ASSESSMENT OF SEASONAL GROUNDWATER FLOW FOR OPERATION OF A LOW FLOW AUGMENTATION RESERVOIR

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ABSTRACT
In 1967, two dams, the north and south dam, were constructed in a 180 hectare area of cedar swamp and farm land to form the Island Lake Reservoir, east of Orangeville, Ontario. The reservoir area forms the headwaters of the Credit River Watershed, and consists of 332 hectares of water and land resources. The reservoir is used to augment low flow in the Upper Credit River to maintain water quality, including assimilation of discharge from the Orangeville Water Pollution Control Plant. A Permit to Take Water specifies the minimum flows to be maintained throughout the year through the south dam. No surface water flow occurs through the north dam into the adjacent Nottawasaga River Watershed. However, groundwater seepage in this area is thought to contribute a portion of flow to the headwaters of the Nottawasaga River. Snowmelt contributes the majority of surface flow into the reservoir. The surrounding Towns of Orangeville and Mono are rapidly developing and utilize groundwater as a water supply. The increasing demand for groundwater and recent summer periods of low precipitation make proper management of reservoir levels essential to meet minimum flow requirements. A groundwater flow model was developed for the headwaters area using the finite element model FEFLOW to assess the contribution of groundwater flow to the surface water system under different seasonal conditions and reservoir levels. The model uses climate and surface water modeling input from the GAWSER surface water model to simulate the seasonal variation. The understanding of the groundwater flow contribution from model simulations has been used to develop a monitoring network and to revise operational guidelines for the reservoir.

RÉSUMÉ
En 1967, deux barrages, le barrage du nord et du sud, ont été construits dans un secteur de 180 hectares de marais de cèdre et de terre de ferme pour former le réservoir de lac island, à l'est d'Orangeville, Ontario. Le secteur de réservoir forme les eaux de plus près de la source de la ligne de partage de fleuve de crédit, et se compose de 332 hectares de ressources de l'eau et de terre. Le réservoir est employé pour augmenter le bas écoulement dans le Credit pour maintenir la qualité de l'eau, y compris l'assimilation de la décharge de la usine de lutte contre la pollution de l'eau d'Orangeville. Une laiss de prendre l'eau indique les écoulements minimum à maintenir tout au long de l'année par le barrage du sud. Aucun écoulement d'eau de surface ne se produit par le barrage du nord dans la fleuve de Nottawasaga. Cependant, on pense l'infiltration d'eaux souterraines dans ce secteur pour contribuer une partie d'écoulement aux eaux de plus près de la source du fleuve de Nottawasaga. Niege contribue la majorité d'écoulement extérieur dans le réservoir. Les villes environnantes d'Orangeville et Mono rapidement développent et utilisent des eaux souterraines comme approvisionnement en eau. La demande croissante des eaux souterraines et les périodes récentes d'été de la basse précipitation rendent la gestion appropriée des niveaux de réservoir essentielle pour répondre à des exigences minimum d'écoulement. Un modèle d'écoulement d'eaux souterraines a été développé pour le secteur d'eaux de plus près de la source en utilisant le modèle FEFLOW pour évaluer la contribution de l'écoulement d'eaux souterraines au système d'eau de surface dans différents conditions et niveaux saisonniers de réservoir. Le modèle emploie le climat et l'eau de surface modelant l'entrée du modèle d'eau de surface de GAWSER pour simuler la variation saisonnière. La compréhension de la contribution d'écoulement d'eaux souterraines des simulations modèles a été employée pour développer un réseau de surveillance et pour mettre à jour les directives opérationnelles pour le réservoir.

1. INTRODUCTION

Water reservoirs, either natural or artificial, are constructed for the purposes of storage, regulation and control of water. These functions serve the rationale of protecting the quality and quantity of water flowing through a watershed system.

Island Lake is a reservoir located at the headwaters of the Credit River watershed, which is maintained and managed by the Credit Valley Conservation Authority (CVC). It was created in 1967 on a 180-hectare area of cedar swamp and farmland. A north and south dam were constructed to impound water in the reservoir. The reservoir's purpose is to meet minimum flow of water for the Town of Orangeville Water Pollution Plant (OWPP). The reservoir also provides a means of flood control, an ecological habitat for wildlife and an area for recreational use.

The south dam marks the beginning of the Credit River and controls the water flow into the Credit River, augmenting low flow periods to maintain water quality in the upper reaches (Figure 1), including assimilation of discharge from the OWPP. There is no flow through the north dam.

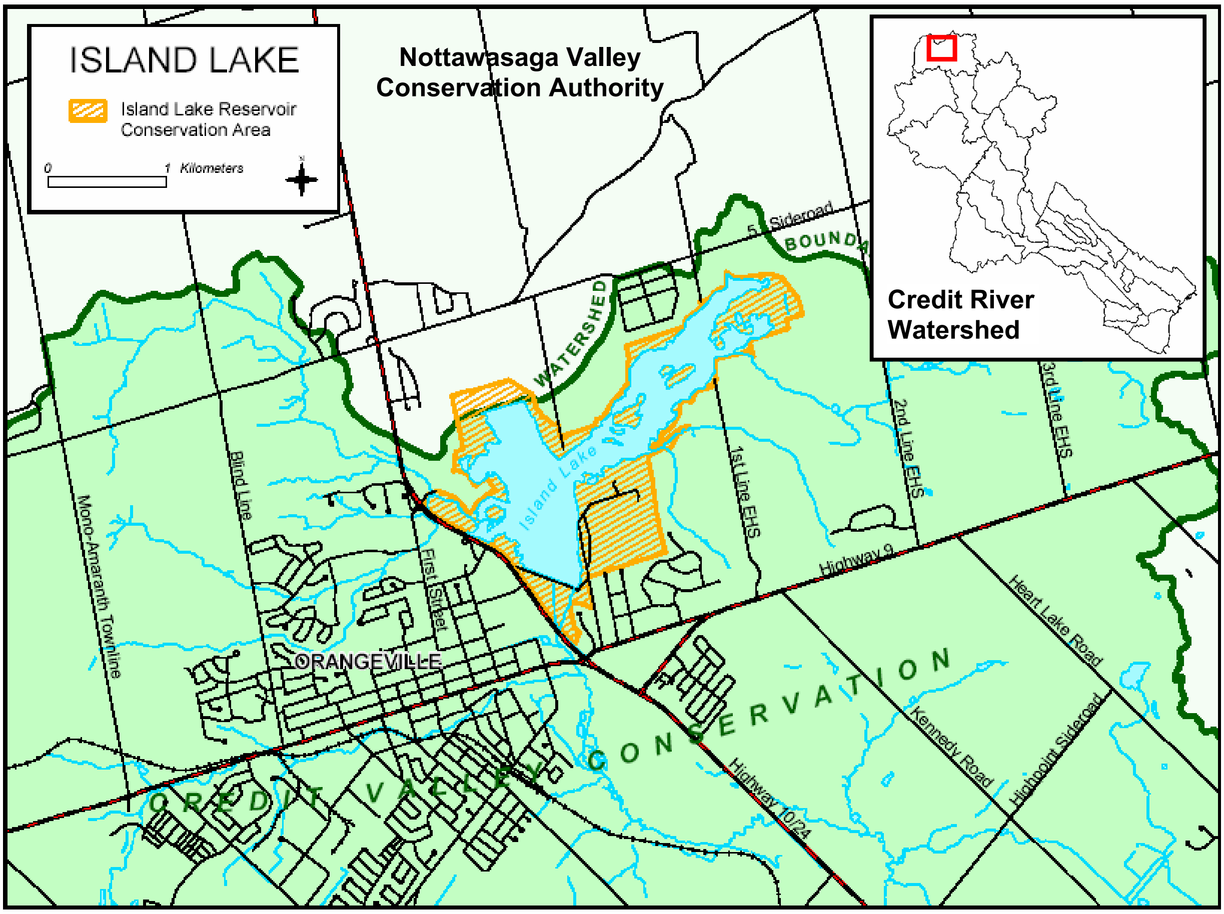

Figure 1. Island Lake Reservoir

Development demands within the Town of Orangeville and Town of Mono are currently being met by municipal groundwater wells. The townships are completely dependent upon a sustainable groundwater supply. The increased demand for groundwater coupled with recent summer periods of low precipitation make proper management of reservoir levels essential to maintain low flows in the Upper Credit.

Long-term management plans are essential tools for operating reservoirs in a responsible manner The purpose of this study is to assess inflows and outflows in relation to the changes in storage in the reservoir using a groundwater flow model for the purposes of developing operating procedures for flow management. This summarizes the modelling completed as part of the first of two phases of the water budget assessment. Once the water budget assessment (Phase 1) has been completed and verified with field data, it can be used to help regulate flows from the reservoir in the Operational Phase (Phase 2). The goal of Phase 2 is to develop rules for effectively regulating flows from the reservoir.

The finite element model, FEFLOW, coupled with the GAWSER surface water model, was used to assess the contribution of groundwater flow to the surface water system under different seasonal conditions and reservoir levels.

2. HYDROGEOLOGICAL SETTING

Topography of the Island Lake study area varies from 520 metres asl at the Orangeville Moraine to 395 metres asl in the Nottawasaga River Valley and the Credit River Valley. Overburden in the area consists of glaciolaustrine silt and clay, glaciofluvial outwash sand

and gravel, and ice-contact deposits. Kames and eskers are scattered throughout the area, in particular in the Orangeville Moraine. Bedrock geology consists predominantly of the Guelph and Amabel Formations (limestones) overlying the Cabot Head Formation (shales), the Manitoulin and Whirlpool Formations (limestone and sandstone) and the Queenston (shale) Formation.

The hydrostratigraphic layer structure in the study area has been thoroughly documented in the Orangeville and Surrounding Areas Groundwater Modeling Study (WHI, 2001) and the Credit River Watershed Groundwater Flow Modeling report (WHI, May 2002 and July 2002). Figure 2 below depicts the hydrostratigraphic units represented in the numerical model.

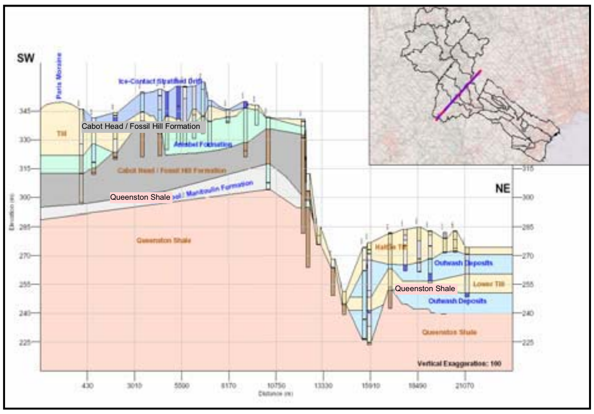

Figure 2. Hydrostratigraphic Units

3. METHODOLOGY

The approach used for this study incorporated the output from the GAWSER surface water model with the finite element model, FEFLOW, to simulate and assess groundwater flow to the reservoir under different seasonal conditions and reservoir levels.

3.1 GAWSER – Surface Water Model

The GAWSER (Guelph All Weather Sequential Event Runoff Model) surface water model of the Island Lake study area was developed by combining and refining the Caledon Creek surface water model (Schroeter and Associates, 1999) and the Credit River Basin Wide model (Schroeter and Associates, 2002).

The GAWSER model uses climate data, surficial soil data, land use, topography and snowmelt data to predict the various components of the hydrologic cycle, such as runoff, surface water flow and groundwater discharge. Parameters such soil data, land use data, snowmelt data, subcatchment boundaries and reach schematics were taken from the above models and incorporated into this study. The long-term meteorological data was derived from the Atmospheric Environment Services (AES) Orangeville MOE station located in Orangeville (6155790).

The model was used to determine the net recharge to the groundwater system and to represent each of the simulation conditions: average annual, wet season, and dry season. Each response unit based distribution was mapped to the finite element mesh for the appropriate simulation as a flux boundary condition.

3.2 FEFLOW – Finite Element Model

A finite element groundwater flow model of the Island Lake study area was developed using FEFLOW (WASY, 2002) by combining and refining the Orangeville Groundwater Flow Model (WHI, 2001) and the regional groundwater flow model developed for the Credit River Watershed (WHI, 2002ab). The model was developed to quantify and characterize groundwater flow in the vicinity of Island Lake and Mill Creek. The FEFLOW model was used to quantify flow into the reservoir and seepage out of the reservoir under a average annual conditions as well as wet and dry season conditions, and utilized particle tracking to illustrate the areas that contribute groundwater flow to the reservoir and Mill Creek under each of these conditions.

3.2.1 Model Application

The extents of the model domain are presented in Figure 3. The model domain was designed to extend to the natural boundaries of the flow system. The finite element mesh consists of 597276 nodes and 1057152 elements. The mesh was refined in areas where it was important to have an enhanced definition of the potentiometric surfaces, enabling representation of all mapped tributaries (CVC, 1998) and municipal pumping wells. The element size ranges from 5 metres around tributaries to 200 metres in peripheral areas.

The domain extended north of the reservoir into the Nottawasaga Valley Watershed to represent seepage from the Island Lake Reservoir, the headwaters of the Nottawasaga River, and observed groundwater flow patterns north of the reservoir (Jagger Hims Ltd., 2002).

The western boundary is located along a river that extends west from Island Lake away from municipal pumping wells, in order to minimize the effect of boundary conditions on model predictions beyond capture zones. The eastern and northeastern boundary of the model is located along part of the Niagara Escarpment and represented as a fixed head and seepage face, respectively.

3.2.2 Model Boundaries

Boundary conditions represent the interaction between the model domain and the surrounding environment. The boundary conditions that are represented in the model include vertical recharge through the upper layer of the model, rivers, lakes at the ground surface and seepage at the Niagara Escarpment. Figure 4 illustrates the location of the boundary conditions in the model.

The finite element mesh was designed to match to the surface water features in the study area. Head dependent (river) boundaries were applied to represent the groundwater-surface water interaction along tributaries.

The resistance to flow is estimated based on the channel bed material properties. This type of boundary condition was used to represent all mapped streams in the wet season simulation, with the stage estimated from the digital elevation model. Only perennial streams were simulated with a boundary condition for the average annual and dry season simulations.

Seepage along the steep sections of the Niagara Escarpment to the north and west of the model domain were also represented with a constrained transfer boundary, whereby water could only leave through the boundary conditions when the water table reached the elevation of the layer.

The Island Lake reservoir was represented as a constant head boundary to reflect information obtained from the Credit Valley Conservation Authority that indicated the yearly variation in the level in the reservoir was less than one metre. The average reservoir level is
411.81 metres asl.

Municipal pumping wells were represented using the well boundary condition and simulated using the 2001 average annual pumping rate. Information on the municipal wells used in this model was derived from the regional CVC groundwater modeling reports (WHI, May and July 2002).

3.2.3 Hydraulic Conductivity Distributions

Hydraulic conductivity information used to calibrate the model was derived from the regional CVC groundwater model and trimmed, within a GIS program, to be incorporated into the current Island Lake model domain. The hydraulic conductivity was extended to represent all three overburden layers using available cross-sections from the Orangeville Model (WHI, 2002).

A cross-section illustrating the variation in the hydraulic conductivity in the model domain is shown in Figure 3 along with a summary of the hydraulic conductivity values.

3.2.4 Model Calibration

The Island Lake model simulations were carried out using steady-state model simulations for each of the three-modeled conditions. This approach provides an estimate of groundwater flow quantities and characteristics under average annual, wet season, and dry season conditions without having to specify a storage value and initial soil moisture condition. The simplified approach still meets the goals of estimating discharge fluxes, reservoir seepage and groundwater flow directions.

Recharge is adjusted between simulations to represent each meteorological condition. Average recharge was developed from monthly GAWSER estimates. The wet condition recharge approximation is based on the March to May period. The June to August recharge estimates simulated the dry conditions.

The FEFLOW model was calibrated to observations of hydraulic head in high quality observation water wells extracted from the CVC water well database under average conditions (WHI, 2002). The model was also calibrated to estimates of baseflow discharge for Monora and Mill Creek.

Calibration statistics for the 72 observation wells indicated an overall mean error of -0.80 m between observed and calculated heads and a NRMS of 8.20%. A model is considered to be calibrated when the % NRMS is less than 10%. An additional check of the ability of the model to represent observed field conditions involves comparing the baseflow discharge estimated from spot flow measurements and the model predicted discharge. For Monora Creek the estimated baseflow is 0.01585 m^3/s and the model predicts a value of 0.0097 m^3/s. For Mill Creek the estimated baseflow is 0.01400 m^3/s and the model predicts 0.007 m^3/s. The model predicts baseflow within +/-50% of single spot flow measurements, which is considered to be reasonable for groundwater discharge to the creek.

4. RESULTS

4.1 Groundwater Particle Tracking

Results of all simulations for the scenarios were compared and analyzed to understand how groundwater flow changes within and around the Island Lake reservoir.

Backward particle tracking was utilized to visualize groundwater flow pathways in the study area (Figure 5). The particles originate at the surface water feature and track backwards through the flow field where they are truncated at the location where they initially recharge to the groundwater system. The particle tracks therefore illustrate the areas contributing discharge to Island Lake.

A visual comparison of the particle tracks for the average, wet and dry seasons indicates that the general groundwater flow patterns are consistent between simulations but that small local differences exist. In all cases the main tributary of Mill Creek exhibits losing conditions along a one-kilometre stretch at a location ending approximately 500 metres upstream of the confluence with the main Credit.

The area of contribution to Island Lake is largest in the dry season and smaller in the wet and average annual season. Seepage out of Island Lake exists under all flow conditions along the northern shore of Island Lake west of the north dam. Seepage in the immediate area

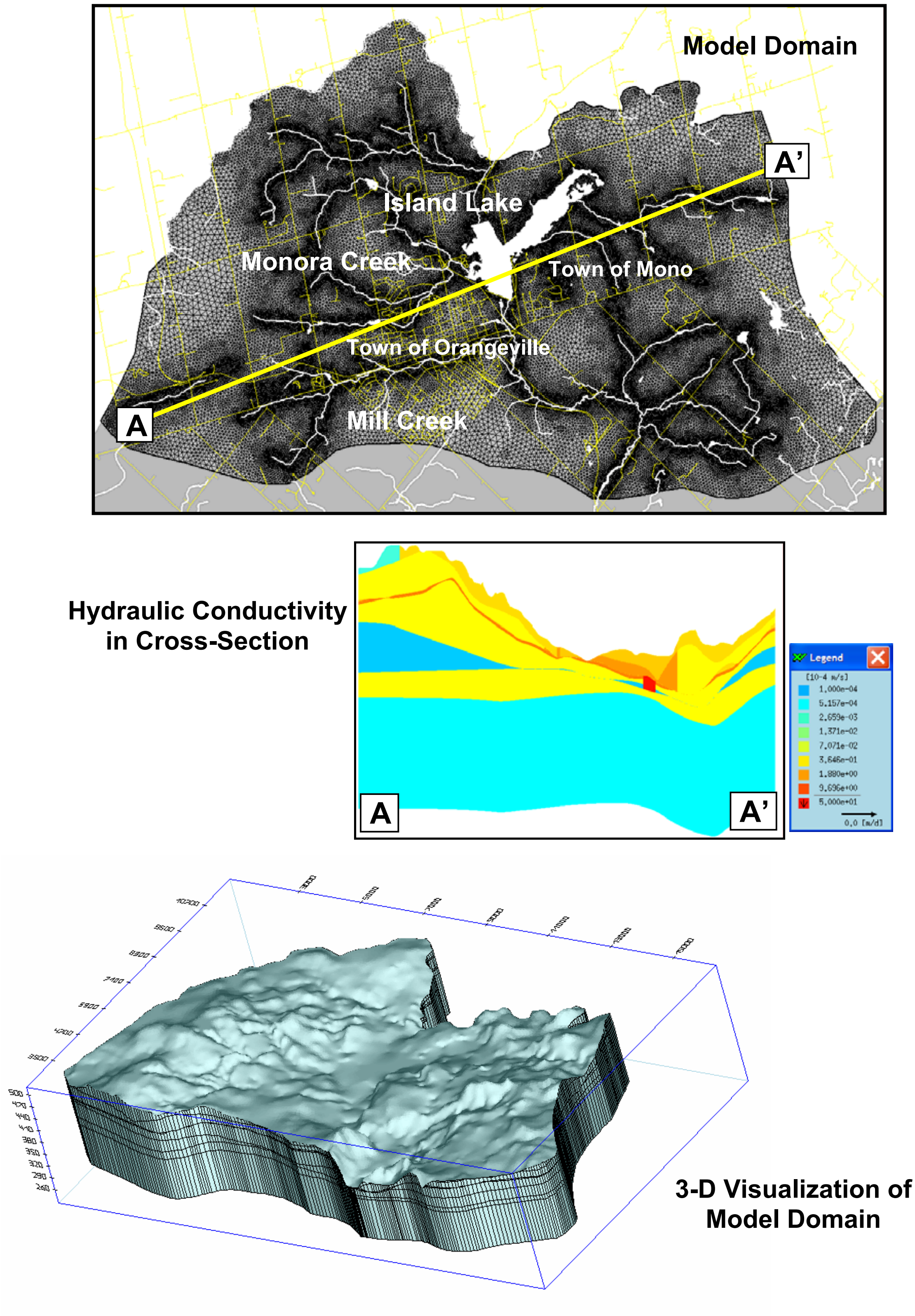

Figure 3. Island Lake model domain

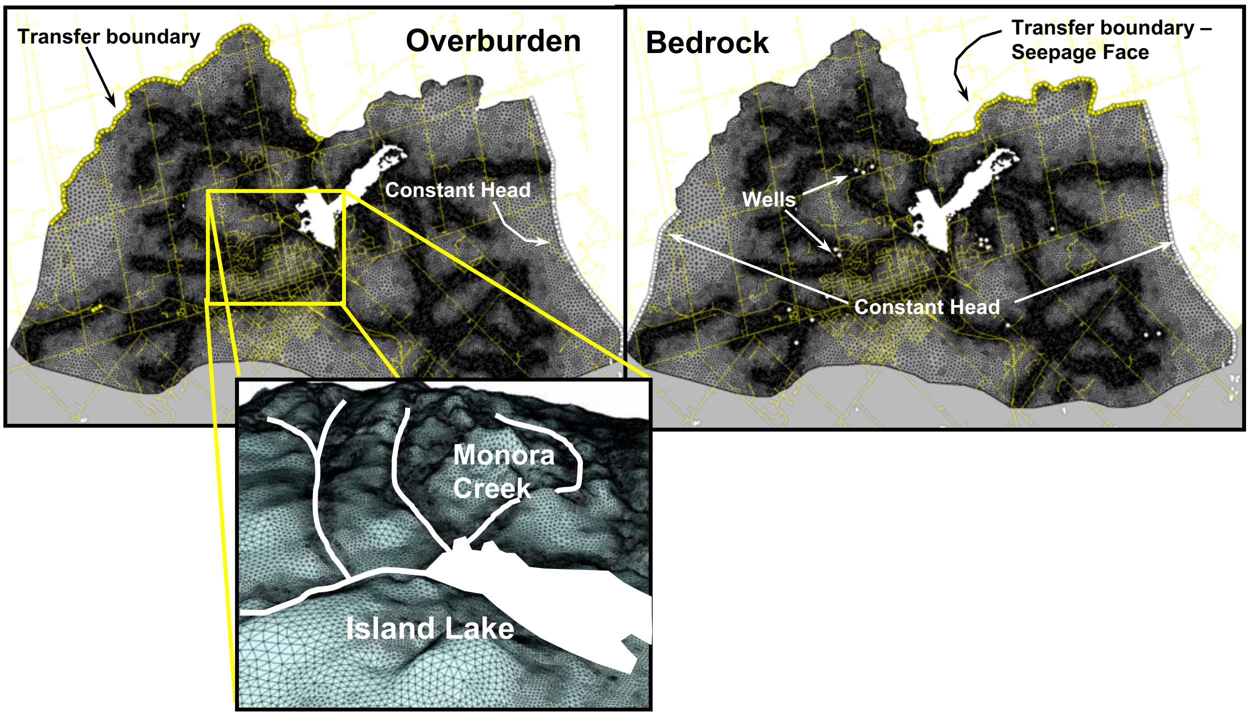

Figure 4. Island Lake model boundary conditions.

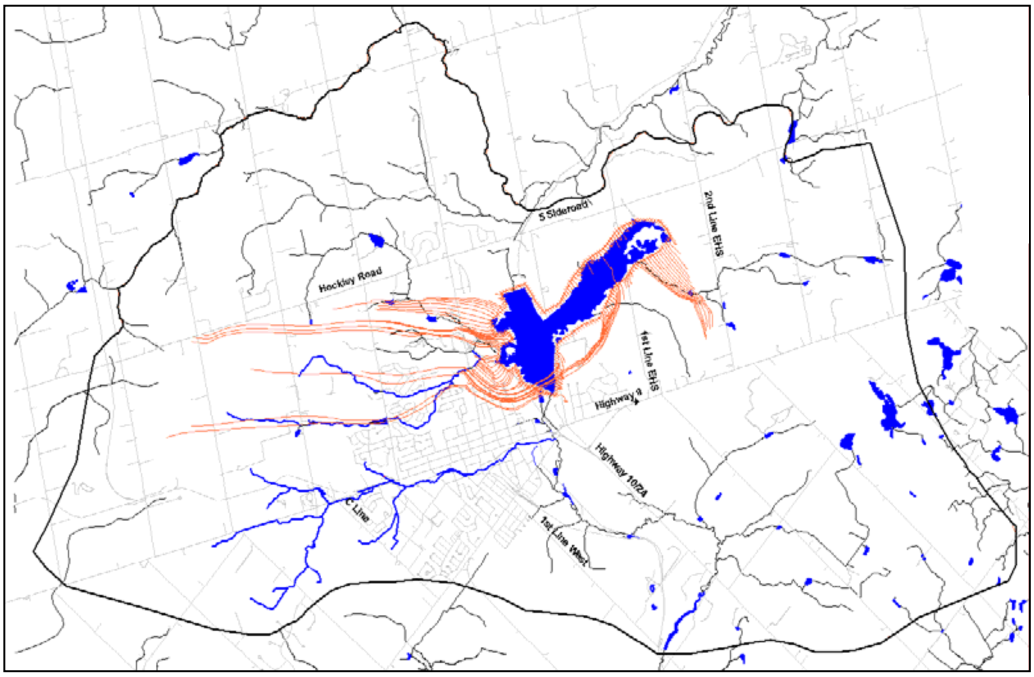

Figure 5. Particle tracks during average conditions.

north dam area, postulated by some to be the source of the headwaters of the Nottawasaga River, does not appear to contribute flow to the Nottawasaga in any of the simulations. Rather the area north of the dam receives discharge from groundwater flow from the area west of the lake. Water that recharges west of the Nottawasaga River appears to be the source of water for the Nottawasaga headwaters, not Island Lake.

4.2 Seasonal Changes of the Island Lake Water Budget

In quantifying the water budget for Island Lake, the Budget and Fluid Flux Analyzer tools included with FEFLOW were utilized to quantify flow in areas of interest. Table 1 summarizes key flow quantities under each of the modelled conditions.

The overall water budget for Island Lake was developed using the combined results of both the surface water model (GAWSER) and the groundwater model (FEFLOW). In addition, the minimum outflow from the South dam was compared to the Orangeville Dam and Reservoir Operations and Maintenance Manual estimates (CVC, 1996).

Table 1. FEFLOW Water budget results for Island Lake

Quantity of Interest	Average Annual Conditions (m^3/d)	Wet Season Conditions (m^3/d)	Dry Season Conditions (m^3/d)
Recharge	14,400	21,465	10,760
Municipal Groundwater Pumping	1,695	1,695	1,695
Net Discharge to Island Lake	4,480	7,790	4,100
Net Discharge to Mill Creek	486	604	448
Estimated Seepage out of Island Lake to groundwater and flowing to Nottawasaga Valley	4,575	3,180	4,250
Estimated Seepage – North Dam	negligible	negligible	negligible
Estimated Seepage – South Dam	negligible	negligible	negligible

The results indicate that under average annual conditions the total flow into the reservoir is composed of 50% from surface water and 50% from groundwater. However 25% of the outflow from the reservoir is to groundwater and 75% supplies flow in the Credit River. Groundwater flow out of the reservoir flows into the Nottawasaga River Watershed (Figure 6), with negligible groundwater flow from the Island Lake area to lower portions of the Credit Watershed (e.g. Mill Creek area).

During the wet season Island Lake receives a 5% increase in surface water inputs primarily from snowmelt, as compared to average conditions (Figure 6). The total flow into the reservoir is 55% surface water and 45% from groundwater. Island Lake contributes 13% of the total outflow to the groundwater while the remaining 87% is released into the Credit River as surface water flow through the south dam. This is a 17% increase, in surface water contribution, from average conditions. Inflow exceeds outflow to Island Lake, which results in an increase in surface water outflow through the south dam and increased reservoir storage (estimated increase of 0.22 m reservoir elevation).

The water budget analysis during the dry season indicates an estimated surface water and groundwater contribution of 46% and 54%, respectively (Figure 6). The Orangeville Dam and Reservoir Operations and Maintenance Manual indicate that the minimum required flow during this period is 9,360 m^3/day. However, during the dry season dam outflow is adjusted more frequently than during the rest of the year. Therefore, this value may not be representative of actual outflow.

Given that the reservoir level is observed to be drawn down by approximately 0.1 m during the dry period and based on the modelled inflows and modelled groundwater outflow, the dam outflow likely exceeds 11,200 m^3/day. The observed decrease suggests that falling reservoir levels over the dry season exceeds inflow, and a reduction in storage in the reservoir.

5. CONCLUSION

Long-term management plans are essential tools for operating reservoirs in a responsible manner. A management plan was needed to address the increasing demand for groundwater for the Town of Orangeville and the Town of Mono in relation to groundwater that flows into the reservoir. This study completes the first of two phases of the water budget assessment. The completion of the water budget assessment (Phase 1) will be used to implement a water-monitoring network that will provide additional hydrogeological information to further our understanding of water contributions to the reservoir and help regulate flows in the Operational Phase (Phase 2). The goal of the operations will be to determine rules for effectively regulating flows from the reservoir.
In Phase 2, inflows to the reservoir will be inferred by knowing changes in storage volume, as provided by the

lake level gauge, surface water discharge from the dam and estimated evapotranspiration losses and seepage losses. The application of the FEFLOW model in conjunction with the GAWSER surface water model provides an excellent tool for modeling groundwater flow and quantifying inflow and outflows for Island Lake during different seasonal conditions.

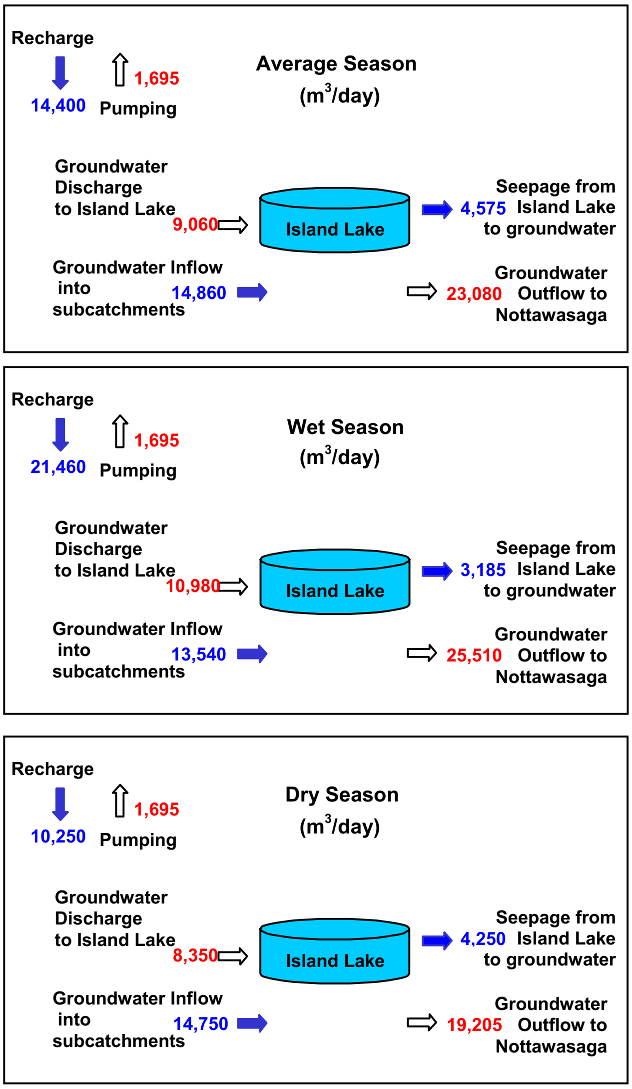

Figure 6. Seasonal Island Lake Water Budget

5. ACKNOWLEDGEMENTS

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