period. Only a slight time-lagged response of the simulated lake level is observed and can be explained as a product of using average daily input values for the model or that overland flow had minimal influence in the context of soil storage or unsaturated conditions. The overall lake level response is similar to the observed lake levels until day 38. Following the major storm event (day 35-38), lake level recession is noticeably faster than that observed.

A comparison of the low n and high n simulations shows that the low n model offers a more realistic overall Bass Lake water level. Again, examination of the major storm events at days 16 and 38 shows that the high n model water level decreases more gradually than does the low n model.

Finally, it is apparent that the low overland n unsaturated flow model offers the most realistic Bass Lake water level simulation; however, all models overestimate the speed with which the water levels decrease following the major storm event starting on day 35.

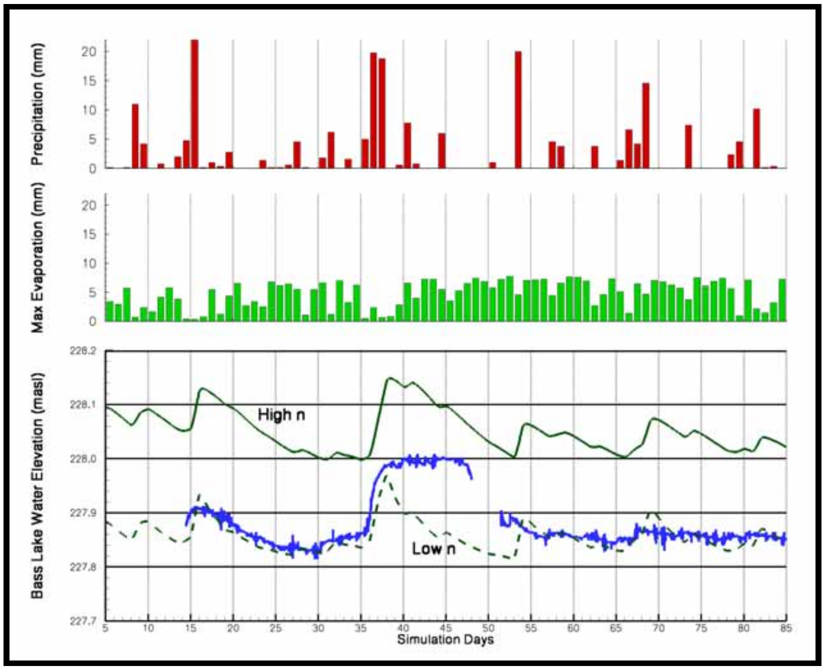

FIGURE 4. Measured and Simulated Bass Lake Water Elevation

6 CONCLUSIONS

The simulation results for the Bass Lake model domain were compared to expected trends and observed field data. However, all of the models overestimated the reaction of the water levels following major storm events. This overestimation could be due to the dynamic nature of natural processes (for example, construction and destruction of beaver dams) occurring within the Bass Lake watershed; their inclusion within a simulation model is a challenge for future research.

The integrated surface water-groundwater model HydroGeoSphere ultimately produced acceptable simulations of the Bass Lake model domain. The construction and execution of the model was not without its issues. Following numerous modifications to the source code, to the model grid, and to the input parameters, HydroGeoSphere remains computationally burdensome. Further source code and general model refinement are required to produce a robust and efficient integrated surface water-groundwater modeling program.

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