Toronto and Region Conservation Authority

Technical Memorandum

Methodology for Delineation of Ecologically Significant Groundwater Recharge Areas

September 2019

Executive Summary:

An Ecologically Significant Groundwater Recharge Area (ESGRA) can be defined as an area of land that is responsible for replenishing groundwater systems that directly support sensitive areas like coldwater streams and wetlands (Greenbelt Plan, 2017). The protection of groundwater-dependent ecologically sensitive areas depends, in part, on understanding where on the landscape the groundwater comes from and taking steps to ensure the recharge function of these areas is protected (Figure 1). ESGRAs are identified using regional-scale modelling to predict where groundwater recharge at a given location will emerge or "discharge" within ecologically sensitive areas.

Mapping ESGRAs and protecting the groundwater recharge function they provide helps to ensure the streams and wetlands they are connected to continue to support important ecological functions, including provision of habitat for groundwater-dependent plants and wildlife. ESGRAs are an important component of watershed planning and are a defined policy term in the *Growth Plan for the Greater Golden Horseshoe* (2019) and *Greenbelt Plan* (2017). The term also has policy associations in TRCA's *Stormwater Management Criteria* (2012). Mapping of ESGRAs can be used to inform decisions around municipal growth through the land use and infrastructure planning processes.

This technical memo outlines the procedure and criteria used to delineate ESGRAs for the watersheds of Toronto and Region Conservation Authority (TRCA). The current mapping exercise is the first time TRCA has comprehensively identified ESGRAs for its entire jurisdiction. The intent of this document is to outline a methodology for mapping ESGRAs that is scientifically defensible, efficient, and that can be repeated by TRCA or in other jurisdictions whenever significant updates to the underlying regional groundwater models become available. This document takes the completion of a reverse particle tracking exercise as its starting point and outlines a methodology for delineating ESGRAs using the model outputs. The methodology presented here was the result of a multidisciplinary collaboration between TRCA staff and representatives from Credit Valley Conservation and the Oak Ridges Moraine Groundwater Program, including hydrogeologists, ecologists, and geomatics and policy specialists.

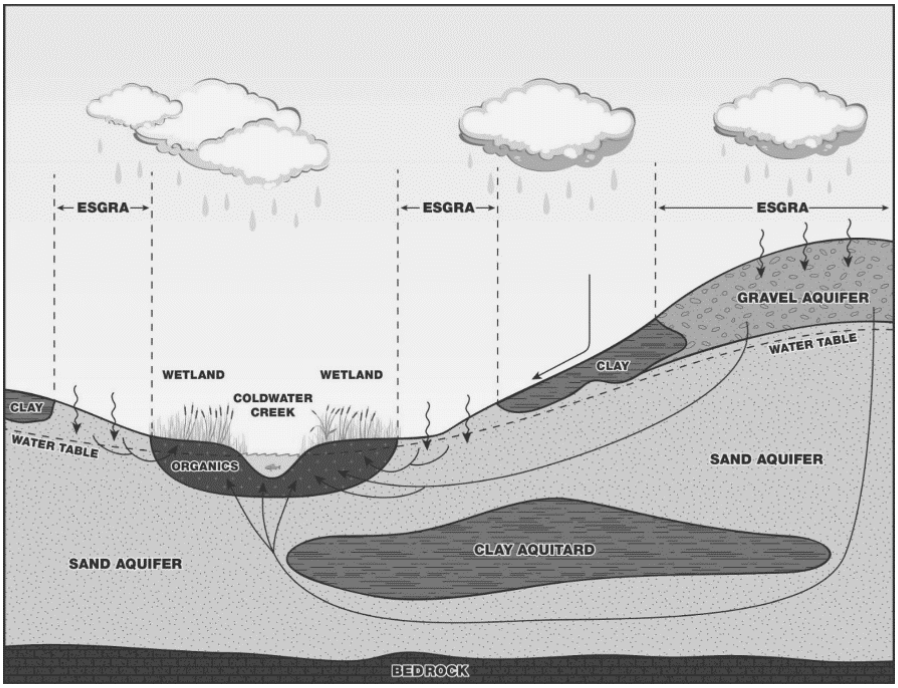

Figure 1: Conceptual drawing of Ecologically Significant Groundwater Recharge Areas in a landscape context

Contents

1 Purpose and Data Requirements

The purpose of mapping ESGRAs is outlined in the Executive Summary. The purpose of this technical memo is to outline a rational, efficient, and reproducible methodology for mapping ESGRAs using the output of a reverse particle tracking model as a starting point. The methodology is intended to be replicable wherever sufficient data is available and whenever significant updates to the underlying regional groundwater models become available. Different numerical criteria have been used in previous assessments to define what constitutes an ESGRA. This methodology seeks to provide a set of objective criteria that maximizes the proportion of ESGRAs associated with highly groundwater-dependent ecosystems (as defined in Section 4.2) while minimizing the total area covered under the ESGRA definition.

This document takes the completion of a reverse particle tracking exercise as its starting point. Further detail on reverse particle tracking methodology can be found in Marchildon *et al.* (2016).

The following datasets are required to apply the methodology outlined in this document:

- Layers describing all known watercourses and wetlands
- Wetland flora species records (points)
- Fish species records (points)
- Locations of fen wetlands (polygons), from Ecological Land Classification mapping or other sources

An overview of the process followed is depicted in Figure 2 on the following page.

2 Policy Context

Under the *Growth Plan for the Greater Golden Horseshoe* (2019; hereafter Growth Plan), municipalities are required to undertake watershed planning to inform the protection of water resources and decisions around planning for growth. Both the Growth Plan and the *Greenbelt Plan* require municipalities to identify and protect the features, areas, and functions of the Water Resource System, of which ESGRAs are one type of area.

TRCA's *Living City Policies* (LCP; 2014) align with provincial policies' and plans' watershed management approach to protecting the Water Resource System and managing development impacts. With respect to water resources management, the LCP asks proponents of development and infrastructure to meet stormwater management criteria including water balance. For implementation guidance on these policies, the LCP refers proponents of development and infrastructure to TRCA's *Stormwater Management Criteria* (2012). Within the *Stormwater Management Criteria*, section 6.2.1 outlines criteria for development and infrastructure applications within three types of significant groundwater recharge area, one of which is ESGRAs. The criteria require that proponents "maintain pre-development groundwater recharge rates and appropriate distribution, ensuring the protection of related hydrologic and ecologic functions." The document states that the criteria "represent a minimum requirement that may be superseded by the results of further studies and local constraints", and that proponents should consult with TRCA staff concerning the site-specific criteria to be applied. Further detail on geographic applicability and study requirements are outlined in appendices D and E of the *Stormwater Management Criteria*.

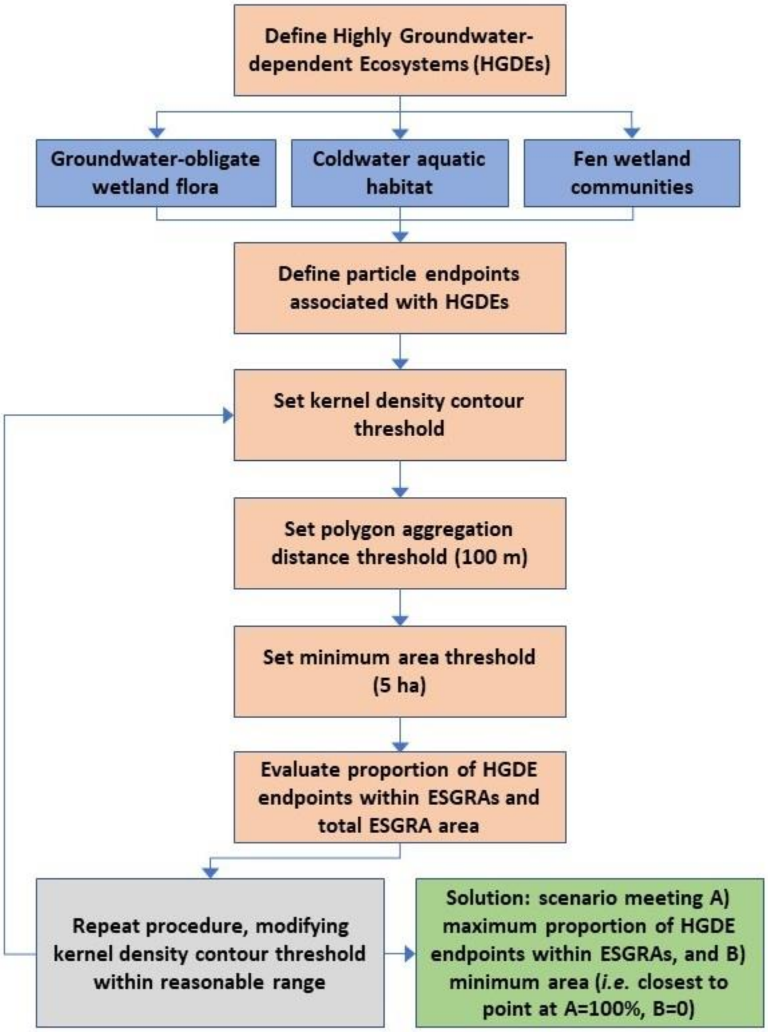

Figure 2: Flowchart depicting process used to develop and select ESGRA mapping scenarios

3 Groundwater Modelling

The ability to establish hydrogeological connections between areas of land and groundwater-supported ecosystems has been enhanced significantly by recent improvements in understanding of regional-scale hydrogeology. The development of water budget models for many watersheds in southern Ontario in the mid-2000s as part of the *Clean Water Act* (2006) Source Water Protection requirements provided the modelling framework necessary for a more detailed assessment of groundwater-dependent ecosystems. The delineation of ESGRAs utilizes a particle tracking methodology already used to meet a number of Source Water Protection requirements including well head protection areas.

There are several precedents for ESGRA delineation in Ontario. In 2012, the consulting firm Earthfx completed an assessment of ESGRAs on behalf of Lake Simcoe Region Conservation Authority (Earthfx Inc., 2012) for several watersheds in the western Lake Simcoe basin using the Marchildon *et al.* (2016)

methodology. Subsequent ESGRA assessments were completed for other Lake Simcoe basin watersheds in 2013 (Earthfx Inc.) and 2015 (Golder Associates Ltd.). Central Lake Ontario Conservation Authority also completed an ESGRA assessment in 2014 (Earthfx Inc.) for all the watersheds under its jurisdiction.

Building on these precedents, TRCA contracted the Oak Ridges Moraine Groundwater Program (ORMGP) to complete modelling using reverse particle tracking for the watersheds of TRCA jurisdiction. The full technical details of this work are outlined in a separate memo (ORMGP, 2018b) but a quick summary is provided here in the following paragraphs.

TRCA provided geospatial layers representing all known wetlands and permanent watercourses in the watershed jurisdiction to ORMGP. The wetlands and permanent watercourses were used to determine the release points, or startpoints, of virtual particles. Particles were distributed within wetlands and along watercourses at an average spacing of 10 m (note that the model horizontal cell size was 100 m × 100 m), with a total of 1,449,023 particles being released. The TRCA Expanded Groundwater Flow Model, constructed using the MODFLOW numerical groundwater model (Harbaugh, 2005) was run in steady-state mode. MODPATH version 6 (Pollock, 2012) was then used to track the virtual particles' flowpaths backwards in time through the steady-state groundwater cell-by-cell flux field, an output file from a MODFLOW model run.

For particles that travelled >100 m horizontal distance (the distance equivalent to the model cell width), an endpoint was defined with the same particle identifier number as the associated startpoint. The endpoints represented 21% of total particles initially released at a startpoint. This proportion indicates that the remaining 79% of particles either travelled to recharge areas that were too close to their associated discharge zones to be defined in the model (in a majority of instances) or were released in groundwater recharge areas as determined by the model.

Using the set of particle endpoints (n=309,477), a cluster analysis was performed using a bivariate kernel density estimation, following the method outlined in Marchildon *et al.* (2016). Kernel density used a symmetric Gaussian kernel with bandwidth h=25 m. The density values from the cluster analysis were projected onto a 25 m × 25 m grid, and values were then normalized by dividing each cell value by the maximum cell value in the domain such that this maximum cell was assigned a value of 1. This procedure provides the density field in relative terms, allowing for a greater degree of output comparability between models irrespective of the model resolution and the number and spacing of virtual particles.

At the completion of the particle tracking exercise, ORMGP provided the following model outputs to TRCA for use in mapping:

a) Particle startpoints layer, with every particle uniquely identified
b) Particle endpoints layer, with particle IDs relatable to the startpoints layer
c) Particle horizontal pathlines layer (for informational purposes, not used in mapping)
d) An initial normalized kernel density grid (25 m × 25 m cell size)

4 ESGRA Delineation Methodology

The following section outlines the GIS procedure used to create the ESGRA mapping for TRCA jurisdiction. Section 4.2 provides the rationale behind the use of groundwater-dependent ecosystems to evaluate efficacy of different mapping scenarios, while the following sections outline the step-by-step GIS procedure. The numerical thresholds used here were selected from among a number of mapping scenarios representing different numerical thresholds for delineating ESGRAs. The selection of this particular scenario was endorsed by a technical committee comprising TRCA staff from a range of disciplines, including hydrogeologists, ecologists, policy specialists, and GIS specialists, as well as staff from Credit Valley Conservation and ORMGP.

4.1 Assumptions and Limitations

It is important to acknowledge the assumptions of this methodology and its limitations in correctly identifying recharge areas associated with groundwater-dependent ecosystems. The following are the primary assumptions and limitations:

- The steady-state groundwater flow model used in the reverse particle tracking analysis (ORMGP, 2018a) is limited by the availability and extent of subsurface data used to construct the model. There is some degree of error between modelled and measured groundwater piezometric heads which varies in magnitude across the model domain.
- The reverse particle tracked flowpaths show the best estimate of the groundwater spatial linkages between natural features receiving groundwater discharge and the areas of the landscape where this water originates as recharge. While the density of particle endpoints is used as a proxy for the volume of water recharged and transmitted, there is no way within the existing modelling framework to correlate particle endpoint densities with groundwater volumes. Accordingly, some ESGRAs may be identified in areas with surficial soils of relatively low permeability, yet this may accurately reflect the hydrogeological connections between these areas and associated discharge areas. Further details on the assumptions and limitations of the groundwater model and reverse particle tracking methodology can be found in ORMGP (2018a and 2018b).
- The minimum separation distance between recharge areas and ecological features in this modelling approach is 100 m, therefore it is likely that many areas within 100 m of streams and wetlands are in reality associated recharge areas but are not captured by mapped ESGRAs.
- The use of Highly Groundwater-dependent Ecosystems (HGDEs, as defined in the next section) in the analysis is meant to indicate the proportion of recharge areas identified as ESGRAs using a particular delineation threshold for all ecosystems receiving groundwater discharge. However, since it is impossible without extensive site-scale studies to verify which particular wetlands and streams receive groundwater discharge as predicted by the model, it is not possible to verify how representative HGDEs may be as indicators for all ecosystems receiving groundwater discharge.

4.2 Defining Highly Groundwater-dependent Ecosystems (HDGEs)

To evaluate the effectiveness of any particular ESGRA mapping scenario in protecting groundwater-dependent ecosystems, a layer describing the most highly groundwater-dependent ecosystems in TRCA watersheds was created. Since it is difficult or impossible to know which particular streams and wetlands receive the highest proportion of groundwater without extensive site-scale studies, this layer of highly groundwater dependent ecosystems (HGDEs) represents those areas in which TRCA staff have the highest degree of confidence that the area's ecology is essentially defined by its reliance on groundwater inputs. This definition distinguishes HGDEs from other sensitive ecosystems which may also receive groundwater. This HGDE layer can be interpreted as an indicator layer, the logic being that if a given mapping scenario identifies a high proportion of the recharge areas associated with HGDEs as ESGRAs, it is therefore an effective solution for protecting all groundwater-supported ecologically sensitive areas.

Three types of HGDE were defined as indicators of a highly groundwater-dependent ecology; these consisted of the following layers:

a) Groundwater-obligate wetland flora, defined by highest concentrations of species records
b) Coldwater aquatic habitat, defined by the highest concentrations of species records
c) Fen wetland communities, defined by Ecological Land Classification mapping

The species used to define HGDEs for a) and b) are listed in Appendix B. For each type of HGDE, the particle startpoints within the HGDE were associated with their corresponding endpoints, indicative of recharge areas, and the proportion of these endpoints captured within areas defined as ESGRAs was assessed for each mapping scenario. The optimal mapping solution was taken to be the scenario which maximized the proportion of recharge zones (i.e. endpoints) associated with HGDEs within ESGRAs while using a minimum total area to do so. Section 4.3 outlines the methods used to define the highest concentrations of species records and associated particle startpoints for HGDEs.

4.3 Step-by-step GIS Procedure

This section outlines the procedures followed to develop and evaluate ESGRA mapping scenarios using ESRI ArcMap 10.4 software with the Spatial Analyst Extension. The input used for the entire procedure is the 25 m × 25 m kernel density raster output from a regional groundwater model, processed as described in Section 3. In order to efficiently test multiple permutations of different thresholds, TRCA staff automated Step 1 using ArcMap’s Model Builder function.

Step 1: Define ESGRA mapping scenario from kernel density raster

Step 1 outlines the process for creating an ESGRA mapping scenario; this process is then repeated using different kernel density thresholds to find an optimal solution.

Step 1.a: Kernel density contour threshold

Using the **Contour** tool, set the input to the kernel density raster and select a contour interval. For the TRCA exercise, values between 0.001 and 0.01 were tested, with the final value used in the optimized scenario being 0.004. These values are in line with those that have been used in previous mapping studies (Earthfx Inc., 2012, 2013, 2014; Golder Associated Ltd., 2015). Name the contour polyline output file to reflect the contour value used.

Use the contour polyline file as input into the **Feature to Polygon** tool to create polygons from the contours. The same naming convention should be used throughout to save outputs. Use the **Dissolve** tool to dissolve features into a unified layer. The **Aggregate Polygons** tool can also be used to dissolve and aggregate features in a single step.

Step 1.b: Aggregate polygon distance threshold

Use the **Aggregate Polygons** tool to aggregate polygons at a specified distance. For the TRCA exercise, values between 0 m and 1000 m were used, with the final value in the optimized scenario being 100 m.

In evaluating mapping scenarios, TRCA staff found that altering the kernel density contour threshold produced more area-efficient solutions for a given coverage of HGDE-associated recharge areas than altering the aggregation distance threshold. Therefore, use of a smaller aggregation distance threshold is recommended. For reference, a 100 m radius aggregation distance is equivalent to filling in all "doughnut holes" within ESGRA polygons less than 3.15 ha in area.

Step 1.c: Minimum area threshold

Use the **Make Feature Layer** tool to eliminate polygons less than the specified minimum area threshold by using the expression builder to specify a minimum polygon size for the new layer. TRCA evaluated minimum area thresholds ranging from 1 ha to 10 ha. For the optimized scenario, a value of 5 ha was used; this is also consistent with the values that have been used in previous evaluations (Earthfx Inc., 2012, 2013, 2014; Golder Associated Ltd., 2015). A minimum area threshold is used to consolidate ESGRAs by eliminating small, isolated recharge areas, facilitating application of ESGRA mapping to development and infrastructure proposal review.

This output of the **Make Feature Layer** tool is the ESGRA mapping scenario that will be evaluated in the subsequent steps. Export and save the layer with an appropriate name that outlines the three thresholds used in Step 1.

Step 2: Create HGDE polygons

Step 2 outlines procedures for creating the three types of HGDE outlined in Section 4.2. Where sufficient data is available, these procedures offer an objective methodology for determining the locations of HGDEs. However, expert knowledge or alternative methods could be used in the absence of sufficient data to define HDGE polygons.

Step 2.a: Groundwater-obligate wetland flora

The point records of groundwater-obligate wetland flora species listed in Appendix B are converted into a density raster using the **Kernel Density** tool with a raster cell size of 25 m × 25 m. The output is processed using the **Reclassify** tool to divide the raster into 10 equal intervals according to kernel density value (i.e. using 'VALUE' as the Reclass field). The top decile of data (the uppermost interval) is assigned a new value of '1', while all other classes are assigned a value of 'NoData'. The reclassified output raster is converted to a polygon using the **Raster to Polygon** tool. This polygon layer is the HGDE layer for wetland flora, representing the top decile (top 10%) of the wetland flora point kernel density, corresponding to the highest density clusters of groundwater-obligate wetland flora within the study area. The wetland flora HGDE polygon (referred to hereafter as ***flora HGDE layer***) is used to select corresponding particle startpoints in Step 3.

Note that TRCA staff determined that the top decile was a logical and appropriate threshold for this HGDE for the watersheds of TRCA jurisdiction, but that other percentile thresholds could be used in other contexts. The exact percentile threshold used is less important than the requirement that the polygons have the essential features of: a) representing a relatively small proportion of the total watershed area, and; b) being reasonably distributed across the watershed area, that is, ideally, not concentrated within a single location. The latter requirement accounts for the fact that error in regional groundwater modelling and the underlying hydrogeological data is not evenly distributed throughout the model domain. These two essential features apply to all three types of HGDE.

Step 2.b: Coldwater aquatic habitat

The point records of the coldwater aquatic habitat indicator fish species listed in Appendix B are converted into a density raster using the **Kernel Density** tool with a raster cell size of 25 m × 25 m. The output raster is then used as the input to the **Extract by Mask** tool, with the watercourse layer used as the masking layer. This is necessary because the species using the coldwater stream habitat are restricted to movement within the watercourse itself, and so, to evaluate the proportion of recharge areas for this type of HGDE falling within an ESGRA, it is necessary to associate the HGDE polygon with the startpoint particles released only from the watercourse itself. (Note that it is important to use the same watercourse layer as was used to define particle startpoints in the groundwater model, to avoid issues of non-overlap).

The **Reclassify** tool is used to divide the masked raster into 10 equal intervals according to kernel density values, as in Step 2.a. As in Step 2.a., raster cells above the value threshold is assigned a new value of '1', while all other classes are assigned a value of 'NoData'

For the TRCA analysis, a threshold of 60% (i.e. the top 60% by species density values, or sixth decile) was used, following the logic outlined in Step 2.a. This threshold provided a satisfactory distribution of HGDE polygons across the watershed area, whereas lower (more restrictive) thresholds constrained the coldwater HGDE polygons to essentially one small subwatershed. The 60% threshold is reflective of the limited geographic distribution of coldwater fish species within TRCA watersheds.

The reclassified masked raster is converted into a linear feature using the **Raster to Polyline** tool. This layer is the HGDE layer for coldwater aquatic habitat, and is referred to as the ***fish HGDE layer*** hereafter. The *fish HGDE layer* is used to select corresponding particle startpoints in Step 3. Note that the conversion from a raster to a line will likely cause differences to emerge between the *fish HGDE layer* and the original watercourse layer; these differences can be compensated for using the **Select by Location** tool as outlined in Step 3. TRCA staff found that a distance of 15 m was able to capture all startpoints within the watercourse without capturing excessive startpoints outside the watercourse.

Step 2.c: Fen wetland communities

For the fen wetland communities layer, referred to hereafter as the ***fen HGDE layer***, no processing is necessary, assuming that the polygons accurately describe the locations of fen wetlands. Fen wetlands are generally assumed to exist in locations where a groundwater constitutes high proportion of the annual water budget (National Wetlands Working Group, 1997).

Step 3: Associate HGDEs with ESGRAs

Step 3 outlines the procedure for associating the HGDE polygons with the ESGRAs for a given mapping scenario. The objective is to evaluate the proportion of recharge areas associated with HGDEs that are located within an ESGRA for a given mapping scenario. It is important to note that not all particle startpoints have a corresponding endpoint, for reasons described previously in Section 3.

Step 3.a: Locate startpoints with corresponding endpoints

Use **Join** to join the particle endpoint and particle startpoint layer attribute tables, using the 'particleID' field as the join field. The **Select by Attribute** tool is used to select rows where 'particleID' is not null. This returns all particle IDs where the startpoint has a corresponding endpoint. Use the **Create Layer from Selected Features** function to create a new layer, then export this layer. For the remainder of this section, **startpoints** refers to the layer created in this step where all startpoints have corresponding endpoints.

Step 3.b: Locate endpoints that fall within an ESGRA

For each of the three HGDE layers (separately), use the **Select by Location** tool to select the startpoints that fall within the HGDE polygons created in Step 2. For the *fish HGDE layer*, the **Select by Location** tool should be used with the relationship specified as 'within a distance' and the distance set to 15 m. (This distance was found to be optimal by TRCA staff for capturing all startpoints within the watercourse without capturing excessive startpoints outside the watercourse).

Create three new layers containing the startpoints corresponding to each of the three types of HGDE, naming them appropriately (e.g. *fen_startpoints*). For the ESGRA mapping scenario being evaluated, use **Select by Location** to select endpoints within the ESGRA layer. **Export Feature** to create a new *ESGRA_endpoints* layer with endpoints that fall within an ESGRA, naming the layer to reflect the mapping scenario being evaluated.

Join the *ESGRA_endpoints* layer to the HGDE startpoints layers (e.g. *fen_startpoints*) one layer at a time, removing previous joins before adding new joins. For each join, use **Select by Attribute** where 'particleID' is not null to select HGDE startpoint particles that have corresponding endpoints within an ESGRA. **Export Feature** to create a layer for the HGDE startpoints that have corresponding endpoints within an ESGRA.

This procedure is repeated for each ESGRA mapping scenario being evaluated.

4.4 Evaluating ESGRA Mapping Scenarios

In order to evaluate each ESGRA mapping scenario, two values must be calculated:

a) The proportion of startpoint particles originating in an HGDE that terminate in an ESGRA, expressed as a percentage (referred to as *%HGDE*)
b) The total area of all ESGRAs, expressed as a percentage of the total watershed area (referred to as *%Area*)

For %HGDE, the proportion is expressed as an average of the individual scores for each type of HGDE, rather than a single percentage representing the proportion of all HGDE startpoints terminating in an ESGRA. TRCA staff determined that calculating %HGDE as an average of the scores for the three HGDE types (flora, fish, and fens) accounted for the fact that there is no data to justify *a priori* that any of these types individually is a superior indicator of ecosystem groundwater dependence. Calculating %HGDE as the proportion of all HGDE startpoints terminating in an ESGRA would tend to bias scores towards indicators with more startpoint particles. However, this would not likely influence mapping scenario selection, as %HGDE should increase and decrease monotonically as the kernel density contour threshold is varied.

Note that the proportion %HGDE is derived from only startpoints that have an associated endpoint, as many startpoints do not. If the proportion of all startpoints terminating in an ESGRA is calculated, this proportion will be much lower, since a majority of particles travel either zero distance or less than the 100 m cell size as described in Section 3.

Using the values derived for %HGDE and %Area for each mapping scenario, plot all scenarios under consideration on a graph with %Area on the x-axis and %HGDE on the y-axis, as in Figure 3.

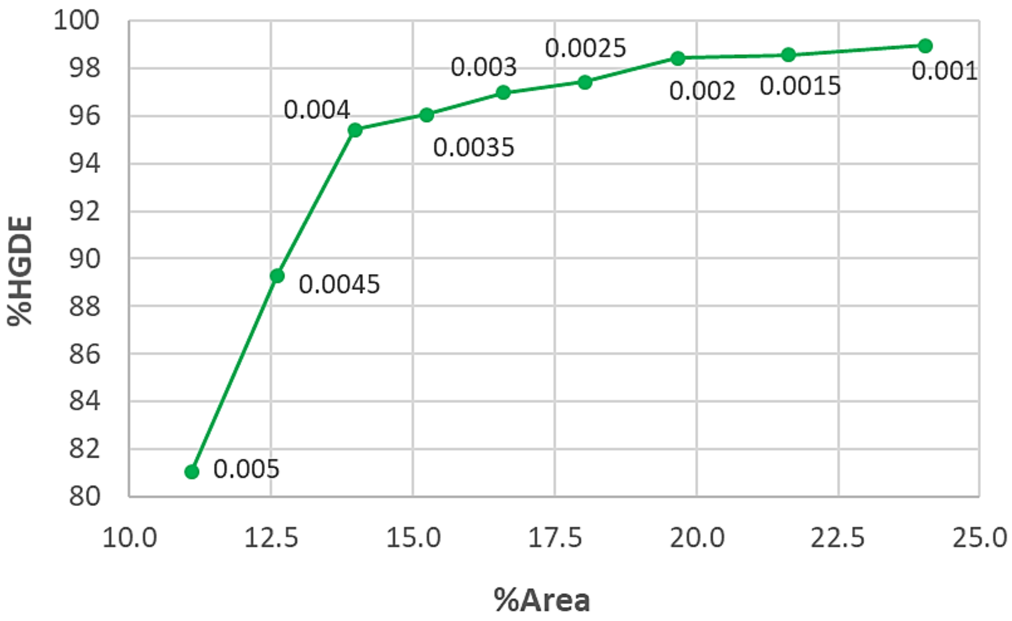

Figure 3: Example of ESGRA mapping scenario optimization; each point represents one scenario

In Figure 3, each point represents one mapping scenario with an associated kernel density contour threshold; threshold values decrease to the right.

The optimal ESGRA mapping scenario is that which protects that maximum proportion of HGDE-associated recharge areas (highest %HGDE) using a minimum total area (lowest %Area). In Figure 3, the scenario represented by the point second from the left is the optimal scenario. An additional criterion may be added to the effect that the optimal scenario should exceed a minimum %HGDE value (e.g. 95%) to ensure that groundwater-dependent ecosystems are adequately protected in the optimal scenario.

Sources Cited

Earthfx Inc. 2012. Barrie, Lovers, and Hewitt Creeks – Ecologically Significant Groundwater Recharge Area Assessment and Sensitivity Analysis.

Earthfx Inc. 2013. Ecologically Significant Groundwater Recharge Area Assessment for the Oro North, Oro South, and Hawkestone Creeks Subwatersheds.

Earthfx Inc. 2014. Ecologically Significant Groundwater Recharge Area Delineation in the Central Lake Ontario Conservation Authority Area.

Golder Associates Ltd. 2015. Maskinonge, East Holland and West Holland River Subwatersheds – Ecologically Significant Groundwater Recharge Area Assessment.

Harbaugh, A.W., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16.

Lake Simcoe Region Conservation Authority (LSRCA). 2014. Guidance for the protection and restoration of significant groundwater recharge areas (SGRAs) in the Lake Simcoe watershed. Final version 1.1, February 2014.

Marchildon, M., Thompson, P.J., Cuddy, S., Wexler, E.J., Howson, K., Kassenaar, J.D.C. 2016. A methodology for identifying ecologically significant groundwater recharge areas. Canadian Water Resources Journal 41:515-527.

National Wetlands Working Group. 1997. The Canadian Wetland Classification System. Second Edition. Eds. Warner, B.G., and C.D.A. Rubec. Wetlands Research Centre, University of Waterloo, Waterloo, ON.

Oak Ridges Moraine Groundwater Program (ORMGP). 2018a. TRCA Expanded Groundwater Flow Model Development. Memorandum to TRCA staff.

ORMGP. 2018b. Ecologically Significant Groundwater Recharge Areas. Memorandum to TRCA staff.

Ontario Ministry of Municipal Affairs and Housing. 2017. Greenbelt Plan.

Ontario Ministry of Municipal Affairs and Housing. 2019. Growth Plan for the Greater Golden Horseshoe.

Pollock, D.W., 2012, User Guide for MODPATH Version 6—A Particle-Tracking Model for MODFLOW: U.S. Geological Survey Techniques and Methods 6–A41, 58 p.

Toronto and Region Conservation Authority. 2012. Stormwater Management Criteria. August 2012, version 1.0.

Toronto and Region Conservation Authority. 2014. The Living City Policies for Planning and Development in the Watersheds of the Toronto and Region Conservation Authority.

Appendix A: ESGRA Mapping for TRCA Jurisdiction

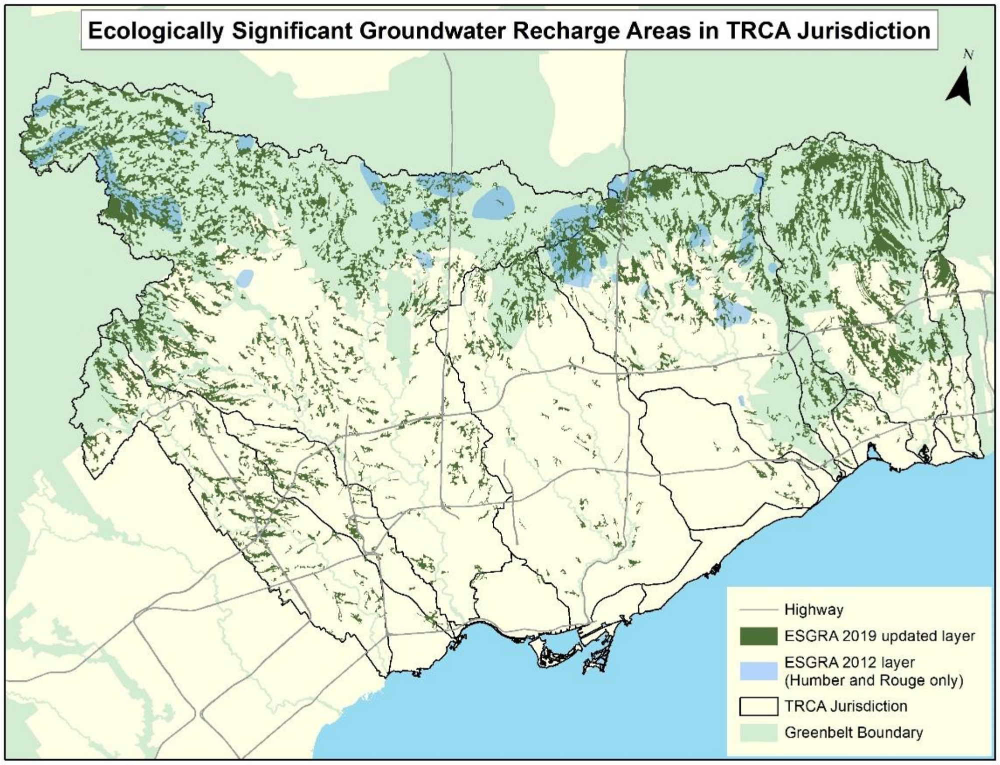

Figure 4: Final optimized ESGRA mapping scenario for TRCA jurisdiction

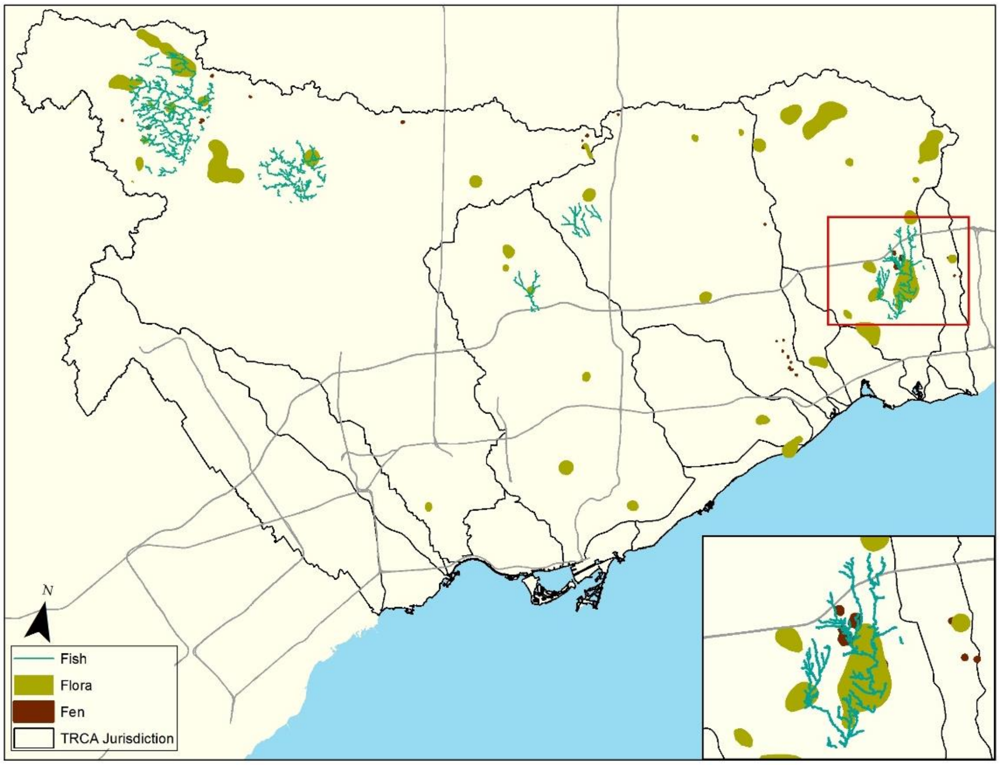

Figure 5: Three types of HGRE used to evaluate ESGRA mapping scenarios, with detail of central Pickering area

Appendix B: Species Lists for Highly Groundwater-dependent Ecosystems

Groundwater-obligate wetland flora: The wetland flora species presented in Table 1 were used to generate the wetland flora HGDE polygons; these are considered by TRCA professional ecologists to be groundwater-obligate species. All available species records were used dating back to 1993.

For application to other jurisdictions, this species list could be supplemented by or exchanged for a more locally applicable list of groundwater-obligate species. Other sources of data or knowledge to identify high concentrations of groundwater-obligate species may also be acceptable for use with this methodology.

Table 1: List of wetland flora species used to generate HGDE polygons

Common name	Scientific name
American speedwell	*Veronica americana*
Bristle-stalked sedge	*Carex leptalea*
Bulblet fern	*Cystopteris bulbifera*
Fen star sedge	*Carex interior*
Fringed brome grass	*Bromus ciliates*
Fringed gentian	*Gentianopsis crinita*
Golden saxifrage	*Chrysosplenium americanum*
Hooded ladies’ tresses	*Spiranthes romanzoffiana*
Loesel’s twayblade	*Liparis loeselii*
Marsh marigold	*Caltha palustris*
Marsh pennywort	*Hydrocotyle americana*
Naked mitrewort	*Mitella nuda*
Rough sedge	*Carex scabrata*
Schweinitz' sedge	*Carex schweinitzii*
Shining ladies’ tresses	*Spiranthes lucida*
Showy lady’s slipper	*Cypripedium reginae*
Skunk cabbage	*Symplocarpus foetidus*
Smooth-sheathed sedge	*Carex laevivaginata*
Thin-leaved cotton-grass	*Eriophorum viridicarinatum*
Three-seeded sedge	*Carex trisperma*
Turtlehead	*Chelone glabra*
Two-seeded sedge	*Carex disperma*
Variegated scouring-rush	*Equisetum variegatum ssp. variegatum*
Water avens	*Geum rivale*
Yellow sedge	*Carex flava*

Coldwater aquatic species: The species presented in Table 2 were used to generate the coldwater aquatic habitat HGDE polygons; these are considered by TRCA professional aquatic biologists to be indicative of true coldwater habitat. All available species records were used dating back to 1949. Use of these older records was justified because while coldwater species may have been locally extirpated from a particular stream reach, the historical presence of coldwater species indicates that a reach consistently receives groundwater discharge and likely continues to receive discharge under the assumption that the hydrogeological setting remains in a quasi-steady-state condition. Local extirpation of coldwater fish species could be attributed to multiple environmental stressors unrelated to water temperature.

For application to other jurisdictions, this species list could be supplemented by or exchanged for a more locally applicable list of coldwater fish species. Other sources of data or knowledge to identify high concentrations of coldwater species may also be acceptable for use with this methodology.

Table 2: List of coldwater aquatic species used to generate HGDE polygons

Common name	Scientific name
American brook lamprey	*Lethenteron appendix*
Brook trout	*Salvelinus fontinalis*
Brown trout	*Salmo trutta*
Mottled sculpin	*Cottus bairdii*
Northern brook lamprey	*Ichthyomyzon fossor*
Slimy sculpin	*Cottus cognatus*