Ecologically Significant Groundwater Recharge Area Assessment for the Oro North, Oro South, and Hawkestone Creeks Subwatersheds

Prepared For:
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This project has received funding support from the Government of Ontario. Such support does not indicate endorsement by the Government of Ontario of the contents of this material.
September 27, 2013

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Newmarket, Ontario,
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RE: Ecologically Significant Groundwater Recharge Area Assessment for the Oro North, Oro South, and Hawkestone Creeks Subwatersheds.

Dear Ms. Howson:

We are pleased to provide a copy of our final report for the Ecologically Significant Groundwater Recharge Area Assessment for the Oro North, Oro South, and Hawkestone Creeks Subwatersheds. Previous reporting described the development and calibration of an integrated surface water and groundwater flow for the Oro Moraine area and the application of the model to conduct the Tier 2 water budget analysis and stress assessment. This report describes the analysis of ecologically significant groundwater recharge areas utilizing the calibrated GSFLOW model.

We trust this report meets with your satisfaction. Should you have any questions, please contact us. We thank you again for the opportunity to work with you on this important study for LSRCA.

Yours truly,

Earthfx Incorporated

# Ecologically Significant Groundwater Recharge Area Assessment for the Oro North, Oro South, and Hawkestone Creeks Subwatersheds

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1 Introduction

The Province of Ontario established the Lake Simcoe Protection Act (2008) and the Lake Simcoe Protection Plan (LSPP) in 2009 to “protect, improve or restore the ecological health of the Lake Simcoe Watershed including water quality, key natural heritage features and their functions, and key hydrologic features and their functions”. The LSPP outlines a number of policies to support the maintenance of adequate flows required to maintain healthy aquatic ecosystems in the Lake Simcoe watershed. Specifically, Policy 5.2.SA requires that LSRCA complete a “Tier 2” water budget and stress assessment for all subwatersheds in the Lake Simcoe and Couchiching/Black River area that have not been assessed at that level under the Source Water Protection program established by the Clean Water Act (2006).

A “Tier 2” water budget is defined as: “a water budget developed using computer-based three-dimensional groundwater flow models and computer based continuous surface water flow models to assess groundwater flows and levels, surface water flows and levels, and the interactions between them” (Director’s Technical Rules for the Clean Water Act, 2006).

Previous reporting described the development and calibration of an integrated surface water and groundwater flow model for the Oro Moraine area and the application of the model to conduct the Tier 2 water budget analysis and stress assessment (Earthfx, 2013).

Policy .36-DP and 6.37-DP-SA discuss the need to define and identify “significant groundwater recharge areas” (SGRA) and “ecologically significant groundwater recharge areas” (ESGRA). SGRAs are defined as areas of above average recharge (1.15 times the average recharge rate) and were delineated for the entire Lake Simcoe basin in an earlier study (Earthfx, 2010). ESGRAs are areas that provide groundwater recharge needed to support ecologically significant features such as coldwater streams and wetlands (discussed further below). ESGRAs are pathway dependent and a linkage must be established between the recharge area and each ecologically significant feature. This report documents (1) the application of the integrated model to analyze groundwater pathlines and thereby establish the linkages and (2) the application of cluster analysis to delineate the extent of the ESGRAs.

1.1 Scope of Work

The Scope of Work for this project includes two main parts: (1) the Tier 2 water budget analysis and stress assessment; and (2) the identification and analysis of ecologically significant groundwater recharge areas.

Part 1 of this study, the Tier 2 water budget and stress assessment, has been completed and was documented in Earthfx (2013). That phase included the following tasks:
• compile and assess available background information and data;
• assess available background information and data relative to the surface water flow/runoff model;
• analyze information and data gaps and define additional data requirements to enable the model to estimate hourly runoff and simulate the hydraulic behaviour of streams in the study area;
• develop and calibrate the integrated surface water and groundwater flow model:
  • apply techniques to enable the model to use hourly climate information as input;
  • calibrate the model to daily observed streamflow records concurrently with monthly and annual volumes to achieve the best overall fit;
  • simulate channel routing and wetland routing; and
  • simulate open-water (i.e., lake/wetland) evaporation and recharge
• estimate surface water/groundwater consumptive use;
• utilize the calibrated integrated surface water/groundwater model to assess water budget elements for each subwatershed; and
• apply the model for scenario analysis (existing and future water use conditions and drought conditions).

Part 2 of this study includes the following tasks:

• conduct an assessment of ESGRAs, utilizing the calibrated model from Part 1, to identify the portions of the landscape that contribute discharge to cold water stream reaches and wetlands delineated by LSRCA; and
• assess data and knowledge gaps for future improvements.

Tasks common to both Part 1 and Part 2 include:

• prepare interim memoranda, meeting minutes, and draft and final reports;
• present various aspects of the project to LSRCA staff and Provincial staff;
• undertake all required project management; and
• transfer all digital information (including modelling files, GIS files, data files, etc.) to LSRCA staff. This will include model set up on LSRCA staff computers and basic instructions of how to run the model.

This report describes Part 2 of the study and presents results of the application of the integrated model to delineate ESGRAs within the study subwatersheds.

1.2 Study Area Location

The Oro North, Oro South, and Hawkestone Creeks subwatersheds are located in the northwest portion of the Lake Simcoe watershed (Figure 1). The subwatersheds are contained within the Township of Oro-Medonte and the City of Orillia, both of which are within Simcoe County. Some general properties of the subwatersheds are provided in Table 1.

The LSPP emphasizes a subwatershed assessment approach and, accordingly, the primary focus of this study is on delineating ESGRAs in the three subwatersheds. It is important, however, to recognize that these subwatersheds are part of a larger hydro-physiographic and geologic feature; the Oro Moraine. The Oro Moraine is an area of high recharge that provides
headwater flow to numerous streams that drain to Lake Simcoe, Minesing Swamp and Georgian Bay. A broader understanding of the hydrology and hydrogeology of the Oro Moraine was necessary to understand the three subwatersheds and, in particular, the movement of groundwater flow across subwatershed boundaries that can influence groundwater pathways and, ultimately, the location and extent of the ESGRAs. Accordingly, a larger Oro Moraine study area, labelled as “Model Boundary”, was defined as shown in Figure 1.

The Oro Moraine model boundary area (Figure 1) defines the extent of the integrated groundwater and surface water flow model developed for the purpose of this ESGRA study. This larger study area contains portions of the City of Barrie and of Springwater, Tay, and Severn Townships and includes most or all of the catchments of Sturgeon River, Coldwater Creek, Silver Creek, Matheson Creek, and Willow Creek.

### 1.3 Model Development

A study methodology was developed to address a number of key watershed and technical analysis issues. While more detail is provided in the Phase 1 report (Earthfx, 2013), one consideration was weighing the benefits and limitations of using one numerical flow models developed prior to the Earthfx (2013) study. It was concluded that no previous model addressed all of the technical requirements for the water budget and ESGRA analyses without a considerable effort to expand or re-work the existing model. Accordingly, a new integrated surface water/groundwater model, specifically designed to incorporate the latest OGS Oro Moraine stratigraphy, was developed for this study.

The technical approach centered on constructing a fully-integrated model using the U.S. Geological Survey (USGS) GSFLOW code. GSFLOW incorporates two submodels – the PRMS hydrologic model and the MODFLOW-NWT groundwater model. The PRMS model was already applied to the Oro North, Oro South, and Hawkestone Creek subwatersheds as part of a larger hydrological model development study for the entire Lake Simcoe basin (Earthfx, 2010). The PRMS model was updated and extended to cover other subwatersheds outside the LSRCA that include portions of the Oro Moraine. Similarly, a new groundwater model (incorporating some of the previous work by Beckers and Frind (2000, 2001) and the other Tier 2 SWPP numerical models), was developed. The new groundwater model incorporates the complete OGS 2011 conceptual hydrostratigraphic model (Burt and Dodge, 2011).

The advantages of the integrated modelling approach are manifold: foremost are (1) that the all headwater streams and provincially significant wetlands are represented properly in the model, (2) the relationships between the surface water bodies and their recharge areas are properly simulated, and (3) all components of the hydrologic cycle are represented directly in the model with feedback provided between the groundwater and surface water systems. As noted, the model area was expanded to include the entire Oro Moraine area (i.e., Coldwater Creek, Willow Creek, and Silver Creek subwatersheds) and, most importantly, the model calibration included data from the gauges on those streams. Beckers and Frind (2001) had concluded that additional data were needed to quantify the water budget for the Oro Moraine. By expanding the model study area to include these stream gauges and the additional PGMN wells in these subwatersheds, Earthfx pursued a logical means of addressing that recommendation. These gauges and observation wells provided additional calibration targets and helped reduce model uncertainty. An integrated model, developed with a focus on the shallow groundwater flow system, headwater streams, and wetlands, was also the best approach to address the finding of
Beckers and Frind that correctly representing the near-surface heterogeneity is critical to the delineation of sensitive recharge areas.

Other key advantages of the GSFLOW code pertinent to this study include:

- Ability to refine the upper model layer to a finer mesh than the deeper groundwater system, so as to provide a better representation of recharge processes;
- Increased computational stability with the new MODFLOW-NWT solver, specifically designed for the simulation of shallow, heterogeneous, partially saturated layers;
- Advanced particle tracking, based on the open-source MODPATH code.

The selected methodology ensured that, in addition to the Tier 2 objectives, the model best represented the recharge processes and discharge to ecologically significant features. A complete description of model development and calibration is provided in the companion Phase 1 report (Earthfx, 2013).

### 1.4 ESGRA Delineation

Ecologically significant groundwater recharge areas are defined as areas of land that are responsible for supporting groundwater discharge that, in turn, helps sustain sensitive features like coldwater streams and wetlands. To establish the ecological significance of the recharge area, a linkage must be present between the recharge area and the discharge to ecologically significant feature (e.g., a reach of a coldwater stream, a wetland, or an area of natural or scientific interest (ANSI)). The identification of an ESGRA is not necessarily related to the volume of recharge that may be occurring and it is not a certainty that ESGRAs will coincide with significant groundwater recharge areas (SGRAs), as they may not represent areas of high volumes of recharge. While ESGRAs and SGRAs are not always spatially correlated, the areas of high recharge often tend to support ecologically sensitive features. Put simply, many SGRAs contain ESGRAs but not all ESGRAs are SGRAs.

The identification of SGRAs has been an important element of recent Source Water Protection initiatives in Ontario. The SGRA methodology delineates areas where recharge is 15% greater than average. This has prompted considerable discussion of the term “significant,” because simply mapping areas of high volume recharge may not be enough to protect the function of key wetlands, riparian areas, stream reaches, or fish spawning areas. Therefore, defining a recharge area as ecologically significant implies that it contributes a substantial portion of the total groundwater discharge received by these ecological features. To address this more stringent definition, a new methodology was developed to assess significance by combining numerical models and statistical analysis to verify the hydrologic connection between recharge areas and ecologically important surface features (Earthfx, 2012). This resulted in a quantitative and repeatable technique for the identification of ESGRAs. This method has been applied in other studies within the Lake Simcoe basin.

The ESGRA delineation methodology, described in detail in the next section, employs particle tracking techniques to identify, visualize and quantify the groundwater flow paths between the ecological feature and the recharge area. To conduct the particle-tracking analysis, a groundwater model is first used to determine groundwater heads and fluxes between all model cells. A velocity flow field is then derived from the cell-by-cell fluxes. Next, virtual “particles” are
released in the model and traced (in either a forward or reverse direction) through the flow field to delineate three-dimensional pathways and transit time to an exit or entry point. Specifically, particles can be tracked backward from areas of ecological interest through the groundwater system to locations of recharge. The particle track endpoints are grouped and analyzing to determine the particle endpoint density. While particle density does not correspond directly to recharge volumes, it does help establish that a significant amount of the recharge in the area is delivered to the ecological feature. Figure 3 illustrates backward particle tracking from a typical significant ecological feature to an area of recharge.
2 ESGRA Delineation Methodologies

Earthfx developed a general methodology for delineating ESGRAs as part of a recent ESGRA delineation study for the Barrie, Lovers and Hewitt Creek watersheds (Earthfx, 2012). Although the flow model code used in the earlier study is different than the one used in this study (FEFLOW versus GSFLOW), the ESGRA methodology was specifically developed to be model-independent. A brief summary of the approach is provided below.

2.1 Particle Tracking

Particle tracking is an accepted methodology for visualizing and understanding groundwater flow paths. It is particularly useful in areas with complex, three-dimensional groundwater flow. As noted above, an integrated groundwater/surface water flow model was developed for the Oro Moraine area based on the USGS GSFLOW code (Markstrom et al, 2008). The model is based on a linkage between two submodels, the PRMS hydrologic model and the MODFLOW-NWT groundwater model. Groundwater recharge and evapotranspiration rates are computed on a daily basis, snowpack energy balance is updated twice daily, and the runoff/infiltration partitioning is computed on an hourly basis by the PRMS submodel. The MODFLOW-NWT submodel is applied to determine groundwater heads in each cell in a three-dimensional mesh used to represent the aquifers and aquitards in the study area as well as to determine the flows across each face of the cell.

The heads and cell-by-cell fluxes are saved for post-processing by the USGS MODPATH v6.0 code (Pollock, 2012). The MODPATH code uses the MODFLOW-NWT output along with estimates of aquifer porosity to determine local groundwater velocities within each cell. Virtual particles can be released at any point within a cell and then forward tracked from one cell to the next until it reaches a model boundary or an internal discharge point (e.g., a stream or well). Particles can also be tracked backwards from any discharge point in the model to their points of origin. Pathlines can be displayed by connecting the points along the flow path (see Figure 3). Particle endpoints (i.e., the location at which the flow path intersect land surface – representing the exit points when forward tracking or the entry points when backward tracking) can also be displayed or recorded in a database for further analysis.

For forward tracking in the direction of flow, particles are usually introduced in a uniform distribution across the model area. Forward tracking can be applied to help define and visualize the regional flow system. With forward tracking it is often necessary to release an extremely large number of particles in order to clearly illustrate the discharge to ecologically significant locations.

With backward tracking, particles are introduced in a dense distribution at a point of interest (e.g., an ecological feature supported by groundwater discharge) and traced back to the point of recharge. A benefit of reverse tracking is that attention can be focused on a limited set of specific ecological features.

Practical limits to the number of particles that can be applied uniformly across the model area and limits in the number of particles that can be packed into a discharge area may cause some small variations in model results. Differences can occur when simulating flow in complex flow...
fields. For example, if groundwater is moving through "windows" in a regional aquitard, it may be difficult to identify all the possible particle paths through the windows if only a limited number of particles are released. Figure 4 is a schematic showing a particle release density that fails to capture flow through a window in a regional aquitard.

Another advantage of backward tracking is that clusters of particle endpoints can help identify recharge areas that are important to a specific ecological feature. The density of particle endpoints can be used as an indicator of the significance of the recharge area. This is the basis for the delineation of ESGRAs in this study.

2.2 Bivariate Kernel Density Cluster Analysis

Once the backward particle-tracking endpoints originating from ecological features have been identified, clusters of endpoints are examined to determine ESGRA boundaries. The method used to identify clusters was adopted from published, peer-reviewed cluster analysis methodologies. Earthfx tested and refined the technique so that it could be applied to other subwatersheds and ensure that delineation of ESGRAs across Southern Ontario could be conducted in a consistent manner. Details of the method developed to objectively evaluate endpoint clusters and delineate ESGRAs are presented in Earthfx (2012).

Typically, particle tracking endpoints cluster in areas of focused higher recharge; while areas of diffuse recharge may end up with distributed, individual or small groups of particles. Manually or visually distinguishing between endpoints belonging to a cluster and isolated particles (outliers) can be rather subjective. For the purpose of this paper, “clusters” are defined as areas with a relatively high density of particle track endpoints. Endpoints that lie outside of the clusters are considered of lower significance and are excluded on the basis that they do not represent an ecologically significant volume of recharge. The delineated clusters are deemed to represent ESGRAs based on the assumption that the density of particle track endpoints correlate to recharge areas that are significant to sustaining groundwater discharge within these ecological features.

A consistent and repeatable method of identifying clusters was developed based on multivariate kernel density function, \( \hat{f}_h \), as defined by Wand and Jones (1993). In its two-dimensional (bivariate) form, it is given as:

\[
\hat{f}_h(d_i) = \frac{1}{2\pi nh^2} \sum_{i=1}^{n} e^{-\frac{d_i^2}{2h^2}}
\]

where:

- \( n \) = the total number of endpoints;
- \( h \) = the smoothing (or bandwidth) parameter; and
- \( d_i \) = the distance between endpoint \( i \) and the point in space being evaluated.

The choice of the Gaussian kernel function is somewhat arbitrary as a uniform, triangular or inverse-squared distance kernel (amongst others) could also be used to define the distribution of particles within a cluster. The Gaussian distribution is consistent, however, with the dispersive processes typically encountered in groundwater flow due to heterogeneity and variations in hydraulic conductivity. It is also our findings that the cluster evaluation is more
sensitive to the bandwidth parameter (i.e., the smoothing parameter) than the choice of kernel. The kernel provides a weighting function; giving stronger weights to endpoints in close proximity to the point in space that is being evaluated.

A second phase of cluster processing is needed to normalize the density field and eliminate areas of relatively small density. This helps to eliminate ESGRAs of very small areal extent and to infill any “doughnut-holes” present in an ESGRA. Removing areas of small density is accomplished by first defining a delineation cut-off threshold ($\varepsilon$) and eliminating all areas where the calculated density is less than a $\varepsilon^{th}$ of the maximum evaluated $\hat{f}_h$ (i.e., eliminating all areas where $\hat{f}_h < \frac{\hat{f}_{h,\text{max}}}{\varepsilon}$).

Earthfx (2012) discussed the results of varying $\varepsilon$ and $h$ on the extent of the ESGRAs. The analysis showed that a delineation cut-off threshold on the order of $\varepsilon = 100$ produced better results and ensured that any area where the evaluated $\hat{f}_h$ is less than 1% of the maximum ($\hat{f}_{h,\text{max}}$) was removed from the final ESGRA coverage. Similar sensitivity analyses were conducted for this study to determine the optimal set of parameters and are discussed in Section 3.2.

In Earthfx (2012), the minimum allowable ESGRA extent was set to 0.045 km$^2$, which corresponded to the average model element area. Similarly, doughnut-holes less than 0.045 km$^2$ were filled in to produce continuous ESGRA delineations. When complete, the Normalized Bivariate Kernel Density Estimation (NBKDE) procedure with the application of the delineation thresholds and the removal of outliers and holes defines the ESGRAs. The advantage of the NBKDE method is that it is unbiased compared to grid-based counting methods which are dependent on grid size, origin, and orientation.
3 **ESGRA Delineation Results**

3.1 **Particle Tracking Results**

3.1.1 **Particle Release Points**

As noted in the Phase 1 report, all mapped streams and wetlands in the Oro Moraine area were represented in the model. Based on consultation with LSRCA staff, all stream reaches and wetlands in the study watersheds, shown in Figure 5, were assumed to be significant for the purpose of this study (regardless of cold water versus warm water stream classification). Figure 6 presents the model release locations for the backward tracking analysis from streams.

Particles were released into the model at the top of layer 1 in a manner consistent with the methodologies outlined by Earthfx (2012). Released particles were tracked backwards from the stream or wetland feature, through the groundwater system to their originating, recharging model cell. Pathlines may cross multiple cells or model layers; particle paths within each cell are determined by the simulated groundwater flows across each cell face. The hydraulic conductivity, porosity, and thickness of each model cell are considered when calculating the groundwater velocities.

Particles were released at surface into all model cells containing a stream segment. In each model cell, particles were released on a 5 m x 5 m spacing to ensure that enough particles were included to delineate the interactions between the groundwater, stream channel and the riparian areas adjacent to the stream. Based on this distribution, a total of 400 particles were released in each 100 m by 100 m model cell.

Particles were also tracked back from wetland features identified in the ELC mapping provided by LSRCA (Figure 5). Particles were released in model cells representing wetland features on a 5 m by 5 m spacing. A total of 1,599,200 particles were released into model cells with significant features for the backward tracking analysis (Figure 6). It should be noted that the mapped wetlands contain areas that may have saturated soils and/or standing water for only parts of the year. The GSFLOW model accounts for the time-dependent variation in soil saturation and water-table position in these areas. For this analysis, however, the full extents of the mapped wetlands were considered as ecologically significant features, not just the permanently saturated or inundated areas.

The total number of particles released was an order of magnitude greater than in the pilot study (Earthfx, 2012), where particle release densities of less than 20 m x 20 m were found to be sufficient. A density of 5 m x 5 m was found to be more than adequate to identify all the relevant recharge pathlines in this model.
3.1.2 Reverse Tracking Endpoint Results

The endpoints of the backward tracked particles released from streams and wetlands, respectively, are shown on Figure 7. Of the particles released, approximately 955,200 (60%) were released into discharging cells. These were used for endpoint analysis and ESGRA delineation. The remaining particles were released into cells that were found to be locally recharging the groundwater system (e.g., a losing stream reach or a part of a wetland contributing groundwater recharge). These particles did not leave the starting cell and were therefore excluded from the endpoint analysis. Of the valid endpoints, about 894,700 (93.7%) remained within the study area subwatersheds, while the rest tracked backward into neighbouring subwatersheds.

3.1.3 Illustrative Pathlines

Figure 8 illustrates the pathlines from the significant features within the study subwatersheds. For illustrative purposes, particles were released at a sparser density of only four particles per model cell (50 m by 50 m particle spacing). (At the finer 5 m by 5 m analysis spacing, the density of the pathlines is so high that individual pathlines cannot be presented on a regional-scale figure). As can be seen, a small number of pathlines cross subwatershed boundaries and track back to recharge areas outside of the study area subwatersheds. As noted, approximately 7% of the pathlines leave the study watershed boundaries and terminate in areas further west along the moraine. While the number of pathlines leaving the study subwatersheds is not large, it does indicate that some significant features, in particular the headwaters of Hawkestone Creek, are likely receiving significant quantities of lateral groundwater inflow from outside the subwatershed.

The pathlines also help to illustrate the connections between the groundwater system and specific surface features. For example, the headwaters of Hawkestone Creek and the east and west tributaries of Bluffs Creek have long pathlines that connect back to the Oro Moraine, an area of high recharge. As noted in Earthfx (2013), groundwater seepage occurs along the entire length of these stream channels. Seepage to these creeks was not significantly affected during the 10-year drought simulation. On the other hand, Shellswell’s Creek and the lower reaches of Hawkestone Creek have short pathlines that do not extend to the Oro Moraine and these features rely on local recharge on the alluvium and the Newmarket Till. These streams were found to be very sensitive to drought conditions. Further discussions can be found in Earthfx (2013).

3.2 ESGRA Delineation

ESGRAs were delineated by analyzing the particle endpoint locations using the bivariate kernel density estimation technique for cluster analysis presented in the previous section of this report.

The sensitivity of cluster analysis results were assessed by varying the NBKDE smoothing parameter (h) and the delineation threshold (ε). The smoothing parameter was varied in steps from 10 to 500 m and the delineation threshold was varied in steps from 10 to 1000. Table 2 presents the percent of the endpoints within the delineated ESGRAs with respect to the number
of particles released (excluding particles that did not leave their starting cell). Table 3 presents the corresponding total area delineated as potential ESGRAs for various values of the NBKDE parameters (h, ε). Area as a percentage of the study subwatersheds is provided on Table 4. Table 5 presents the ESGRA cluster density (i.e., the number of endpoints that are contained within a potential ESGRA divided by the total combined ESGRA coverage area). Based on the results shown in Table 2 through Table 5 and on consultation with LSRCA staff, the optimal kernel smoothing parameter h was set to 25 m, which is equal to the grid cell spacing for the kernel analysis. A delineation threshold, ε = 200 (or 1/ε = 0.005), was chosen because it proved to consistently identify particle clusters while meeting the following criteria:

- rejection of endpoints that clearly did not belong to any cluster;
- delineation of clusters with a relatively high density of particle endpoints; while
- not incorporating areas where endpoint density is low or zero.

The final combined ESGRA mapping using these parameter values is provided in Figure 9, which shows ESGRA delineation for all ecological features including streams, riparian zones, ponds, and wetlands. To visually illustrate the clustering, Figure 10 overlays all reverse particle tracking endpoints (black dots) on top of the final ESGRA zones. Of the released particles, 96% are included in ESGRA zones. ESGRAs having an area less than 0.045 km² were excluded, consistent with the approach of Earthfx (2012).

Table 6 provides a breakdown of the ESGRA coverage within each subwatershed. The coverage varies between the catchments, with 15% coverage within the Oro South subwatershed versus 26% and 23% within the Hawkestone and Oro North subwatersheds, respectively. The smaller percent ESGRA coverage in the Oro South subwatershed is likely a result of the presence of a silty to sandy silt till at surface that reduces recharge to the groundwater system. This is consistent with the Phase 1 report analysis (Earthfx, 2013). Topography on the drumlinized till plain also helps to create localized shallow flow systems.

### 3.3 Forward Tracking Verification

Forward particle tracking was used verify the reverse particle tracking analysis and demonstrate that:

- the particle release density used in the backward tracking was sufficient; and,
- other significant recharge areas contributing to the streams and wetlands were not missed.

Forward tracking also provides a tool to assess linkages between recharge areas within the study area and ecologically significant features in adjacent subwatersheds.

#### 3.3.1 Area-wide Forward Tracking

Particles were released on a 10 m by 10 m spacing across the upper faces of all cells in the three study area subwatersheds. A small buffer area around Lake Simcoe (which is represented with constant head boundaries) was excluded. Approximately 1.6 million particles were released within the study area. Of these, about 1.2 million particles moved to a point
outside of the release cell. (The others were placed in cells that proved to be discharge points in the model.)

Figure 11 illustrates the resulting forward-tracking particle endpoints. Approximately 4% of the forward particle tracks are seen to cross the topographical watershed divide to the north and west. The forward tracking results suggest that the study area subwatersheds may be a source of recharge to other catchments, in particular Bass Lake and the headwaters of Coldwater Creek, through cross-boundary flow.

### 3.3.2 Forward Tracking from ESGRA Zones

As a verification exercise, forward tracking was conducted from the delineated ESGRAs shown in Figure 9. Particles were released on a 5 m x 5 m spacing grid over the ESGRAs and forward tracked to a final destination. Results are shown in Figure 12. It can be observed that the majority of the particle tracks end either in, or adjacent to, the stream and wetland features. Because of the cross-watershed boundary flows, some particles released from the ESGRAs exit the study area and may help support ecological features in other catchments.

It can also be noted that the western portion of the Hawkstone Wetland has no forward-particle tracking endpoints because the backward-tracking analysis showed that much of the recharge was coming from outside the subwatershed. Many of the wetlands in the centre of the Oro South and Hawkstone subwatersheds, for example those northeast of Guthrie, have no particle endpoints. These wetlands are situated in low-lying areas on the drumlinized till plains and are likely supplied primarily by runoff which collects and recharges the water table.

Comparing the endpoints of the forward tracked particles released across entire study area (Figure 11) to the endpoints of forward-tracked particles released only at ESGRAs provides a qualitative assessment of the adequacy of the ESGRA delineation. (Forward tracking from the study area could show pathlines that were unaccounted for in the backward-tracking exercise.) By comparing the two figures, it can be seen that there are no additional pathlines intersecting ecologically significant areas. This confirms that the number of backward tracked pathlines (or the resolution of released particles) was sufficient to delineate ESGRAs with the groundwater model.

### 3.4 Comparison of ESGRA and SGRA Results

Significant groundwater recharge areas were delineated by Earthfx (2010) for the Lake Simcoe watershed utilizing a PRMS-based hydrologic model. SGRAs were delineated as per Technical Rule 44(2)(1) as: areas where the rate of recharge is greater than a factor 1.15 of the average recharge across the area (MOE, 2009). The SGRAs identified in the study area are shown in Figure 13. It should be noted that these SGRAs were defined based on the average recharge across all watersheds contributing to Lake Simcoe.

As noted earlier, it is not a certainty that these areas of higher than average recharge coincide with ecologically significant groundwater recharge areas (ESGRAs). Figure 14 compares the ESGRAs delineated in this study with the SGRAs identified in Earthfx (2010). While the total area of the study subwatersheds delineated with each method is similar, the ESGRAs and
SGRAs vary in spatial distribution. Substantial differences can be seen over the till plain where the SGRA analysis misses the lower-volume local recharge systems.

Better correlation is evident on the Oro Moraine where the high-volume recharge areas help to sustain the headwater creeks and the streams and wetlands in the Oro North subwatershed. Much of the differences between the mapped extents of the SGRAs and ESGRAs is likely a result of delineating the SGRAs using only a surface water model while the ESGRAs are delineated using an integrated model. The integrated model provides the linkages between the recharge and discharge areas and can help identify the portions of the SGRAs that provide significant recharge to the target areas. Also, using an integrated modelling approach captures the interaction between the surface and groundwater processes and includes the feedback mechanisms that affect the distribution of recharge and groundwater flow patterns. As an example, most areas mapped as surficial sands would likely be identified as high volume recharge areas. By including the subsurface geology and the water-table response to recharge in the integrated model, sandy areas with high water table and sandy areas underlain by shallow tills would have less recharge and more runoff than areas with thicker sands and deeper water table.

To better understand the movement of recharge away from the defined SGRAs, forward tracking was undertaken from these areas. Particles were released on a 5 m x 5 m grid over the SGRAs and tracked forward to the pathline endpoints shown on Figure 15. Some endpoints do terminate within the ecologically significant features in the study area. However, a significant portion of the SGRAs appear to contribute to features outside the study area, such as Bass Lake and the Coldwater River watershed. In summary, while the SGRAs represent high volume recharge areas, ESGRAs better represent recharge areas that contribute to features of ecological significance within the study subwatersheds. Areas where ESGRAs and SGRAs overlap, for example, on the Oro Moraine, provide significant volumes of recharge to ecologically sensitive features in the study area subwatersheds. The SGRAs may also provide flow to areas outside of the study area subwatersheds. ESGRAs which don't coincide with SGRA, such as those on the till plain, tend to represent lower volume, localized flow systems which provide flows needed to maintain the ecologically significant features.
4 Supplemental Analyses

4.1 Regional Recharge from the Oro Moraine

To better understand the role of the Oro Moraine in sustaining the function of hydrologic features in the model area, regional-scale forward tracking from the Oro Moraine physiographic zone was completed. For endpoint analysis, particles were released on a 20 m by 20 m spacing (25 particles per cell) across the upper faces of all cells on the moraine. (To illustrate pathlines in the report figures, only one particle per cell was released.)

Particle pathlines are shown in green on Figure 16 along with the particle endpoints. The pathlines show that groundwater flow is radially outward from the Oro Moraine. The endpoints, shown as red dots, cluster in the groundwater discharge areas and illustrate that the Oro Moraine serves to provide flow primarily to the headwater streams and to the wetlands at the base of the moraine zone. The moraine also provides flow to Bass Lake. Some endpoints are located at larger distances from the moraine, for example, near Bluffs Creek East Wetland and the wetlands at the headwaters near Carley (between Sugarbush and Moonstone). Some of the particle tracks reach the Lake Simcoe shore. This illustrates the deeper flow systems that exist beneath the till confining units.

The shallow and deep flow systems can be clearly seen when the flow lines are projected on cross sections through the Oro Moraine. The locations of two diagonal sections are shown on Figure 17. Figure 18 shows the flow paths along northwest-southeast section A-A’ and Figure 19 shows the flow paths along east-west section B-B’. The figures highlight the mainly vertical flow through the aquitards and lateral flow through the aquifers. The tracks also show the direct linkage between the Oro Moraine and the Hawkstone Creek and Bluffs Creek wetlands. As noted in Earthfx (2013) the connection to the groundwater stored in the Oro Moraine helps sustain these features during prolonged drought. The complexity of the groundwater flow paths reflect the complexity and spatial variability in aquifer and aquitard hydraulic properties, thickness, and continuity as well as the variability in recharge and degree of interaction with surface water features. For example, leakage through the tills is focussed in areas where the tills thin out. Also shown is the influence of the tunnel channels which capture a large number of flow paths from the moraine, shown on Figure 18. Flow moves vertically through the regional aquitards (Newmarket Till, AT1, and AT3) and then moves north towards the tunnel channel through the regional aquifers AF3 and AF4 and eventually discharges to the Coldwater River.

4.2 Groundwater-Lake Interaction

As an additional exercise to better understand groundwater interaction with Bass and Little Lake, forward and backward tracking was conducted at these two locations. In the backward tracking analysis, one particle was released per cell to trace the pathlines. Results of the backward tracking are presented in Figure 20 and show that Little Lake has a fairly small contributing area and may be fed primarily from stream inflows, surface runoff and rainfall. Bass Lake has a much larger capture zone which extends almost to the centre of the Oro Moraine.
Forward tracking was done by placing points in cells representing the lakes. Results, shown in Figure 21, confirm that Bass Lake is a groundwater discharge area (no particle tracks originate from the lake). Tracks emerging from Little Lake indicate that there are seepage losses from the bottom of the lake that appear to contribute to two City of Barrie municipal wells.
5 Conclusions

An Ecologically Significant Groundwater Recharge Area (ESGRA) assessment was completed for the Oro North, Oro South, and Hawkestone Creeks subwatersheds using the calibrated Oro GSFLOW model. Reverse particle tracking and cluster analysis techniques were used to define ESGRAs.

The ESGRA methodology was applied in this study to establish linkages between specific recharge areas and ecologically significant surface water features. For this study, the LSRCA designated all streams and all wetlands in the three study area subwatersheds as significant. Cluster analysis was used to convert the particle endpoint distribution into a uniform gridded parameter that was evaluated for significance and compared across watersheds and features. Application of the normalized bivariate kernel density estimation technique provided a quantitative and repeatable method for cluster endpoint density analysis ESGRA delineation. Further screening of the delineated ESGRA, based on optimized $h$ and $\varepsilon$ values, eliminated isolated ESGRAs having an area less than 0.045 km² and infilled small holes, consistent with the approach of (Earthfx, 2012)

The backward tracking and cluster analysis delineated ESGRAS across the study area. The analysis indicates that both local recharge and regional recharge from the high volume recharge area of the Oro Moraine helped to sustain these features. Regional recharge from the Oro Moraine dominated in the headwaters of Hawkstone and in the Oro North subwatershed; local recharge dominated in the lower reaches of Hawkstone Creek and in the Oro South subwatershed. As shown in Table 6, the ESGRA coverage within each subwatershed ranged from 15% coverage in Oro South to 26% and 23% in Hawkestone and Oro North, respectively. The smaller percent ESGRA coverage in the Oro South subwatershed is likely a result of the surficial tills reducing recharge to the groundwater system. Topographic variation on the drumlinized till plain also creates localized flow systems.

Forward tracking across the study area and from the delineated ESGRAs was used to confirm the analyses and ensure that no critical flow paths were overlooked. Comparisons with previously defined SGRAs showed that there is some correlation between SGRAs and ESGRAs, but only parts of the SGRAs (about half the area) contributed to ecologically significant features while the SGRA analysis generally did not account for local recharge in the vicinity of streams and wetlands on the till plain.

It should also be noted that there appears to be a limited amount of cross-watershed boundary flows where recharge occurring within the study area discharges beyond the study area limits; and recharge from outside the study area feeds features within the study area. This demonstrates the benefit of a more regional-scale modelling approach as a foundation for ESGRA analysis

Two additional exercises were conducted to analyze recharge from the Oro Moraine and Lake-groundwater interaction around Bass Lake and Little Lake. These exercises show that the integrated groundwater/surface water model can be applied to better understand fairly complex interactions on a regional and local scale. It is hoped that the integrated model can be used by the various partner agencies as a collaborative tool to assess, manage, and protect the surface and groundwater resources of the Oro Moraine area and Lake Simcoe.
6 Limitations

Services performed by Earthfx Incorporated were conducted in a manner consistent with that level of care and skill ordinarily exercised by members of the environmental engineering and consulting profession.

This report presents the results of data compilation and computer simulations of a complex geologic setting. Data errors and data gaps are likely present in the information supplied to Earthfx, and it was beyond the scope of this project to review each data measurement and infill all gaps. Models constructed from these data are limited by the quality and completeness of the information available at the time the work was performed. Computer models represent a simplification of the actual geologic conditions. The applicability of the simplifying assumptions may or may not be applicable to a variety of applications.

This report does not exhaustively cover an investigation of all possible environmental conditions or circumstances that may exist in the study area. If a service is not expressly indicated, it should not be assumed that it was provided. It should be recognized that the passage of time affects the information provided in this report. Environmental conditions and the amount of data available can change. Discussions relating to the conditions are based upon information that existed at the time the conclusions were formulated.

All of which is respectively submitted,

EARTHFX INC.

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7 References


8 Tables

Table 1: Tier 2 subwatershed areas.

<table>
<thead>
<tr>
<th>Subwatershed</th>
<th>Minimum Elevation (masl)</th>
<th>Maximum Elevation (masl)</th>
<th>Mean Elevation (masl)</th>
<th>Area (km$^2$)</th>
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<tr>
<td>Hawkestone Creek</td>
<td>218.0</td>
<td>380.4</td>
<td>291.5</td>
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<td>Oro Creeks North</td>
<td>215.1</td>
<td>375.9</td>
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<td>75.3</td>
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Table 2: Percent of endpoints covered by every ESGRA with varying smoothing parameter ($h$) and delineation threshold ($\varepsilon$).

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<th>$h = 25$</th>
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<th>$h = 100$</th>
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<td>0.1</td>
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<td>69.6%</td>
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<td>17.9%</td>
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<td>60.9%</td>
<td>83.7%</td>
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<td>0.01</td>
<td>65.0%</td>
<td>88.1%</td>
<td>96.8%</td>
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<td>99.8%</td>
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<td>100%</td>
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<tr>
<td>0.005</td>
<td>83.4%</td>
<td><strong>96.2%</strong></td>
<td>99.2%</td>
<td>99.9%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
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<tr>
<td>0.001</td>
<td>99.1%</td>
<td>99.9%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
<td>100%</td>
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</tbody>
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Table 3: Total area (km$^2$) of potential ESGRAs with varying smoothing parameter ($h$) and delineation threshold ($\varepsilon$).

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<tr>
<th>$\varepsilon$</th>
<th>$h = 10$</th>
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<th>$h = 50$</th>
<th>$h = 100$</th>
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Table 4: Percent area covered by potential ESGRAs with varying smoothing parameter ($h$) and delineation threshold ($\varepsilon$).

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<tr>
<th>$1/\varepsilon$</th>
<th>$h = 10$</th>
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<th>$h = 50$</th>
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<td>93%</td>
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<td>0.36%</td>
<td>2.0%</td>
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<td>23%</td>
<td>39%</td>
<td>66%</td>
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<tr>
<td>0.01</td>
<td>5.3%</td>
<td>16%</td>
<td>31%</td>
<td>55%</td>
<td>71%</td>
<td>93%</td>
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<td>11%</td>
<td>24%</td>
<td>40%</td>
<td>63%</td>
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<tr>
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<td>53%</td>
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<td>90%</td>
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<td>135%</td>
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Table 5: Potential ESGRA point density (end points per km$^2$) with varying smoothing parameter ($h$) and delineation threshold ($\varepsilon$).

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<th>$h = 10$</th>
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<th>$h = 50$</th>
<th>$h = 100$</th>
<th>$h = 150$</th>
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<td>200,786</td>
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Table 6: Percentage of subwatershed covered by potential ESGRAs ($h = 25$).

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<thead>
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<th>Subwatershed</th>
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<tr>
<td>Oro North</td>
<td>22.6%</td>
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<tr>
<td>Hawkestone</td>
<td>26.1%</td>
</tr>
<tr>
<td>Oro South</td>
<td>14.6%</td>
</tr>
<tr>
<td>Total</td>
<td>21.4%</td>
</tr>
<tr>
<td>Area outside of study area</td>
<td>2.2 km$^2$</td>
</tr>
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</table>
9 Figures

Figure 1: Tier 2 study area and model area.
Figure 2: Surficial (shallow) hydrogeology of the Oro Moraine area (Burt & Dodge, 2011).
Figure 3: Example of backward particle-tracking from a significant feature (Bluffs Creek West Wetland, Oro Creeks North Subwatershed) to areas of ecologically significant recharge (Note: for clarity not all particles tracks are shown).

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Figure 21: Forward tracking from Bass Lake and Little Lake.