MEMORANDUM

Date: Thursday 29th November, 2018

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From: Mason Marchildon P.Eng, M.A.Sc

Re: Ecologically-Significant Groundwater Recharge Areas

Background

The Ecologically-Significant Groundwater Recharge Area (ESGRA) methodology was designed to be used with existing regional-scale groundwater models built for, amongst other things, Source Water Protection (Marchildon et. al., 2016). The methodology itself isn't novel, rather it combines modelling outputs with GIS techniques to produce a map of areas on the landscape where groundwater recharge is interpreted to directly contribute to the hydrological function of pre-specified ecological features, such as wetlands and cold-water streams.

The methodology makes use of groundwater pathlines, tracked backward in time, originating from ecological features of interest. Pathline generation is a post-processing technique widely used in the groundwater modelling community to delineate capture zones of groundwater sources. By tracking particles backward in time, ecological features (e.g., wetlands, head water streams, etc.) that receive groundwater discharge (as predicted by the model), can be linked to areas on the land surface where the discharging water originates. Where pathlines, tracked backward in time, intersect the land surface, "endpoints" are created. While every endpoint is linked to an ecological feature, many of them may be found isolated, while others tend to converge in large clusters. These clusters are of main interest owing to the fact that the ESGRA methodology is premised on the principle that endpoint clusters are a surrogate for the likelihood that the area indeed supports the hydrological function of some identified ecological feature. To identify the clusters, automated cluster-identification routines common to many GIS platforms are utilized. A normal bivariate kernel density estimation procedure was used for this study (as in Marchildon et. al., 2016).

With the ESGRA methodology, it is important to note that the pathlines are in no way indicative of the quantity/volume of the water received by the feature of interest, only that it "points" to its likely origin. The exercise has been performed here using a steady-state numerical groundwater flow model, meaning that the model output used in creating the pathlines is assumed to be representative of long-term average groundwater flow conditions. In reality, the flow condition changes with seasonality, water use, climate and land use changes. Consider, for instance, that many of the pathline travel times (i.e., the time a particle of water should take to travel the distance from an ESGRA to an ecological feature) exceed 1000 years; so surely, it is unreasonable to expect that the groundwater system would remain steady throughout that time period. However, aside from large scale pumping, most of the changes mentioned above would likely not significantly alter the regional flow system in general. Particle tracking remains a well-practiced methodology that allows for insight into the groundwater system and the users and features it supports.

This memo also proposes a procedure that may satisfy the needs to identify "Significant Surface Water Contribution Areas" (SSWCAs) as outlined in the Growth Plan for the Greater Golden Horseshoe (OMMAH, 2017). This proposed methodology is offered to leverage existing numerical models developed for Source Water Protection (SWP).

Discussion regarding the construction of the model (named the TRCA expanded groundwater flow model—TEGWFM for short) has been detailed in a previous memo entitled: *TRCA expanded groundwater flow model development*, dated November 22, 2018. This memo provides a brief description of the steps taken in the delineation of ESGRAs and SSWCAs for the TRCA jurisdiction. For a more detailed discussion on the ESGRA methodology, the reader is referred to Marchildon et. al.(2016).

ESGRA Generation

Particle Tracking

Ecologically-Significant Groundwater Recharge Area generation was conducted using the particle tracking package MODPATH version 6 (Pollock, 2012). MODPATH is specifically designed for use with MODFLOW numerical groundwater flow models, such as the TEGWFM.

The TEGWFM has a resolution of 100 m×100 m cells. These cells can incorporate linear features, such as watercourses, from which the groundwater system drains, yielding groundwater discharge to streams. Two-dimensional features, however, are limited by cell size; thus any such feature (in this case wetlands) smaller in extent than one hectare may be over-represented in terms of their interaction with the groundwater system. Wetlands larger than a 100 m×100 m cell would be represented in the model as many cells as required to reasonably represent the wetland within the model.

Table 1 details the watercourse layer provided by the TRCA. Mean channel gradient was derived from the LiDAR DEM also provided by the TRCA and weighted according to mapped channel length. For simplicity, cross-sectional channel geometry is assumed as a function of channel topological order defined by Strahler (1952). The watercourse layer was first topologically corrected such that the model could correctly route water in a downstream order. The MODFLOW package used, namely the Stream-Flow Routing (SFR) package (Niswonger and Prudic, 2005), allows for greater realism in its representation of flow routing and groundwater-surface water interactions.

Table 1: Analysis of mapped TRCA watercourses according to Strahler (1952) stream order.

Order	Total Length (km)	Mean Gradient[1] (–)
1	1331.7	0.014
2	867.8	0.012
3	606.9	0.008
4	362.6	0.005
5	255.8	0.004
6	78.5	0.002
7	66.1	0.002

[1] weighted to channel length.

Figure 1 presents a density plot of mapped wetlands applied to the model. As can be seen, the mode of the wetland areal extent distribution is below the cell resolution of the TEGWFM. Regardless of the wetland size, all 100 m×100 m model cells that contained a wetland (or in some cases more than one) were represented as wetland cells. The coarseness of the model grid relative to the wetland size will influence the ESGRA delineation process in cases where the modelled water table is slightly above the base of the wetland. In such cases the ground surface of the 100 m×100 m cell might not accurately reflect the elevation of the deepest part of the wetland. This might result in the model treating these wetlands as isolated from the groundwater system, when in reality there might be a connection. This is a limitation to all ESGRA studies performed in Ontario using this method in conjunction with SWP models.

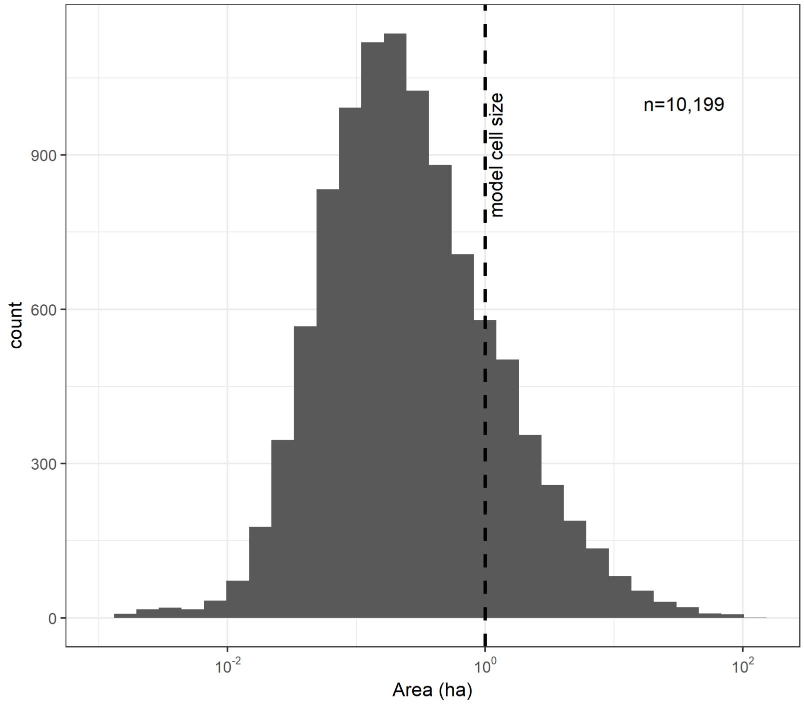

Figure 1: Distribution of areal extent for wetlands used in the model (n=10,199).

Particles were released within wetland boundaries and along all watercourses at an even spacing of roughly 10 m (Figure 2). In all, 603,650 particles were released from wetlands and 845,373 particles were released from watercourses. From all mapped wetlands and watercourse reaches provided by the TRCA, particles were released. A constant porosity of 0.3 was assigned for the entire domain;[1] however, it must be noted that since porosity only impacts the velocity of particles, it in no way affects particle pathline trajectory. The delineated ESGRA clusters are therefore independent of the porosity assigned.

Particles released from these 1,449,023 locations were backward-tracked within the TEGWFM's steady-state flow field (a saved model output file) until they either reach a model boundary (e.g., the ground surface, lakes, losing stream reaches, recharging wetlands, etc.). Note the many particles were left stranded, meaning that the particles were not released in an area where groundwater discharge is occurring and therefore could not travel (backwards) through the flow system. Of the 1,449,023 particles released, 383,452 (26%) were left stranded and 278 (0.02%) exited at the constant head boundaries (i.e., lakes), the remaining 1,065,293 particles exited the model at the origin of their recharge.

Most of these "recharging" particles, however, did not travel far as they recharged in very close proximity to their discharge points. In total, 755,816 (52% of all) particles travelled less than 100 m from their place of recharge to their place of discharge, and were excluded from the ESGRA analysis on the basis that this distance is shorter than the model's cell resolution. A typical situation to explain where these short-travelled particles could occur is where recharge occurring in flood plane riparian areas immediately discharges into the nearby watercourse, making the watercourse's flood-prone width its own ESGRA.

The remaining, 309,477 (21% of all) endpoints were found to exist in areas distant from the features they were backward-tracked from; these were the endpoints use in the ESGRA delineation.

Endpoint Cluster Analysis

Endpoint cluster analysis was performed using a bivariate kernel density estimation following methodology outlined in Marchildon et. al. (2016). The kernel chosen was a symmetric Gaussian kernel with a bandwidth

[1]Please note that porosity is not a required parameter for steady-state groundwater flow models.

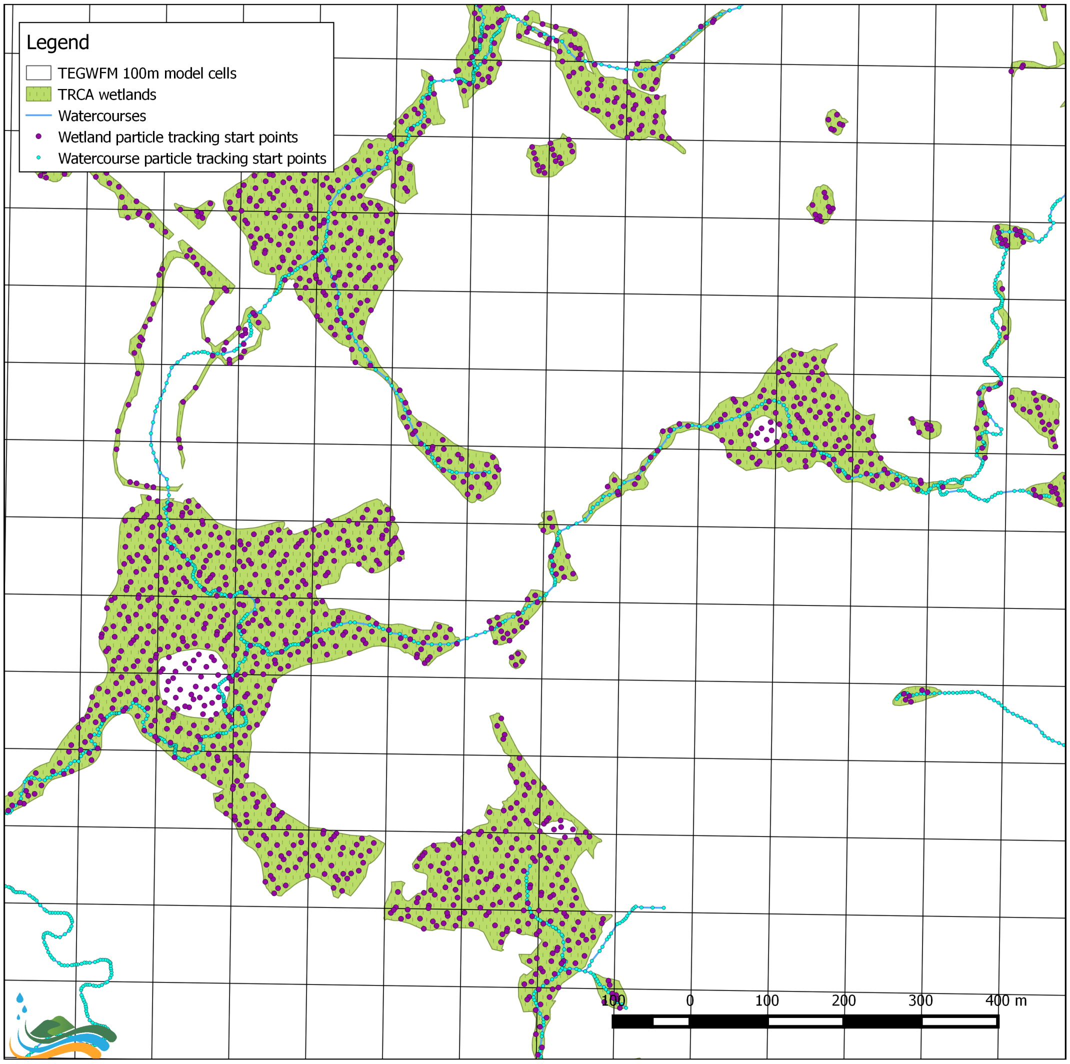

Figure 2: Distribution reverse particle tracking startpoints used in producing ESGRAs.

$h = 25\,\mathrm{m}$ (Wand and Jones, 1994).

The cluster analysis was then projected onto a $25\,\mathrm{m}\times 25\,\mathrm{m}$ grid (as in Marchildon et. al., 2016). The density values assigned to this grid were normalized by dividing each value by the maximum kernel density estimate. This way, the density field is provided in a relative scale and TRCA staff can decide upon a threshold to define the "significance" of the recharge area. For example, in Marchildon et. al. (2016), the decision made by the Lake Simcoe Region Conservation Authority (LSRCA) was to consider normalized densities greater than 0.5% as signifying the presence of an ESGRA. This threshold was determined from an optimization exercise where the greatest amount of endpoints were captured within the smallest overall ESGRA coverage.

Once the threshold is defined, a standard contour analysis can be used to automatically delineate the ESGRAs. Figure 3 shows a sample of the kernel density estimation superimposed by the particle endpoints.

ESGRA Discussion

Another solution to the optimization of the ESGRA threshold follows a discussion with the TRCA team on October 29, 2018. Here it was speculated that from observation of a cumulative density plot, one could identify a breakpoint from which a threshold value would be taken to constrain delineated ESGRAs. Figure

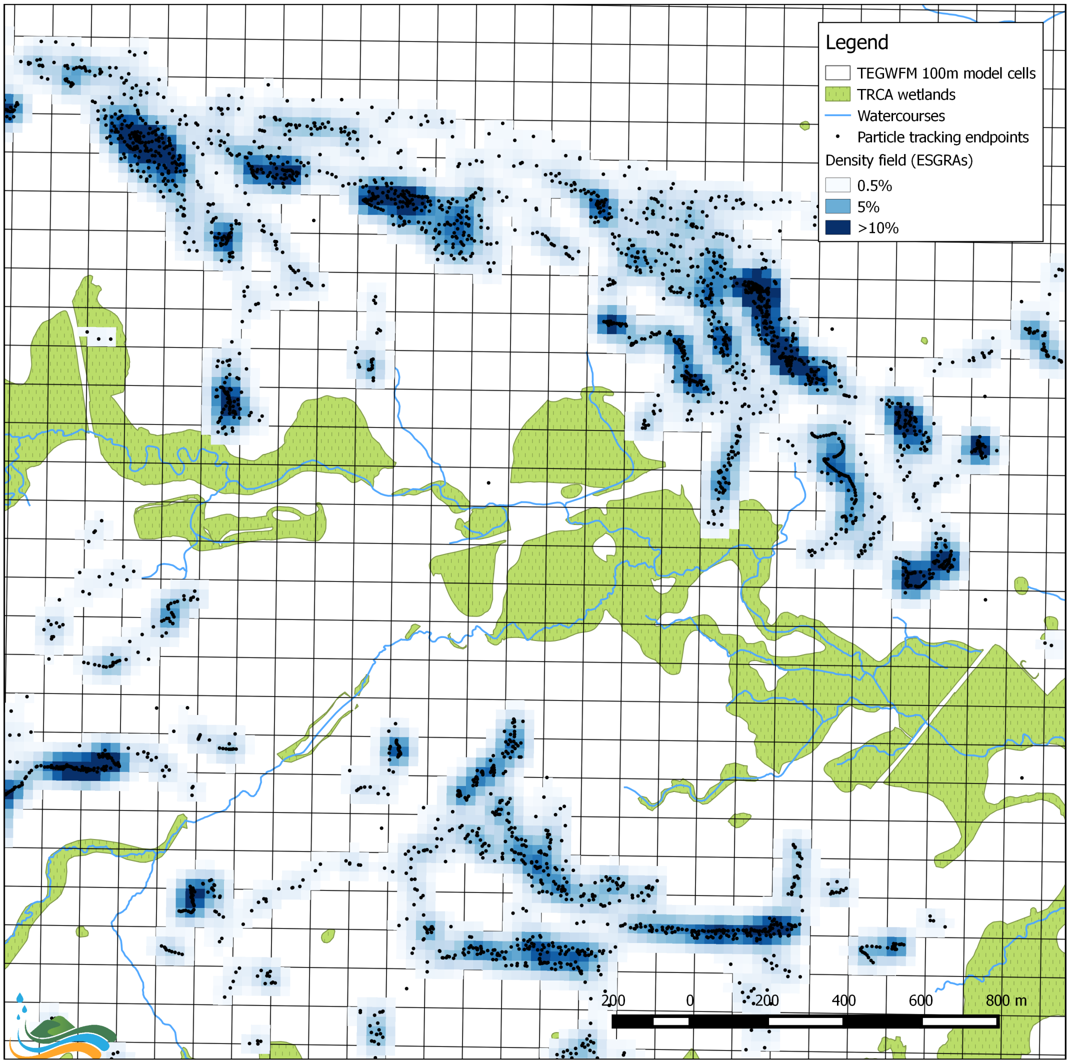

Figure 3: Distribution reverse particle tracking endpoints used in defining ESGRAs for the TRCA.

4 shows such a plot for the exercise performed here. Essentially, the inflection point would be where the "breakpoint" lies, should the TRCA wish to adopt the optimization routine followed by the LSRCA. From visual observation of Figure 4, it's apparent that the inflection point occurs close to the 0.5% threshold, the same as identified by the LSRCA optimization procedure (Marchildon et. al., 2016).

As an alternative approach, this plot could potentially be used by TRCA staff should they wish to aim for a particular area of coverage, and pull the associated threshold from this plot. For example, if an area of, say, 60,000 ha was a desired ESGRA target area for the TRCA jurisdiction (as determined by some external process), then a threshold of about 0.1% of the maximum kernel density estimate could be used.

The point of greatest curvature could also be used to identify a threshold where ESGRA coverage is most sensitive to threshold change; in this case, a threshold of 2% appears to coincide with the point of greatest curvature, reflecting an estimate of only 10,000 ha of ESGRAs delineated. (Note that these are only suggestions.)

Figure 5 provides another means of analyzing the distribution of endpoint cluster density. Here, the distribution of non-zero density estimates has been plotted. Interestingly, the mode of this distribution also coincides with the 0.5% value (as expected as the peak is precisely where the point of inflection of the cumulative plot—Figure 4—occurs).

It is unclear as to what the significance of 0.5% is, only that this value was found to be optimal in past

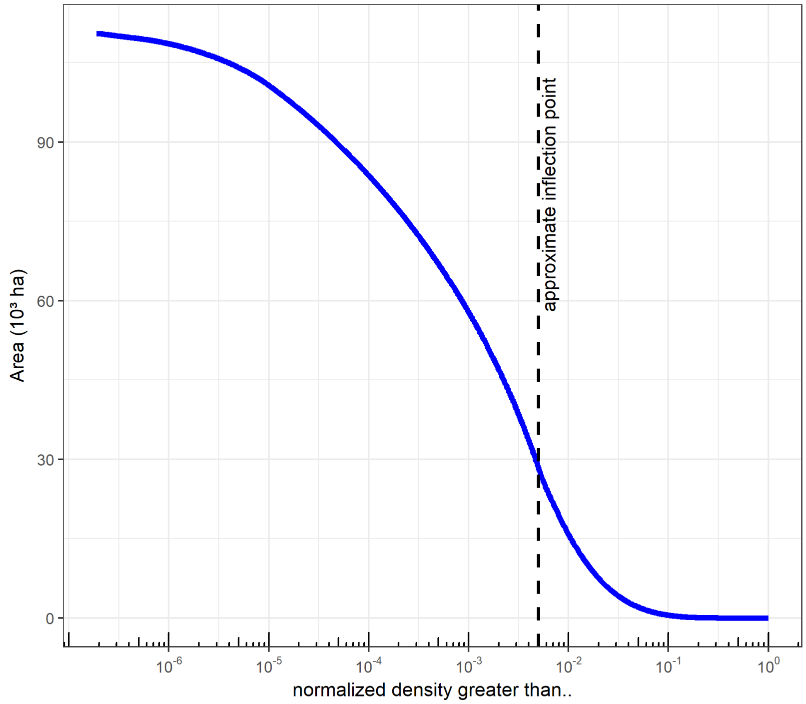

Figure 4: ESGRA cumulative density plot.

ESGRA work. While it is ultimately up to the TRCA to determine a threshold, it is recommended that this threshold value of 0.5% be used as it: (i) would be consistent with other jurisdictions; and (ii) has some analytical foundation for its selection (e.g., Figures 4 and 5).

Once a threshold is chosen, the following steps need taking in order to finalize the ESGRA mapping:

1. Using a standard contouring function found in many GIS platforms, create contours of the kernel density estimation field provided.
2. Set the contours to only one level, that of the chosen density threshold.
3. Save contours as a polygon shapefile—these features are the ESGRAs.
4. Some selectivity may be required. For instance, ESGRAs less that a hectare were omitted in the LSRCA.

Proposed Significant Surface Water Contributing Area (SSWCA) Identification

To date, no methodology has been proposed in Ontario to delineate Significant Surface Water Contribution Areas as discussed in the Growth Plan for the Greater Golden Horseshoe (OMMAH, 2017). In proposing this methodology, there are certain points of discussion and definitions within the OMMAH document that have been considered:

> This Plan requires the identification of water resource systems and the protection of key hydrologic features and key hydrologic areas, similar to the level of protection provided in the Greenbelt. — pg. 39

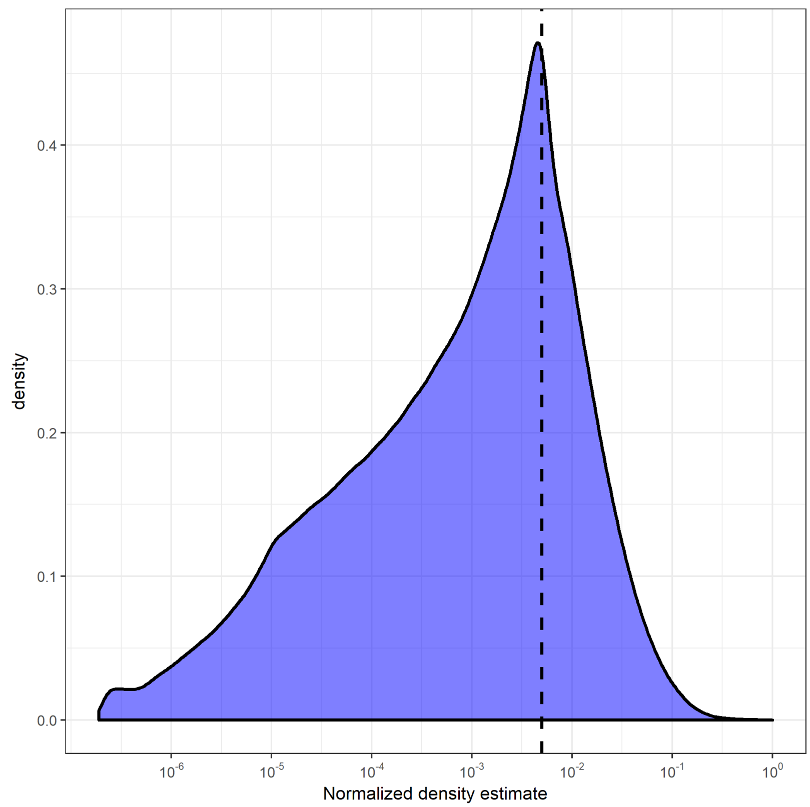

Figure 5: Kernel density distribution. (Hashed line placed at the density of 0.005.)

> Water resource systems will be identified ... for the long-term protection of key hydrologic features, key hydrologic areas, and their functions. — pg. 41
>
> *Key Hydrologic Areas*: Significant groundwater recharge areas, highly vulnerable aquifers, and significant surface water contribution areas that are necessary for the ecological and hydrologic integrity of a watershed. — pg. 75
>
> *Key Hydrologic Features*: Permanent streams, intermittent streams, inland lakes and their littoral zones, seepage areas and springs, and wetlands. — pg. 75
>
> *Significant Surface Water Contribution Areas*: Areas, generally associated with headwater catchments, that contribute to baseflow volumes which are significant to the overall surface water flow volumes within a *watershed*. — pg. 84

Ultimately, the Growth Plan speaks to the protection of the hydrologic function of key hydrologic features and areas. As the name (and definition) suggests, SSWCAs speak specifically to the "areas" that contribute to baseflow volumes[2] that support "overall surface water flow volumes." These areas, however, would traditionally have been called recharge areas that have already been identified using the ESGRA methodology. In addition, part of the rigour of the ESGRA analysis also tends to demonstrate that it is not always true that SSWCAs, as defined above, are "generally associated with headwater catchments," especially in consideration of the complex hydro-physiography of southern Ontario.

That said, what is neglected in the ESGRA delineation procedure is the identification of the key hydrologic features that receive groundwater discharge from the ESGRAs. Protection of the key hydrologic features that "contribute to baseflow volumes which are significant to the overall surface water flow volumes within

[2] The term "baseflow" is being interpreted here as groundwater discharge to streams only.

a watershed" is equally important to the *watershed's* hydrologic function. With this in mind, the model output and methodology presented below, results in the delineation of Significant Surface Water Contribution *Features* on the basis for their role as significant watershed *seepage areas*.

Figure 6 is an example output of the TEGWFM where the seepage rates (i.e., groundwater discharge to streams) projected by the model is mapped back onto the watercourse layer provided by the TRCA. The map uses a colour scheme to identify: (i) reaches contributing relatively high proportions of long-term surface water flow volumes; (ii) loosing reaches, which may in fact be ESGRAs to other hydrologic features; and (iii) dry (i.e., ephemeral) reaches as predicted by the model.[3] Values given in Figure 6 are reported as unit discharge to streams (m^2/d), calculated as total discharge to streams from a model cell (m^3/d) divided by total stream length within that cell.

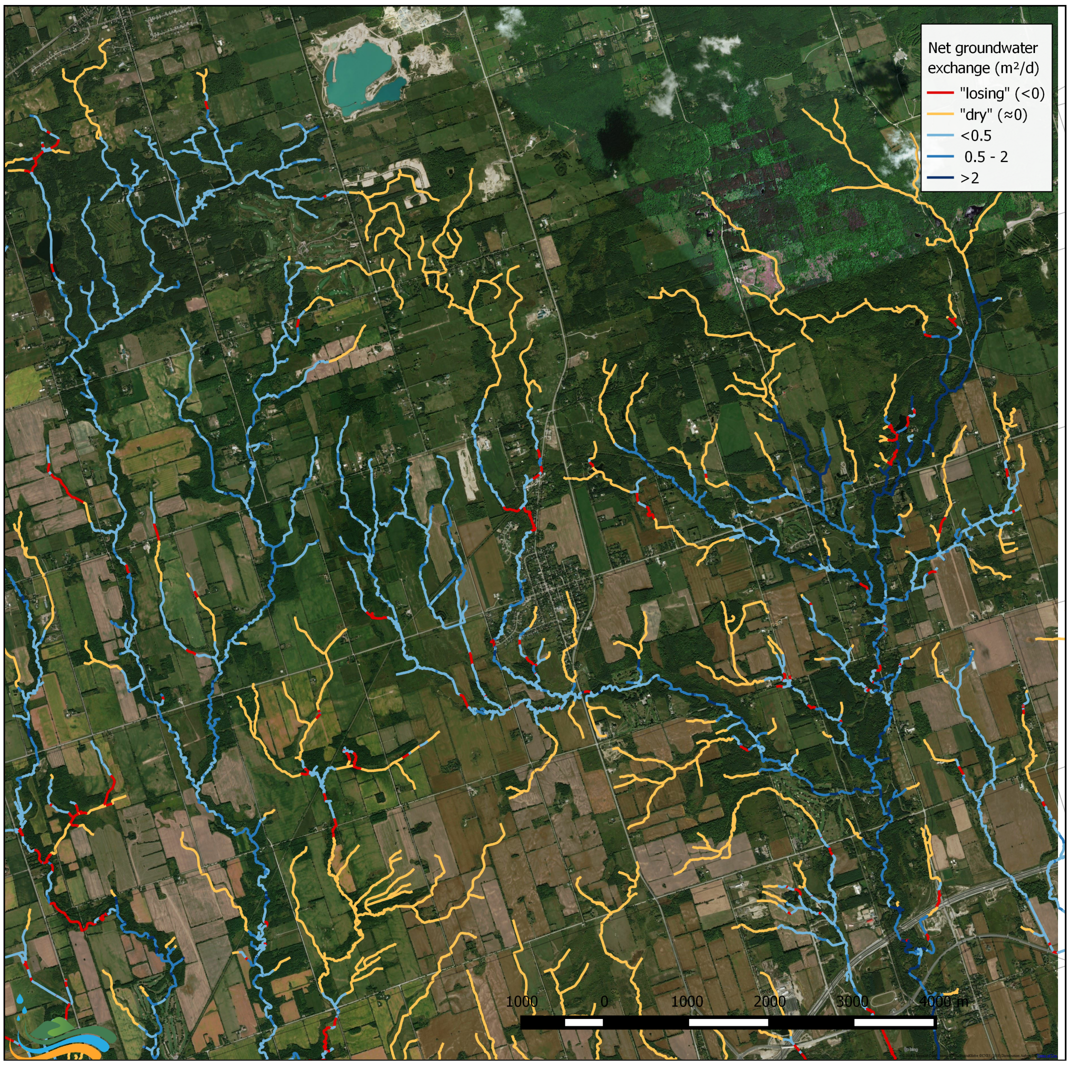

Figure 6: Significant Surface Water Contribution Features. Reaches shaded a darker blue "contribute to baseflow volumes which are significant to the overall surface water flow volumes within a watershed" (OMMAH, 2017)

The methodology and resultant figure presented here is similar in spirit to that used for the ESGRA methodology in that the SSWCA identification is the product of existing numerical groundwater flow models

[3]More consistently, these are reaches experiencing a net groundwater exchange close to zero; however these reaches are most likely dry, i.e., experiencing neither groundwater discharge or recharge.

initially built for SWP purposes. The advantages of the SSWCA delineation methodology presented here are:

(i) It is universal (equivalent everywhere) and translatable (applicable everywhere);

(ii) It employs standard numerical modelling and GIS methodologies;

(iii) It is readily applicable using existing regional numerical groundwater flow models. (In fact, many of the existing models may have already produced these values, they only need to be mapped back onto a watercourse layer.); and,

(iv) It can be compared to other non-modelling information, such as field data (e.g., benthic, fisheries, spawning surveys, etc.).

The SSWCA delineation methodology put forward here does not exactly match the definition incorporated into the Growth Plan; but as discussed, the OMMAH (2017) definition, as it stands, basically refers to what has already been accomplished through the ESGRA analysis. The methodology is put forward in the spirit of making effective use of existing modelling tools and to help in paving a path to assist planners and other watershed specialists in interpreting the intent of Growth Plan document.

In closing, I'd like to thank you for this opportunity. If there are any question, comments or concerns, please do not hesitate to contact me.

Yours Truly,

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Attachments

This section lists the files that are attached to this memo. The files are all of the outputs from this exercise needed to complete the delineation of ESGRAs and SSWCAs. Additional information provided below should enable TRCA staff to delve into the results by, for example, isolating particles originating from features of a particular interest and identifying ESGRAs associated with them. (Note: all files provided are projected to UTM NAD83 zone 17.)

TRCA_TEGWFM_ESGRA_kernel_density_181121.asc

Normalized kernel density estimation field: this is the resulting field using to delineate the ESGRAs (see discussion above). It is a 25 m×25 m raster given as real values ranging from 0.0 to 1.0 (i.e., least to most dense in terms of particle endpoint cluster density).

TRCA_TEGWFM_ESGRA_startpoints_181029.shp

All 1,449,023 particle startpoints. Attribute `Status` determines whether the particle was "Stranded" (see discussion above) or "Normally Terminated," meaning that the particle tracked to a point of origin.

TRCA_TEGWFM_ESGRA_endpoints_181029.shp

The 309,477 particle endpoints used in deriving the *TRCA_TEGWFM_ESGRA_kernel_density_181121.asc* layer.

TRCA_TEGWFM_ESGRA_pathlines_181029.shp

Particle pathlines. This shapefile contains information detailing the approximate time of travel (in years) a particle of water should take to get from their point of origin (the ESGRA) to the feature it supports. These polylines have 3-dimensional coordinates and illustrate the connection between particle startpoints and endpoints.[4] Pathline lengths are given in metres. This layer does not include stranded particles plus an additional 146 pathlines computed as having a travel time of zero.

TRCA_TEGWFM_SSWCA_181027.shp

This is the watercourse mapping provided by the TRCA returned with the net groundwater gains estimated by the TEGWFM distributed along the each channels' length, given as unit discharge (attribute `DrnFlx`—m^2/d). From this information the SSWCA delineation was drawn (Figure 6).

File Attributes

The above-listed vector shapefiles all share attribute fields that are meant to aid future analysis of this particle tracking exercise:

- `ParticleID` is a unique identifier for each particle. This field will allow for join relationships among the three vector shapefiles that can help isolate ESGRAs contributing to specific ecological features.
- `Group` is a field that indicated how the start points were generated (this field is termed "Name" in *TRCA_TEGWFM_ESGRA_pathlines_181029.shp*):
  - *WatercourseOrphans_mmCorrected_31Jul2018_segments_tpl_pntfield.shp*:
    is the startpoint field derived from the watercourse layer provided by the TRCA. The watercourse layer was topologically processed prior to it being utilized by the TEGWFM ESGRA analysis.

[4]Please keep in mind that since reverse (or backward) particle tracking was applied here, that the terms "endpoints" and "startpoints" are meant from the perspective of reverse time. In real time, particles would be recharging at an "endpoint", would course along the pathlines and end up discharge an ecological feature at the "startpoint."

- *TRCA_wetlands_Final100m_jur_noholes_pntfield.shp*:
  is the wetland startpoint field based on the wetland layer provided by the TRCA. This wetland layer was processed by removing polygon holes from some wetlands prior to point field development (see, for example, Figure 2 which shows a number of wetlands with polygon "holes" and the point field distribution that ignores them).

- `TravTimeYR` is the computed travel time for the particles, given in years.

References

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