Toronto and Region Conservation Authority

Carruthers Creek Watershed Plan
Groundwater Modelling

Prepared for the Region of Durham

March, 2019

FOREWORD

The Region of Durham recognizes watershed plans as an effective tool to inform the management of Durham's water resources, natural heritage, and natural hazards, such as flooding. In 2015, the Region retained Toronto and Region Conservation Authority (TRCA) to update the watershed plan for Carruthers Creek.

This four-year study will build upon the goals, objectives, and management recommendations established in the 2003 *Watershed Plan for Duffins Creek and Carruthers Creek*.

The following report is one of a series of scenario analysis technical reports that follow the watershed characterization studies (completed in 2017). Information contained in these technical reports will examine potential impacts of future growth and land use changes in combination with other influences such as climate change. Additionally, these technical reports provide the knowledge base necessary to develop the plan's management recommendations. Any recommendations contained in the scenario analysis technical reports are consolidated in the Carruthers Creek Watershed Plan's management framework. The Watershed Plan is the final source for goals, objectives, indicators and management recommendations related to Carruthers Creek. Readers are encouraged to refer to the technical reports for more detailed implementation suggestions.

The following report was prepared by the Oak Ridges Moraine Groundwater Program (ORMGP) under the direction of TRCA. Given the specialized expertise and experience of the engineers at ORMGP, TRCA commissioned the groundwater modelling assessment as one of the series of technical reports that were prepared as part of the scenario analysis for the Carruthers Creek Watershed Plan.

OakRidgesMoraine
GROUNDWATER PROGRAM

MEMORANDUM

Date: Monday 17th December, 2018

To: Mr. Gary Bowen, Watershed Specialist, Duffins Carruthers Petticoat and Great Lakes Advisor
Toronto Region Conservation Authority

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

Re: Carruthers Creek Watershed Plan: Groundwater modelling

Background

As detailed in the memo entitled: *TRCA expanded groundwater flow model development*, dated November 22, 2018 (hereinafter referred to as the "TRCA Expanded Model memo"), a steady-state numerical groundwater flow model named the TRCA Expanded GroundWater Flow Model (TEGWFM) has been produced to, amongst other needs, address the impact of varying land use scenarios on the Carruthers Creek watershed. This modelling has been requested by the TRCA to fulfill its watershed planning requirements (OMMAH, 2018).

The TEGWFM was derived from the amalgamation of three existing numerical models built as part of Source Water Protection (SWP) and managed within the ORMGP's model custodianship program. With few exceptions (see the TRCA Expanded Model memo), the TEGWFM was neither refined nor updated beyond the original SWP models, nor was there a re-calibration performed. The model amalgamation was required, in part, to extend existing numerical model coverage to the east of the Carruthers Creek watershed boundary to better handle possible lateral groundwater movement in and/or out of the watershed's easternmost surface water divides, thereby reducing the influence of model boundary conditions on the overall water budget of the Carruthers Creek watershed.

Model Structure

The TEGWFM was constructed using the MODFLOW numerical groundwater modelling code (Harbaugh, 2005) and consists of uniform $100\,\mathrm{m}\times 100\,\mathrm{m}$ cells by 10 layers. The model is regional, meaning that is best suited for large-scale assessments of the groundwater system. For instance, within this region much of the groundwater recharge that replenishes the groundwater system, and in turn supports head water streams, occurs along the Oak Ridges Moraine (Figure 1). While the mapped extent of the Oak Ridges Moraine does not intersect the Carruthers Creek watershed, one cannot discount the influence of this physiographic feature on the hydrologic function of the watershed.

The model is run in steady-state mode, meaning that it is assumed to be representative of the long-term average state of the groundwater flow system. Of the 434,280 ($\times$10-layers) numerical model cells, only 3,806 cells are contained within the $\approx 38\,\mathrm{km}^2$ Carruthers Creek watershed boundary. Topography within the watershed trends toward the south-south-east with a mean gradient of roughly 0.7% (Figure 2).

Boundary conditions for the model have been discussed in the TRCA Expanded Model memo. Figure 3 identifies the boundary conditions within the Carruthers Creek watershed. Recharge applied to the watershed was derived from the existing York regional Tier 3 groundwater flow model (Earthfx Inc., 2013). Groundwater recharge estimates were extrapolated on the basis of combined land use and surficial geology distribution and subsequently re-mapped to the model domain according to the scenario land use mapping provided by the TRCA (discussed below).

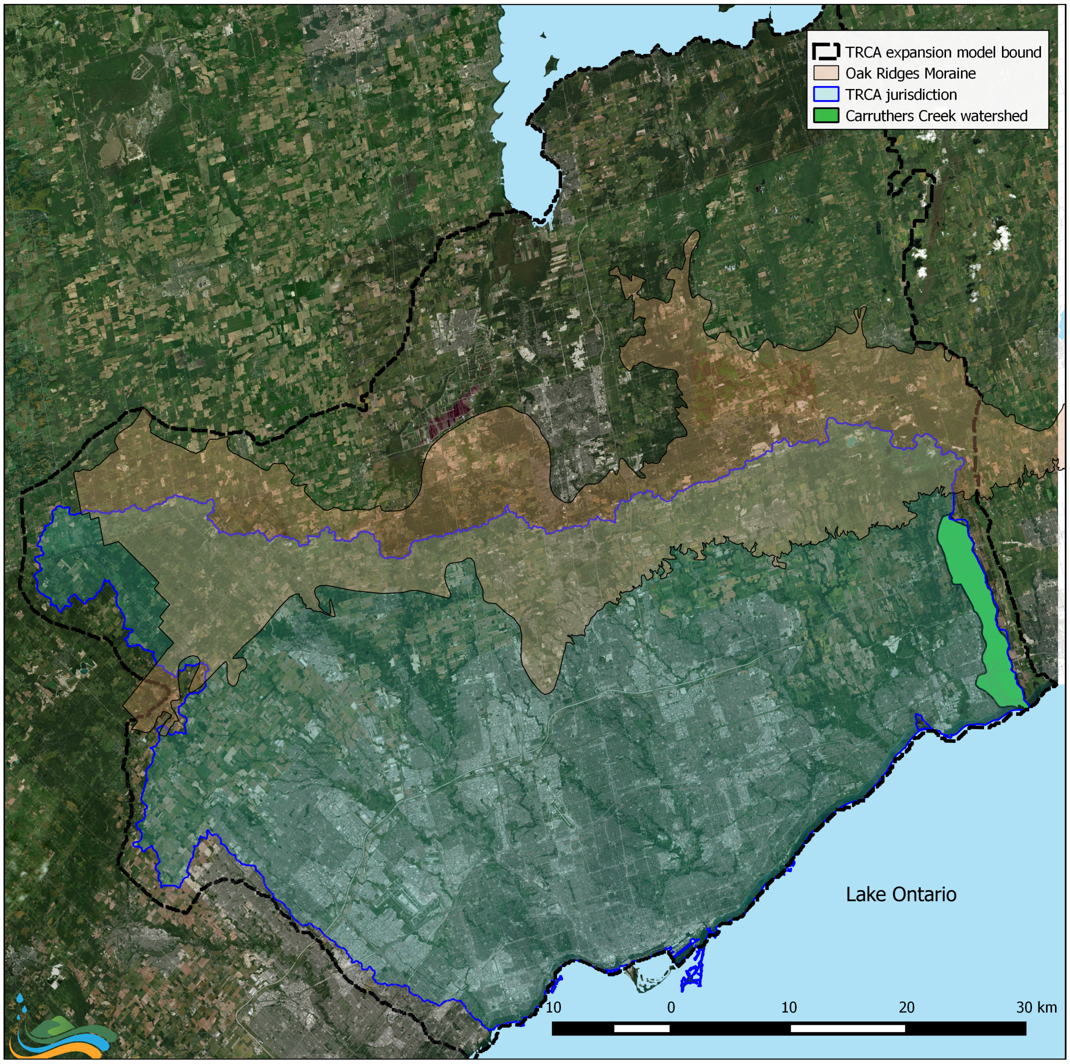

Figure 1: Map of model bounds relative to the Carruthers Creek watershed.

Model Scenarios

Five sets of land use scenarios have been received from TRCA staff and been applied to the model to investigate potential impacts to the groundwater flow system:

Scenario 1: historic (1999) Carruthers watershed land use.

Scenario 2: current (2015) land use.

Scenario 3: current + official plan land use.

Scenario 4: current + official plan + enhanced natural heritage system.

Scenario 5: current + official plan + enhanced natural heritage system + full build-out.

The first run reflects the "base case" scenario and is used as a comparison to the remaining scenarios. The four additional scenarios reflect current and potential development scenarios. The changes in land use have been imposed on the model by changing the rates and distribution of long-term average groundwater recharge on the basis of the land use scenario polygons provided by the TRCA. Table 1 lists the four land use polygon attributes (as received from the TRCA) related to the SOLRIS (OMNR, 2008) land classification scheme.[1]

Table 1: Scenario land use and associated model land use classification used to assign groundwater recharge.

TRCA land use classification	SOLRIS land used (used for cross-reference)	Approximate range of applied groundwater recharge[a] (mm/yr)
Natural areas	Mixed Forest	135–485
Rural areas	Agriculture[b]	95–440
Urban areas	Built Up Area–Impervious	15–170
Golf course	Undifferentiated	95–440

[a] Rates dependent on underlying surficial materials

[b] SOLRIS land class "Undifferentiated" is commonly representative of agricultural/rural land use

Based on the land use types provided by the TRCA, and the underlying mapped surficial geology mapping built into the existing models, estimated groundwater recharge was mapped to the model cells within the Carruthers Creek watershed model boundary for each of the five scenarios. Land use type (in particular impervious cover) affects the rate of infiltration, while surficial geology affects the rate of downward percolation toward the watertable. Figures 4–8 illustrate the distribution of land use (which was discretized to the 100 m×100 m model cell resolution), and Figures 9–13 present the resulting distribution of estimated long-term average groundwater recharge applied for each scenario.

Analysis of Results

The modelled scenarios clearly demonstrated impact to the groundwater flow system due to change in the groundwater recharge regime attributed to the changes in future land use. The following section discusses the model outputs and offers considerations for water management and land use decision making within the Carruthers Creek watershed.

Impacts to Modelled Groundwater Recharge

Figures 14–17 illustrate the distributed changes to the groundwater recharge regime as compared with the base case scenario 1 (i.e., decreases/increases from the base case). As expected, changes in groundwater recharge are consistent with the changes in land use distribution. For each land use scenario, Table 2 summarizes the overall estimated recharge across the watershed as well as the percent deviation from the base case. All of the land use scenarios resulted in a decrease in overall estimated groundwater recharge relative to the historic (Scenario 1) rates. Interestingly, enhanced natural heritage systems (Scenario 4) appear to offset the reduction in recharge caused by the official plan development when compared with current conditions (Scenario 2).

Table 2: Summary of changes to basin-wide long-term average groundwater recharge.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Estimated recharge (mm/yr)	165	152	147	152	141
Percent change	–	-8%	-11%	-8%	-14%

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[1] As discussed in the TRCA Expanded Model memo, land use distribution for the existing models (Earthfx Inc., 2013; 2014) used in constructing the TEGWFM was based on SOLRIS.

Impacts to Modelled Groundwater Discharge to Streams

With changes to applied groundwater recharge comes changes to the hydrologic regime of the Carruthers stream network. A reduction in recharge could potentially lead to an overall reduction in long-term average groundwater discharge to streams.

A summary of groundwater discharge to streams has been made with respect to three main sub-catchments of the Carruthers Creek watershed (Figure 18): one for each branch of the upper watershed, and the other for the lower reach. Table 3 presents the results from within these sub-catchments. The table refers to both model "Drains" and "Rivers" which are both the names of the MODLFOW boundary condition used in representing the function of these stream reaches. The main difference between these two boundary condition types is that while both will allow groundwater to drain via these mapped channels, only "Rivers" will allow for streamflow loss back to the groundwater flow system in cases where the groundwater table lies below the base of the streambed (Harbaugh, 2005). Typically, groundwater modellers prohibit the use of River-type boundary conditions for low order streams as they are assumed ephemeral in nature and thus should not be expected to be points of continuous groundwater recharge. Only the lower reach of the Carruthers Creek system has been modelled as a River-type boundary condition in the TEGWFM (see Figure 3).

Table 3: Summary of changes in groundwater discharge to mapped stream channel features (mm/yr) for each sub-catchment. (Note: "Polygons" refer to those shown in Figure 18)

Sub-catchment	Boundary type	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Polygon 1	Drain	42	36	34	35	35
	River leakage out	-25	-26	-26	-26	-26
	River leakage in	67	63	61	61	61
Polygon 2	Drain	92	91	91	92	91
Polygon 3	Drain	37	37	37	39	34
Net groundwater discharge		212	201	197	201	194
Percent change		–	-5%	-7%	-5%	-8%

Figures 19–22 show the relative changes to groundwater exchange along the model cells where mapped stream channels are present. As can be seen, changes to the groundwater recharge regime has a direct impact to the groundwater-surface water interface, and these impacts are complex. Of note is a general pattern of decreased groundwater discharge to streams relative to the historic base case (Scenario 1). One interesting pattern of note is with respect to Scenario 4 (official plan development with an enhanced natural heritage system), where there is some apparent recovery in groundwater discharge in the upper reaches (as indicated by the blue and green cells, particularly in reach 3); this reflects the positive gains the enhanced natural cover has on streamflow.

Groundwater Surplus into the Carruthers Creek Watershed

To illustrate the role of the regional groundwater system as it relates to the Carruthers Creek watershed, which also emphasizes the need to consider the use of a regional model for watershed planning, Table 4 has been added to highlight the surplus of water captured by the Carruthers stream network that originates from outside of the watershed boundary. In every modelled scenario, Carruthers Creek appears to receive an estimated 50 mm/yr of additional groundwater supply above and beyond what is estimated to originate from recharge within the watershed boundary; this equates to roughly a third of total annual groundwater recharge.

If the Carruthers Creek watershed was modelled on its own without the broad context of the regional model, the modeller would necessarily have to unreasonably increase the groundwater recharge estimates within the Carruthers Watershed in order to make up the surplus. This would result in a gross misappropriation of the water budget components and thus throw the results into question.

Table 4: Summary of surplus groundwater received annually from sources outside of the watershed boundary (mm/yr).)

Boundary type	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Recharge	165	152	147	152	141
Drains	171	164	162	166	159
Rivers–losses[1]	25	26	26	26	26
Rivers–gains[1]	67	63	61	61	61
Surplus groundwater supply[2]	47	49	50	49	53

[1] Rivers–gains/losses (i.e., in/out) are considered here from the perspective of the stream network

[2] $Surplus\ groundwater\ supply = Drains + Rivers\ gains - Recharge - Rivers\ losses$

Conclusions

As expected, numerical groundwater modelling suggests that land development in the Carruthers Creek watershed will have an impact on the groundwater flow system. Increased urbanization leads to a decrease in recharge, which, in turn, causes a decrease in simulated groundwater discharge to the stream reaches within the watershed. Even with the substantial groundwater water surplus that is moving into the watershed, changes to the groundwater recharge regime will cause notable changes to the hydrologic function of the Carruthers Creek stream network. The modelling effort undertaken here indicates that an enhanced natural heritage system will act to mitigate the impacts of future planned development as per the official plan.

Groundwater surplus (water recharged from outside of the watershed boundaries) contributes significantly to Carruthers Creek's overall water balance. This emphasizes the need for a more broad based approach (i.e., regional hydrologic modelling) when assessing hydrologic impacts to watersheds and subwatersheds within the TRCA's jurisdiction. Watershed models that fail to consider the regional context must be used with caution.

The results presented here, and the model outputs produced, are intended to satisfy the TRCA's watershed planning requirements (OMMAH, 2018). It is strongly recommend that for future work, the TRCA move toward improving the regional numerical model within their jurisdiction. The TEGWFM built here was intended to meet TRCA's immediate needs under a limited scope and budget.

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,

Mason Marchildon P.Eng, M.A.Sc
Hydrologist
Oak Ridges Moraine Groundwater Program
mmarchildon@owrc.ca

References

Earthfx Inc., 2007. Wellhead Protection Area Study for Municipal Residential Groundwater Systems Located within the Toronto and Region Conservation Authority Watersheds Caledon East Wells 2, 3, and 4 and Palgrave Wells 2 and 3.

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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.

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Ontario Ministry of Natural Resources, 2008. Southern Ontario Land Resource Information System [computer file]. Peterborough, ON.

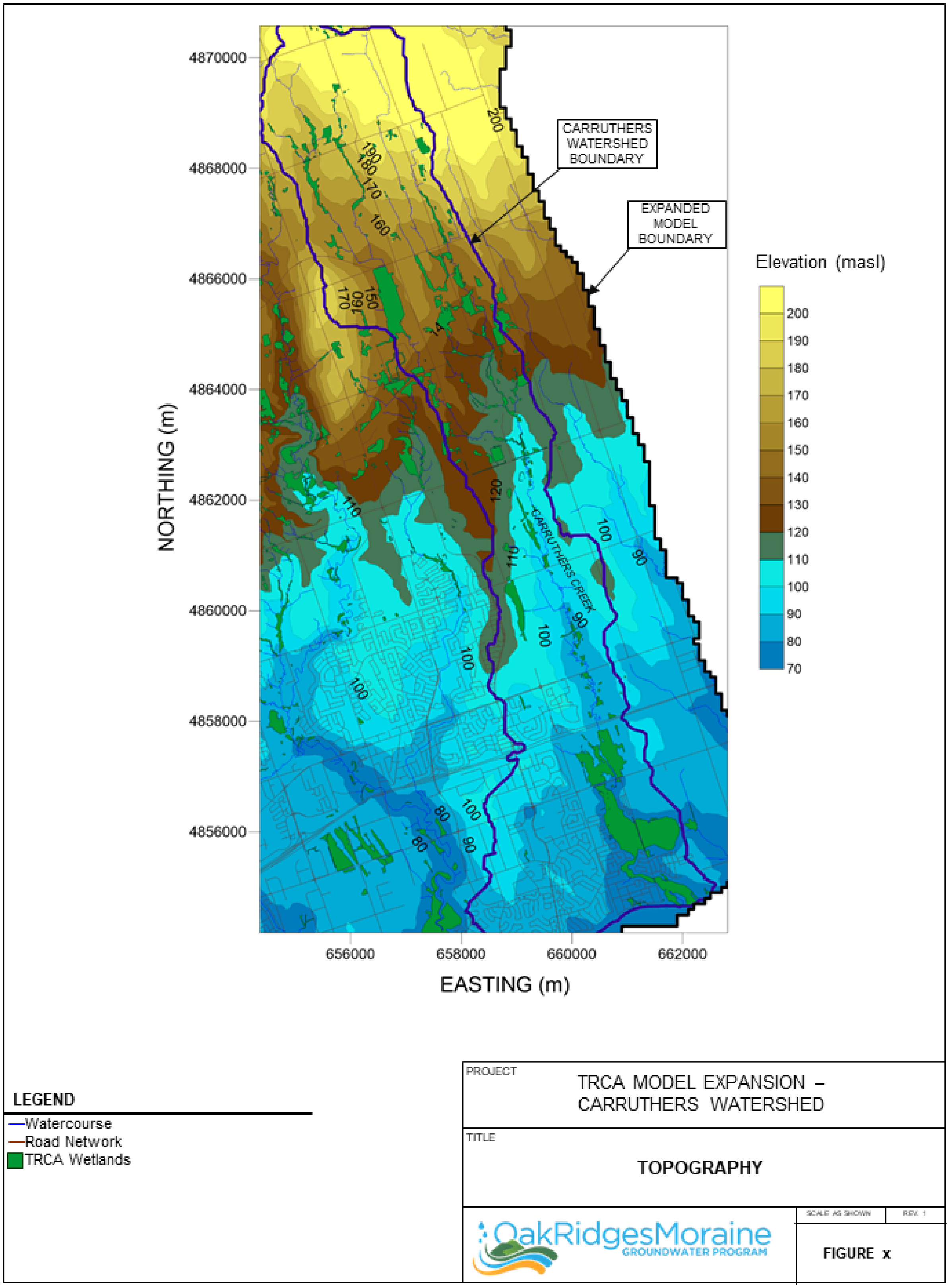

Figure 2: Ground surface topography of the study area.

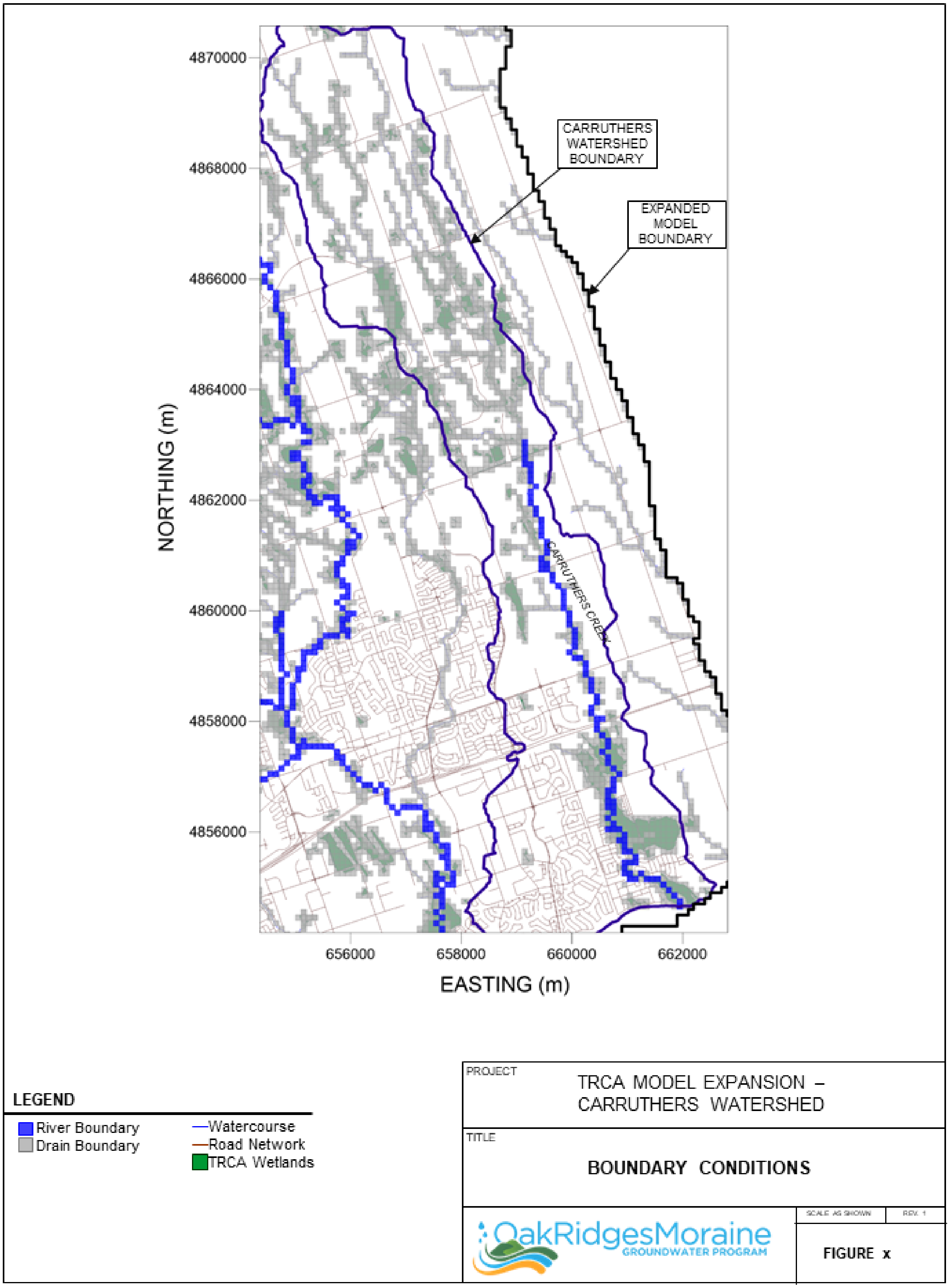

Figure 3: Location of model boundary conditions within the Carruthers Creek watershed. (Note: the terms "River" and "Drain" refer to boundary condition types used in MODFLOW—see Harbaugh, 2005)

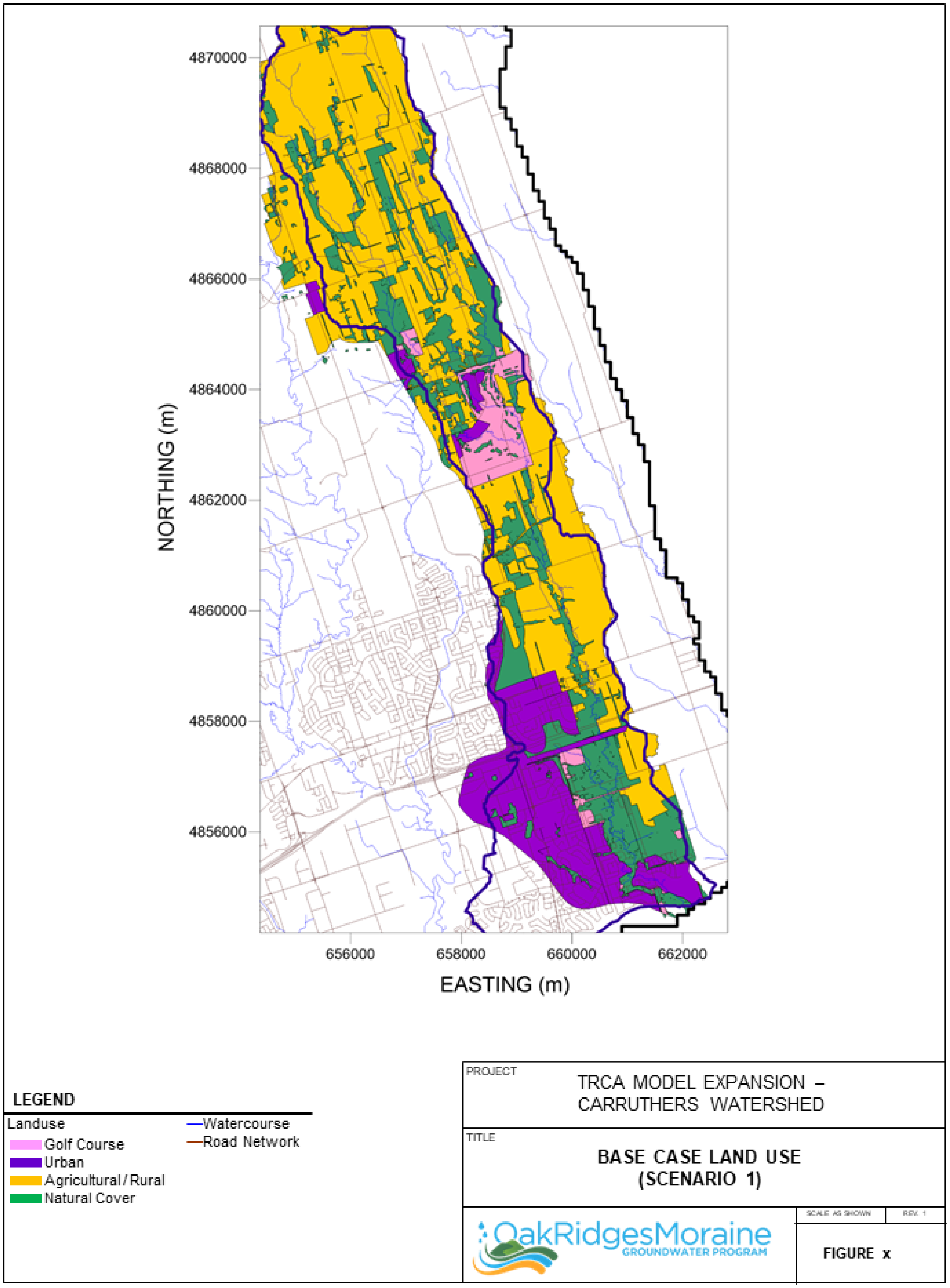

Figure 4: Base case land use (Scenario 1).

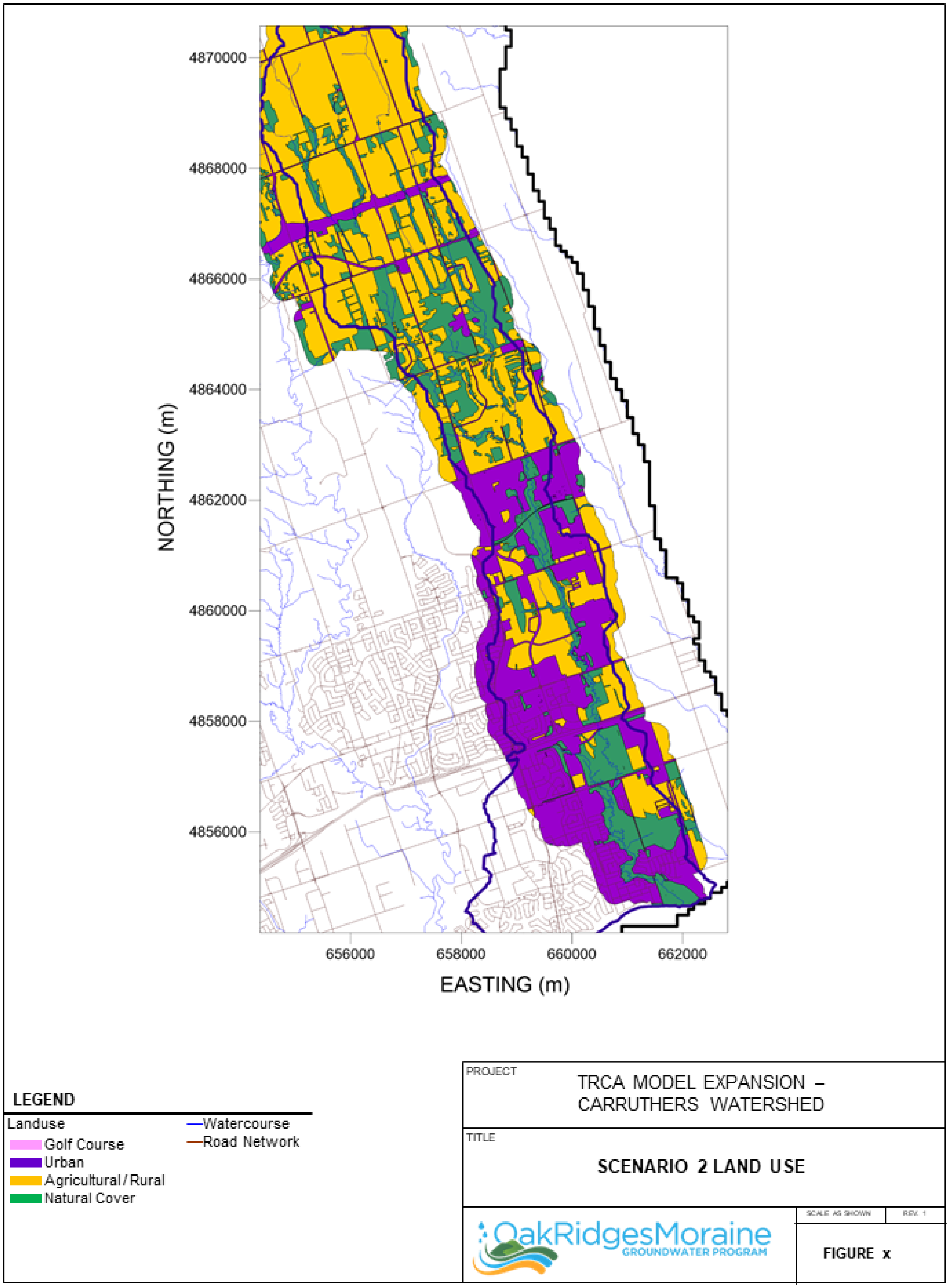

Figure 5: Scenario 2 land use.

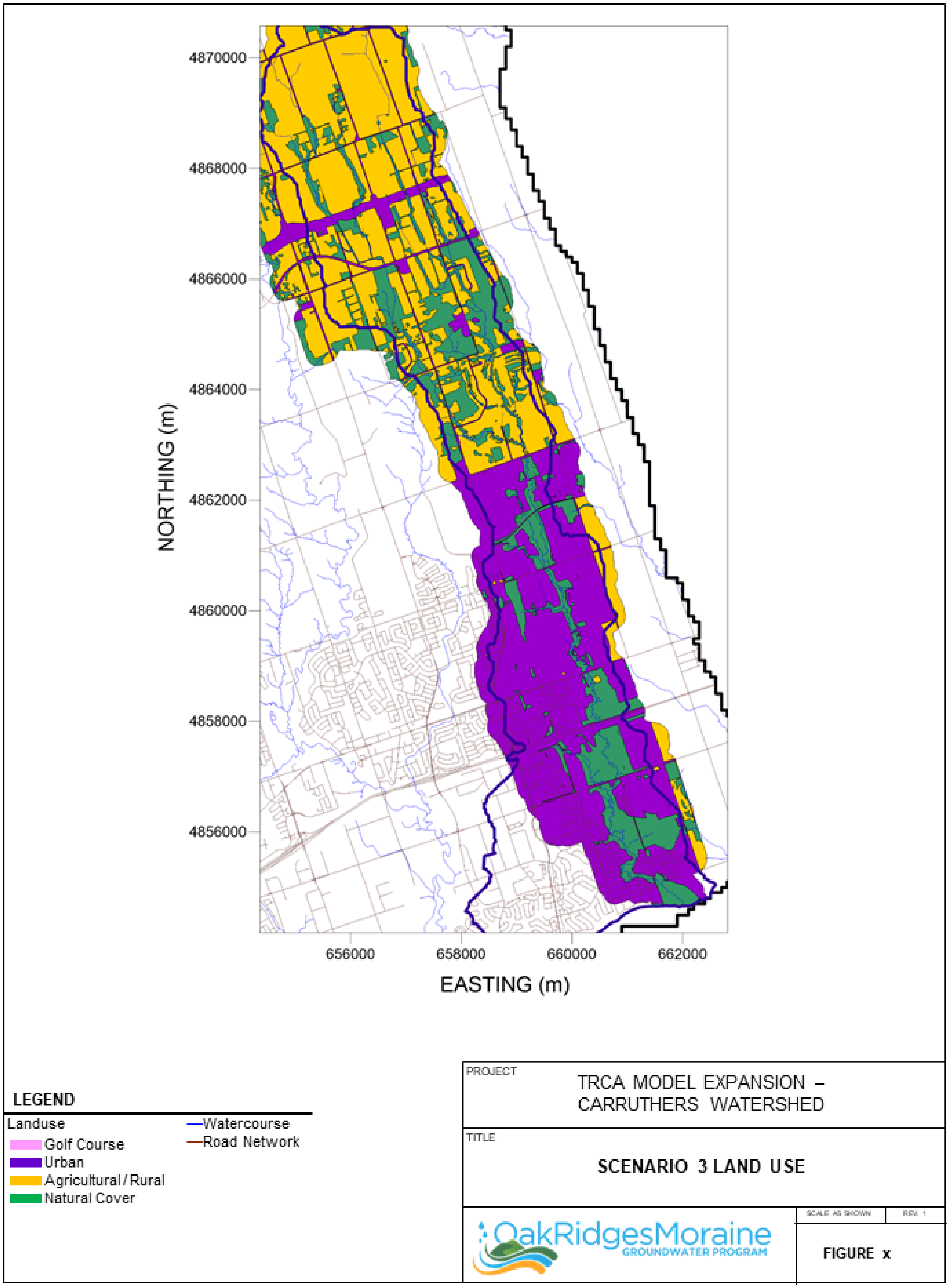

Figure 6: Scenario 3 land use.

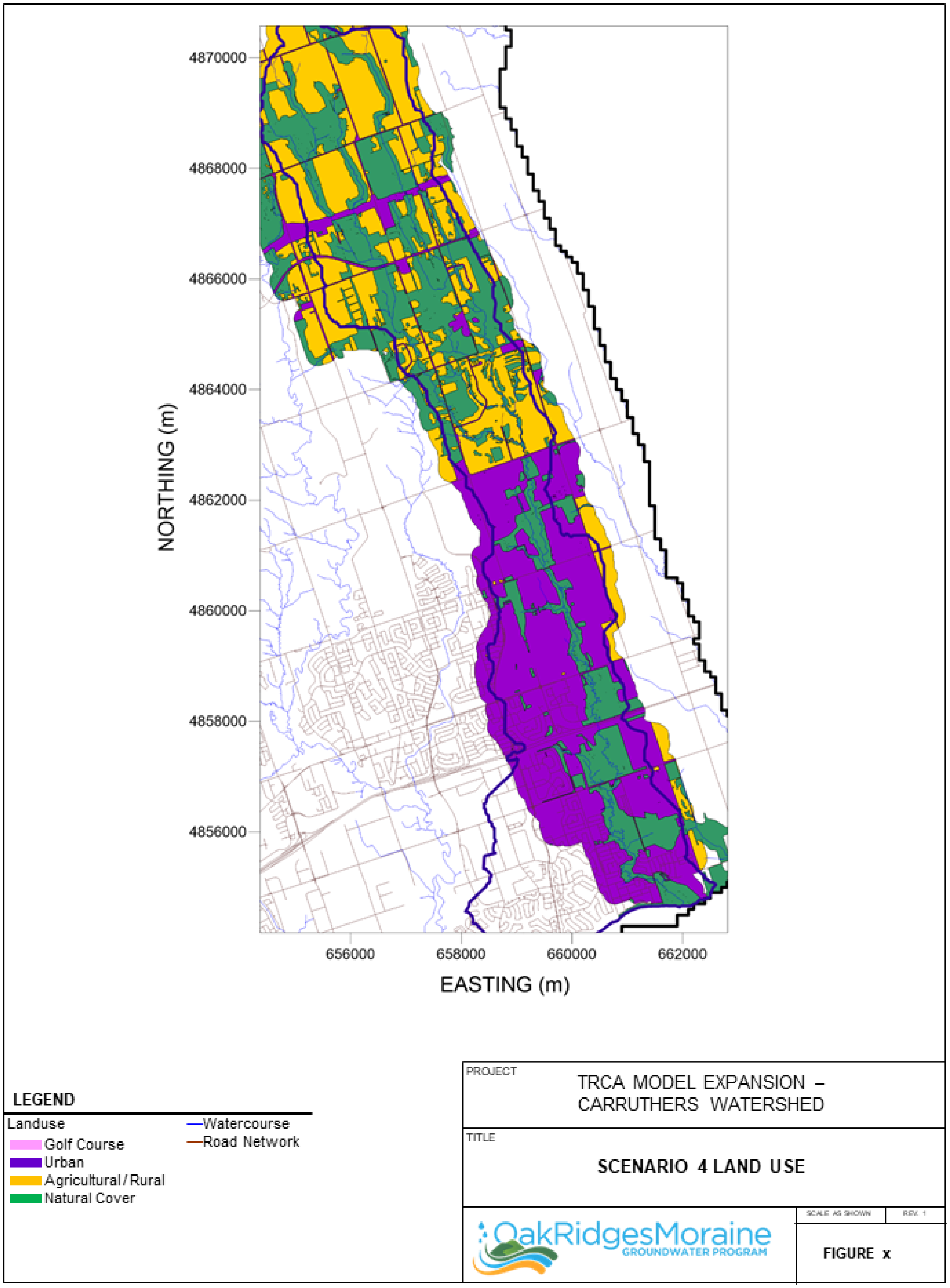

Figure 7: Scenario 4 land use.

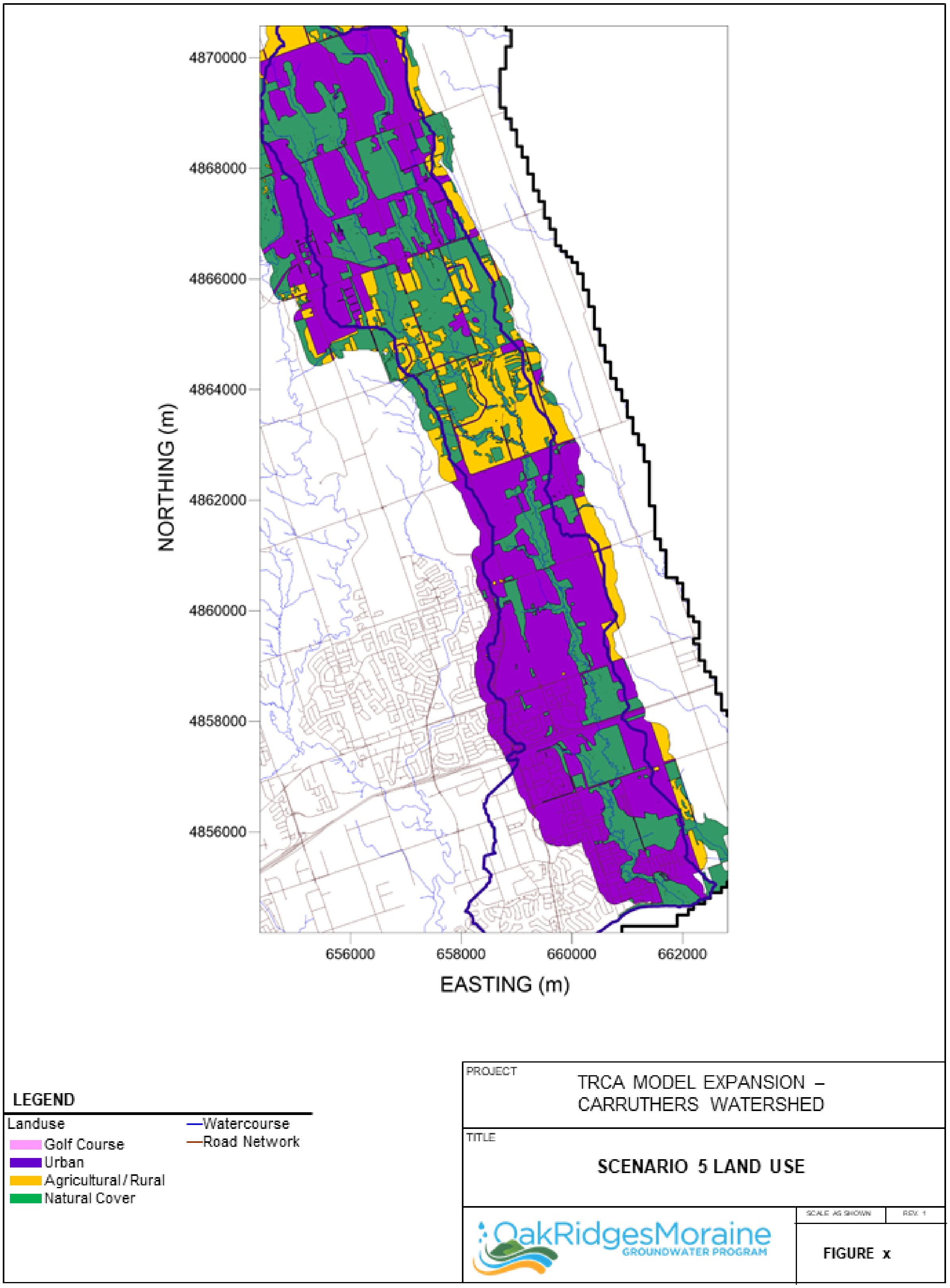

Figure 8: Scenario 5 land use.

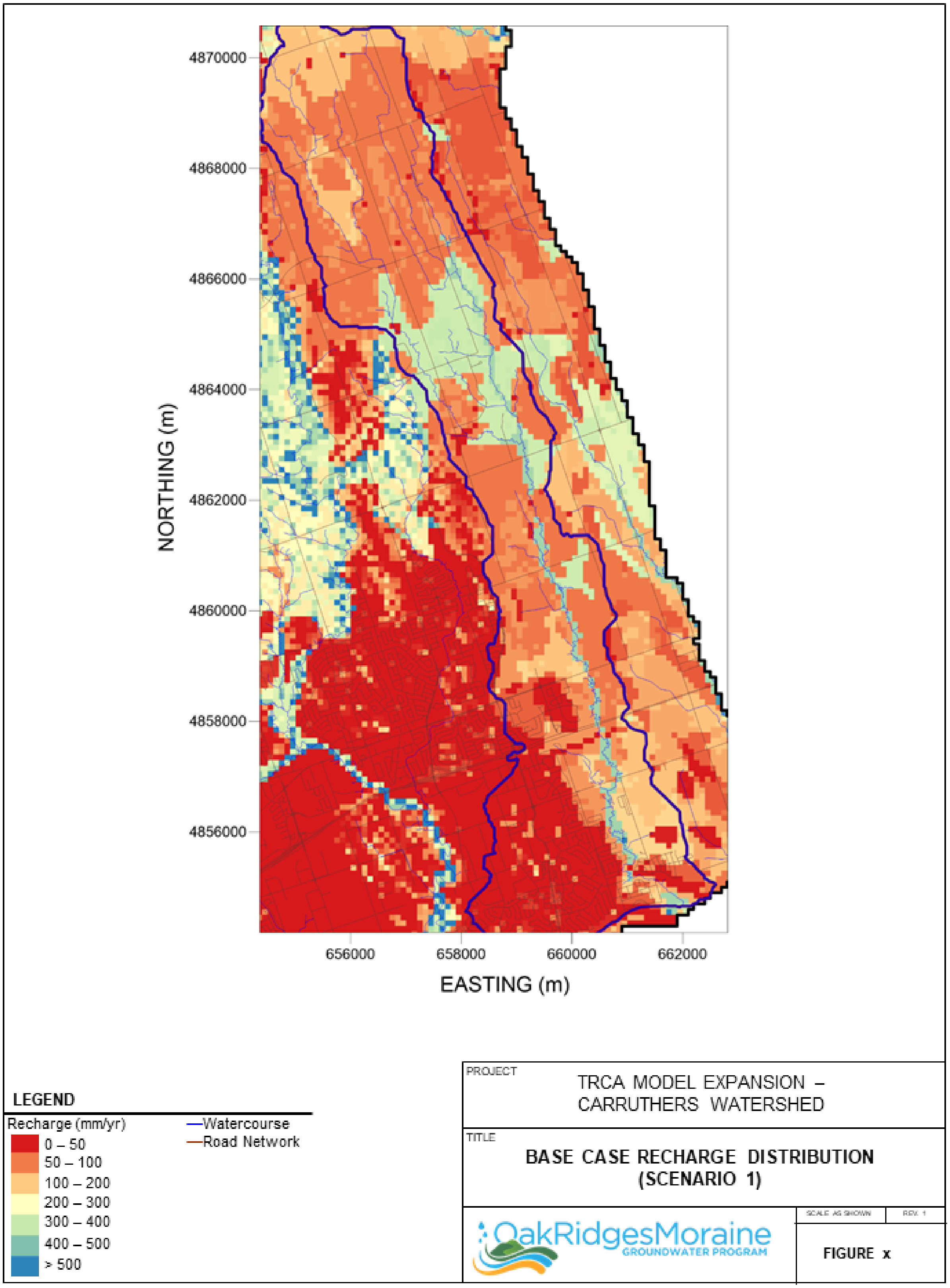

Figure 9: Applied scenario 1 groundwater recharge (mm/yr).

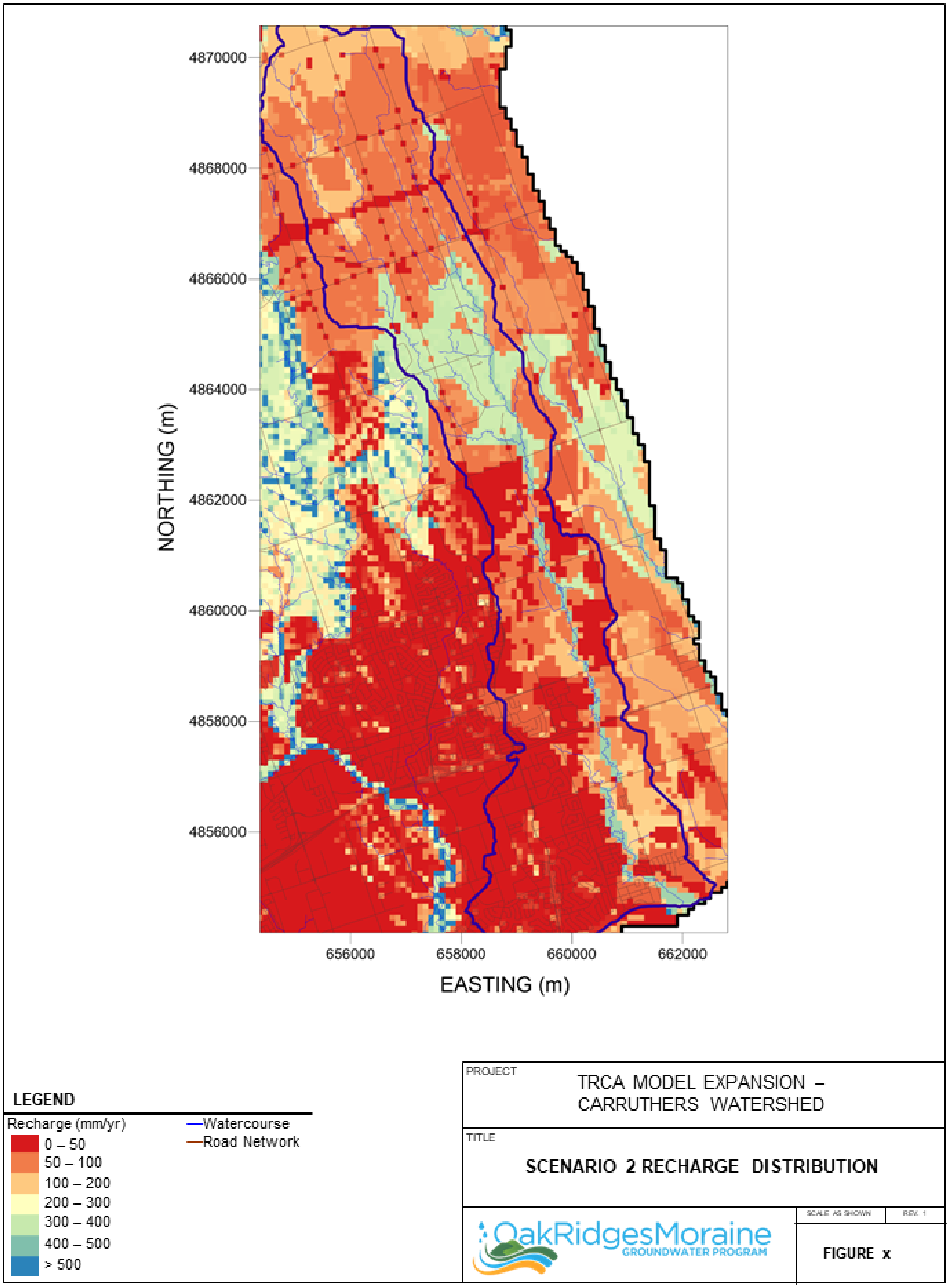

Figure 10: Applied scenario 2 groundwater recharge (mm/yr).

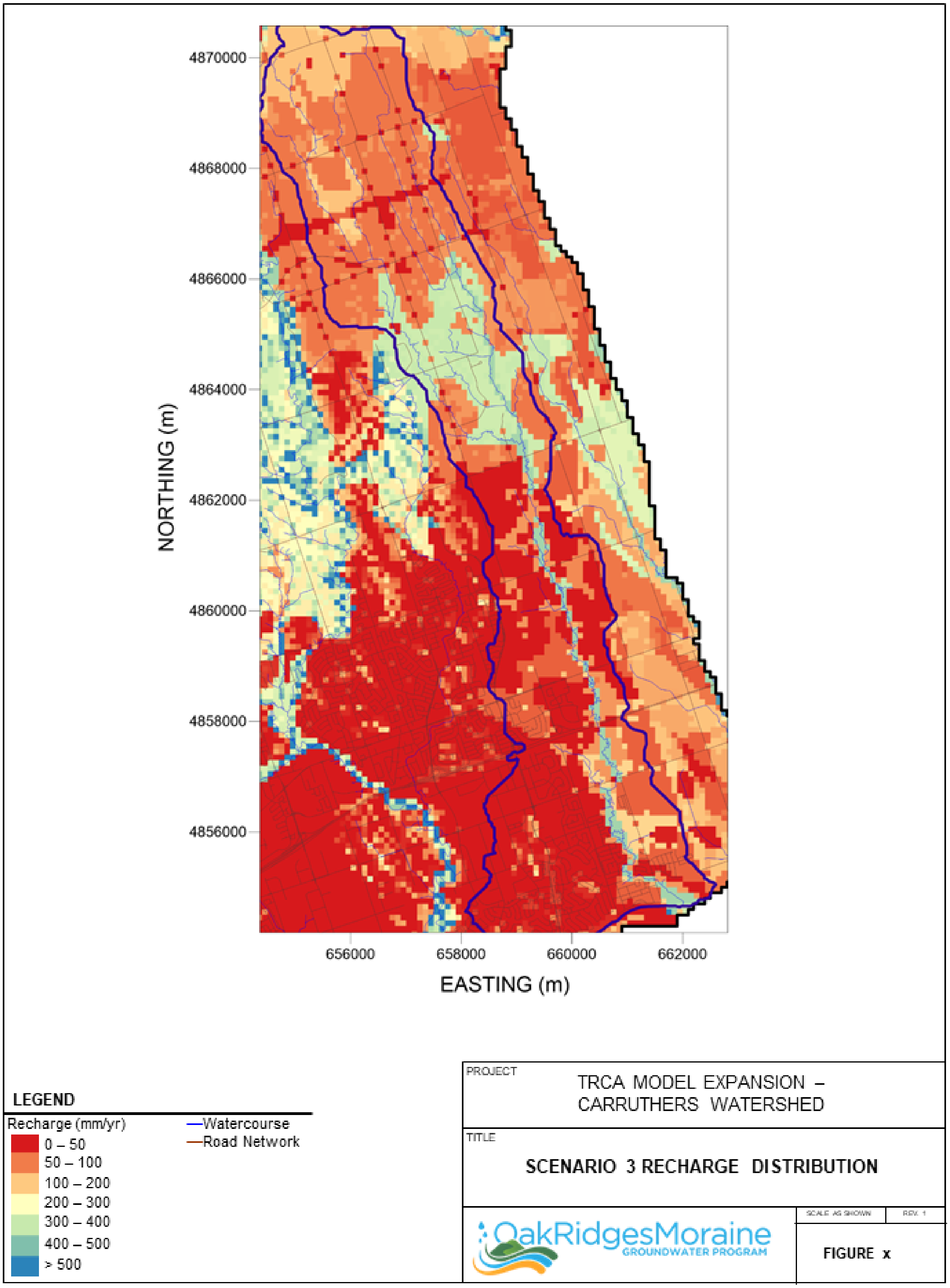

Figure 11: Applied scenario 3 groundwater recharge (mm/yr).

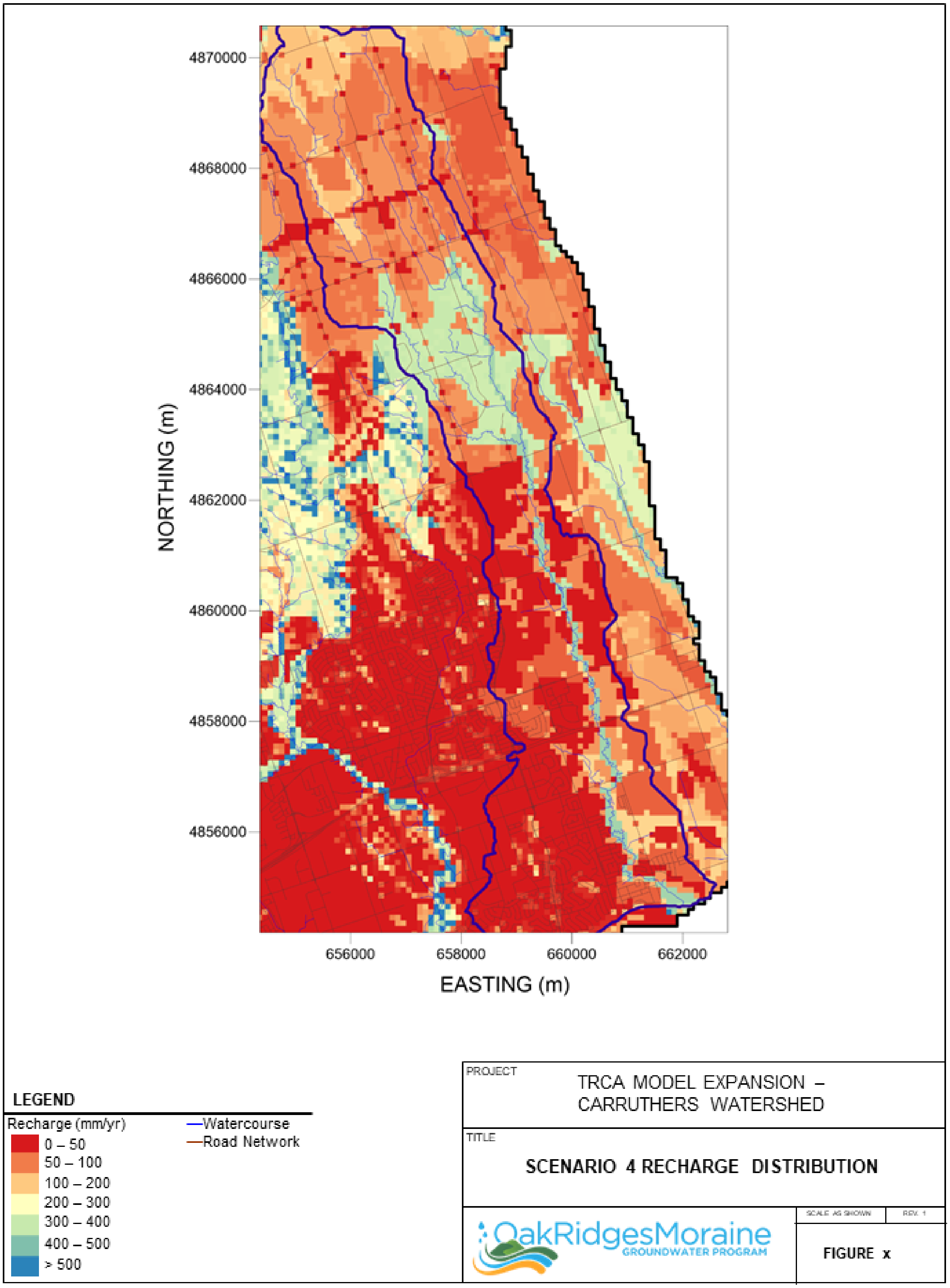

Figure 12: Applied scenario 4 groundwater recharge (mm/yr).

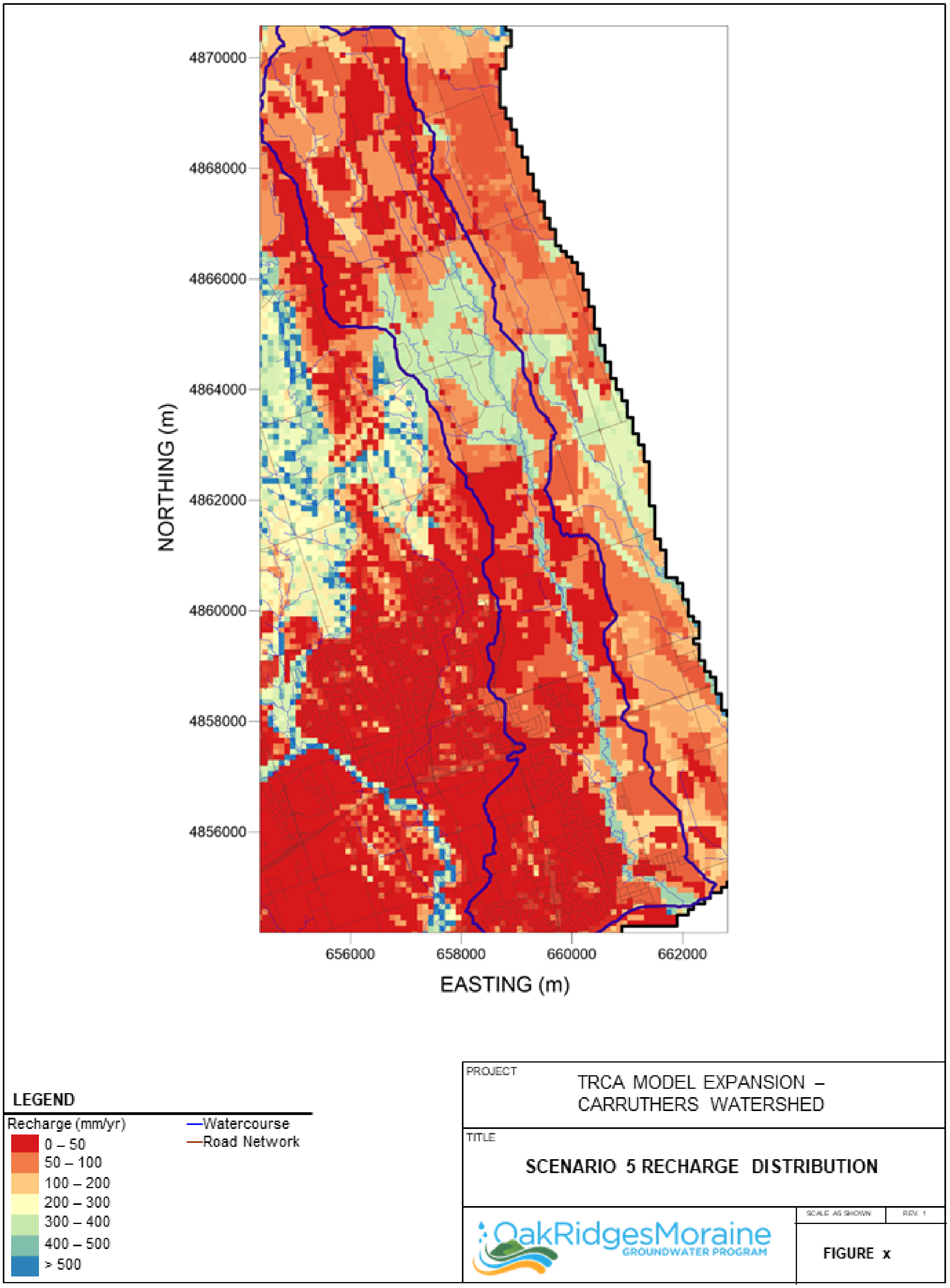

Figure 13: Applied scenario 5 groundwater recharge (mm/yr).

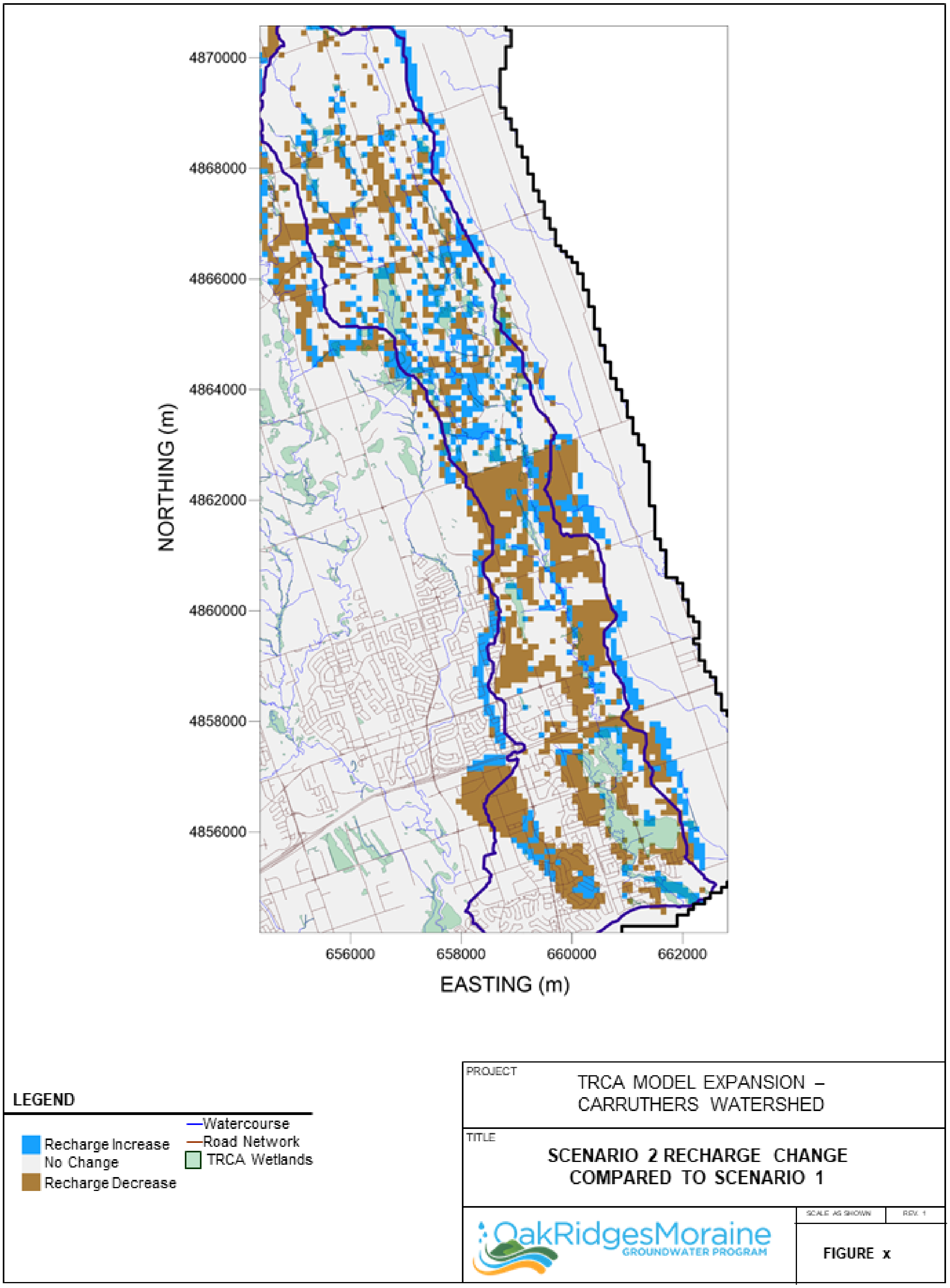

Figure 14: Change in scenario 2 groundwater recharge relative to the base case (Scenario 1).

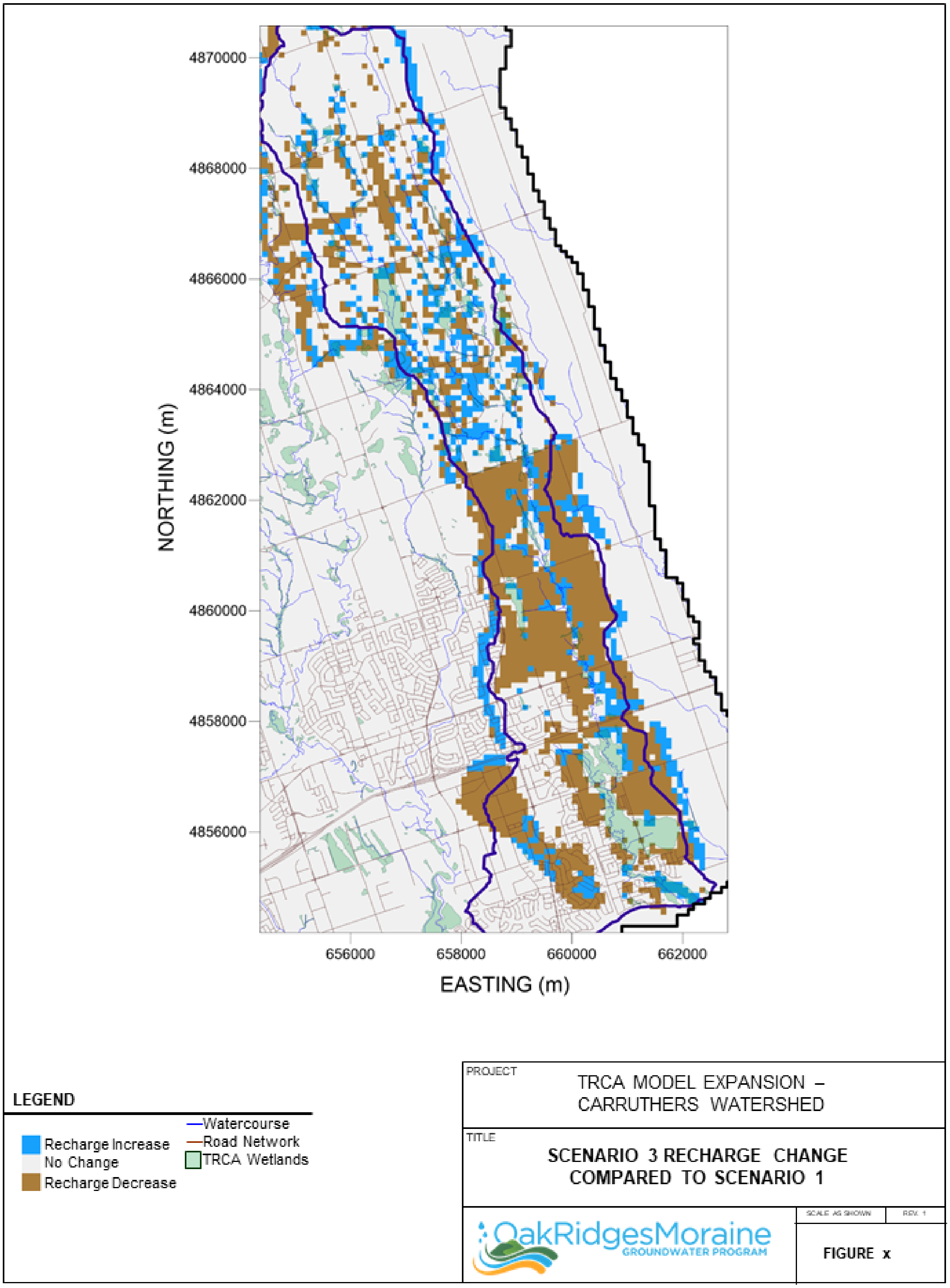

Figure 15: Change in scenario 3 groundwater recharge relative to the base case (Scenario 1).

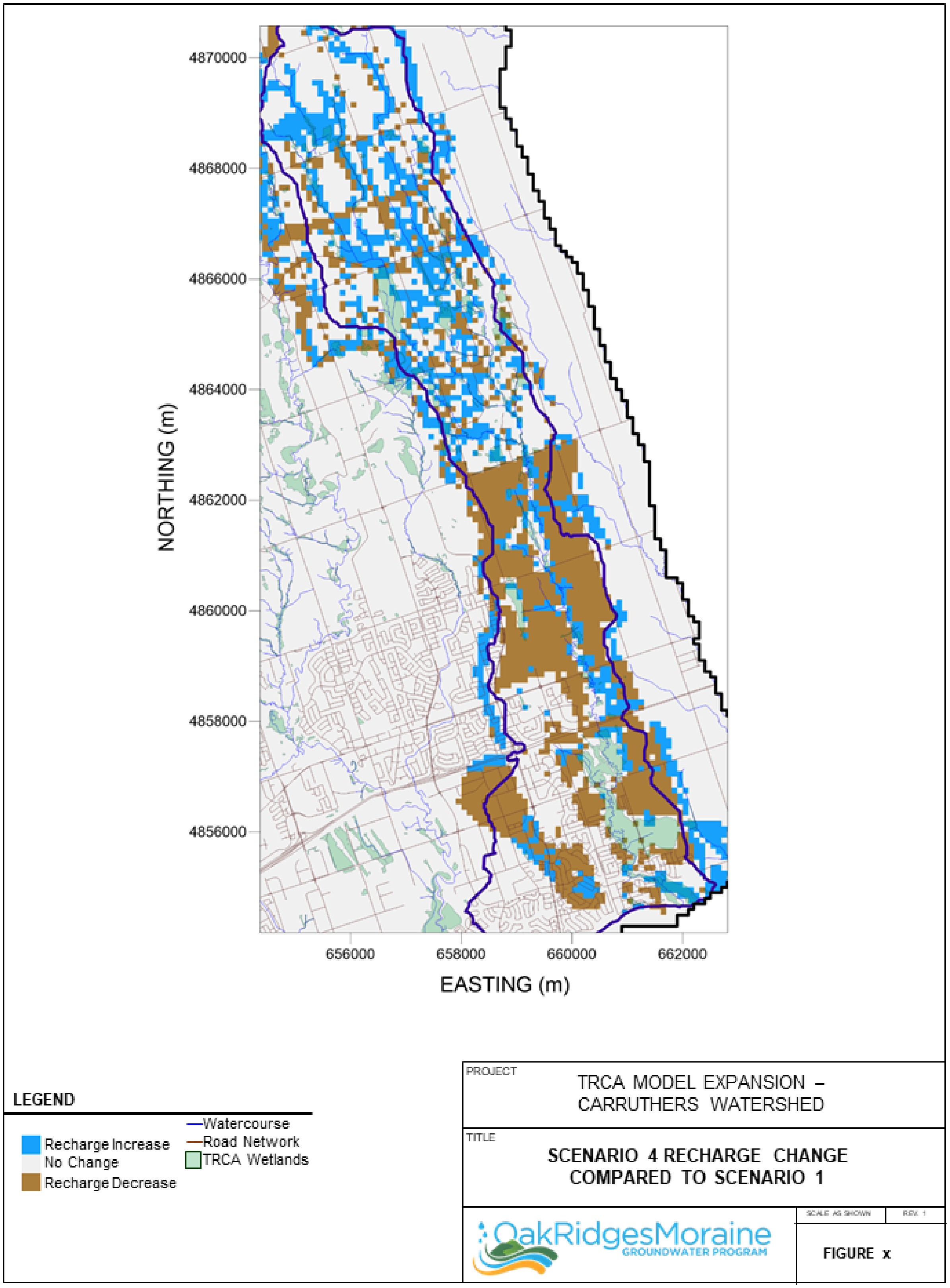

Figure 16: Change in scenario 4 groundwater recharge relative to the base case (Scenario 1).

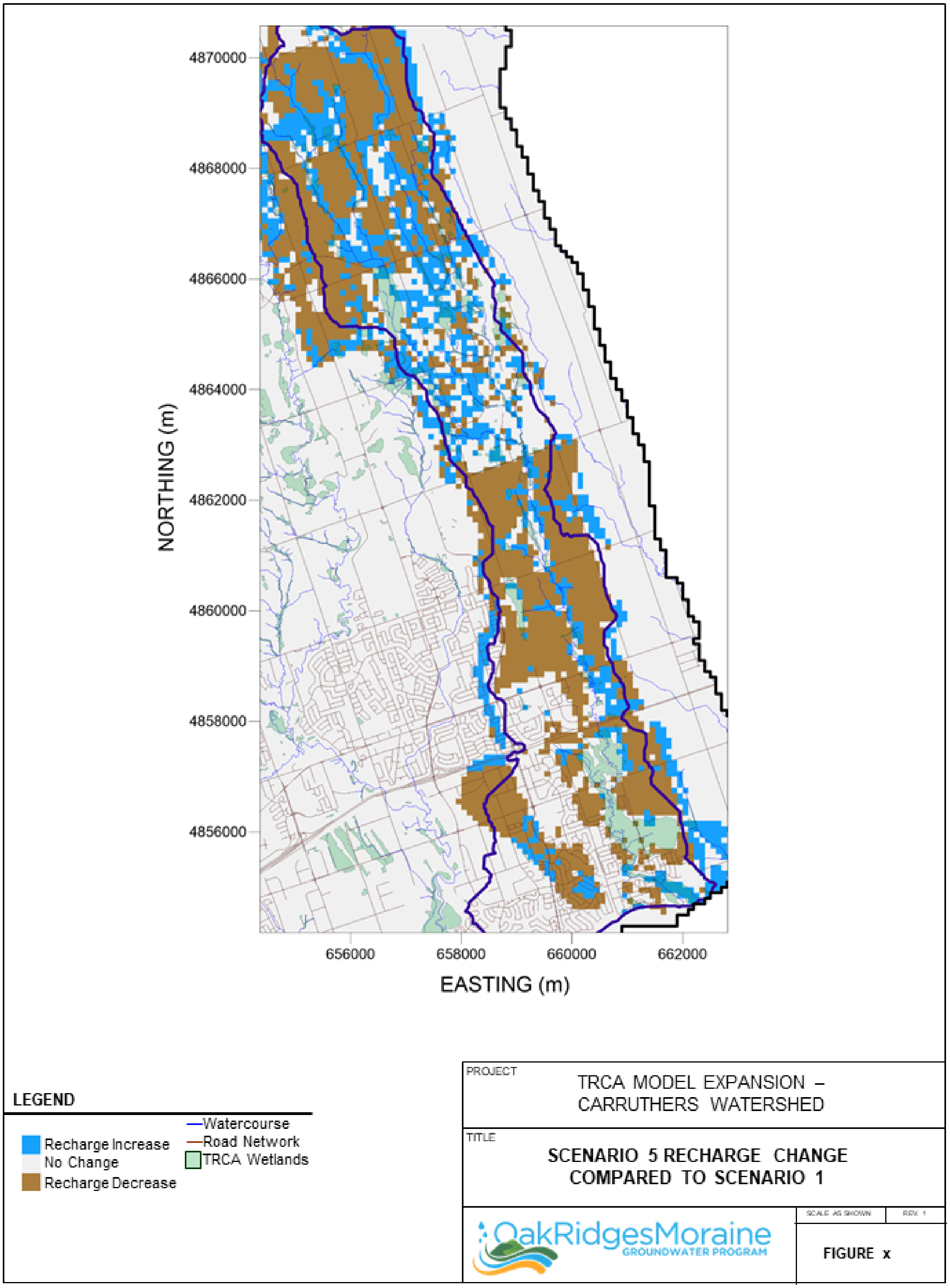

Figure 17: Change in scenario 5 groundwater recharge relative to the base case (Scenario 1).

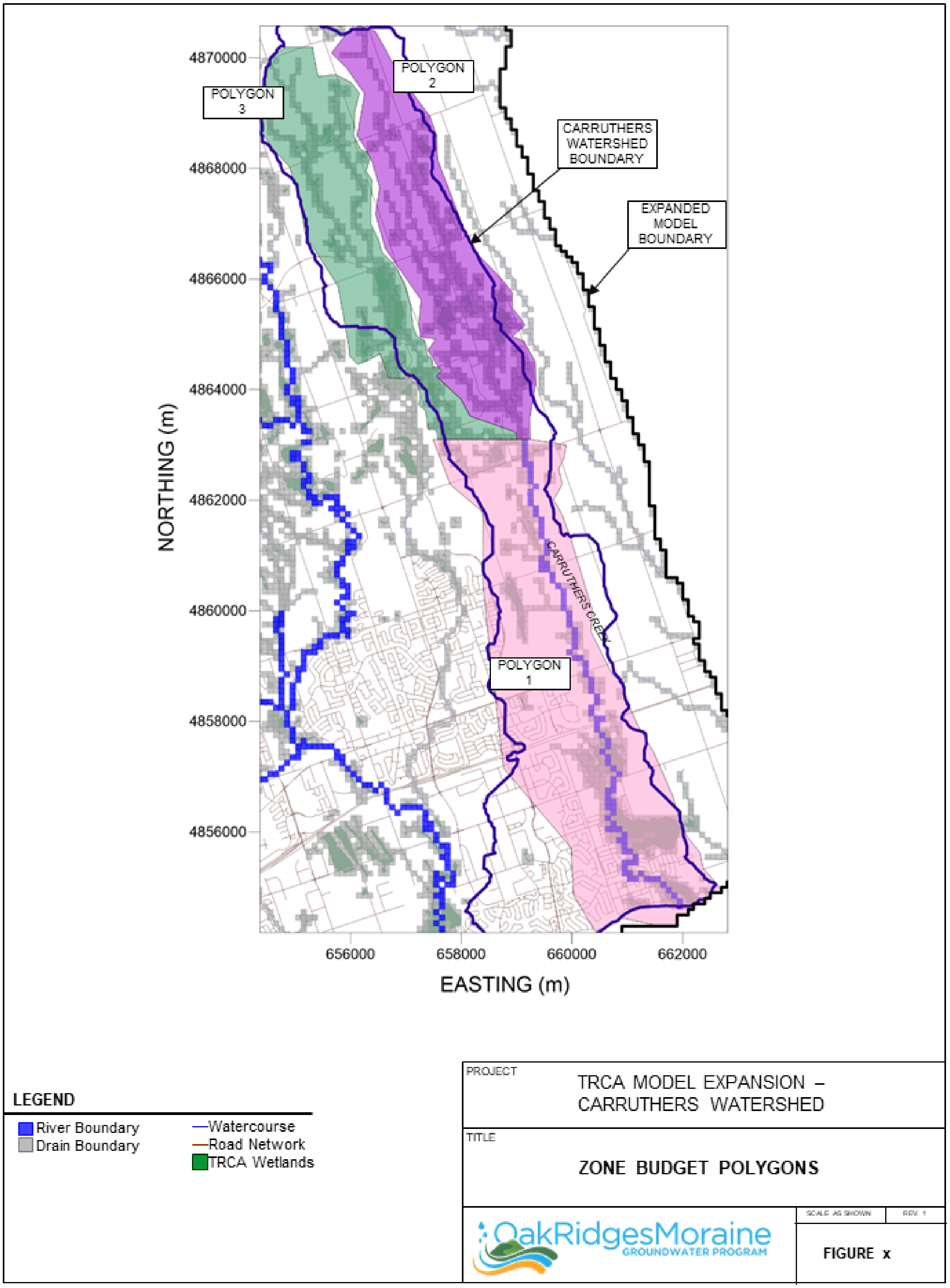

Figure 18: Location of Carruthers Creek sub-catchments (otherwise termed "zones" in Harbaugh, 2005) from which results presented in Table 3 are drawn.

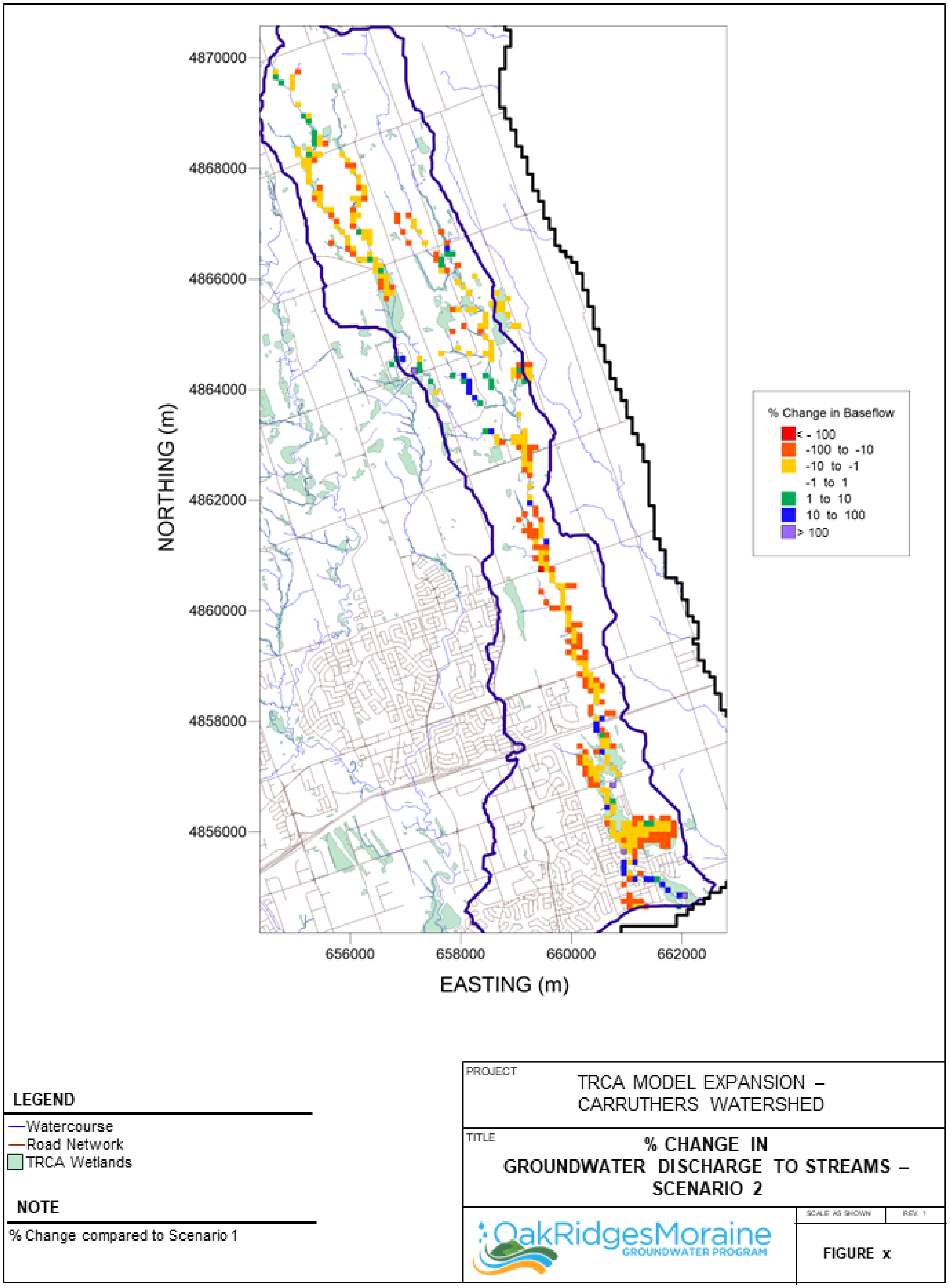

Figure 19: Change in scenario 2 groundwater exchange to streams relative to the base case (Scenario 1).

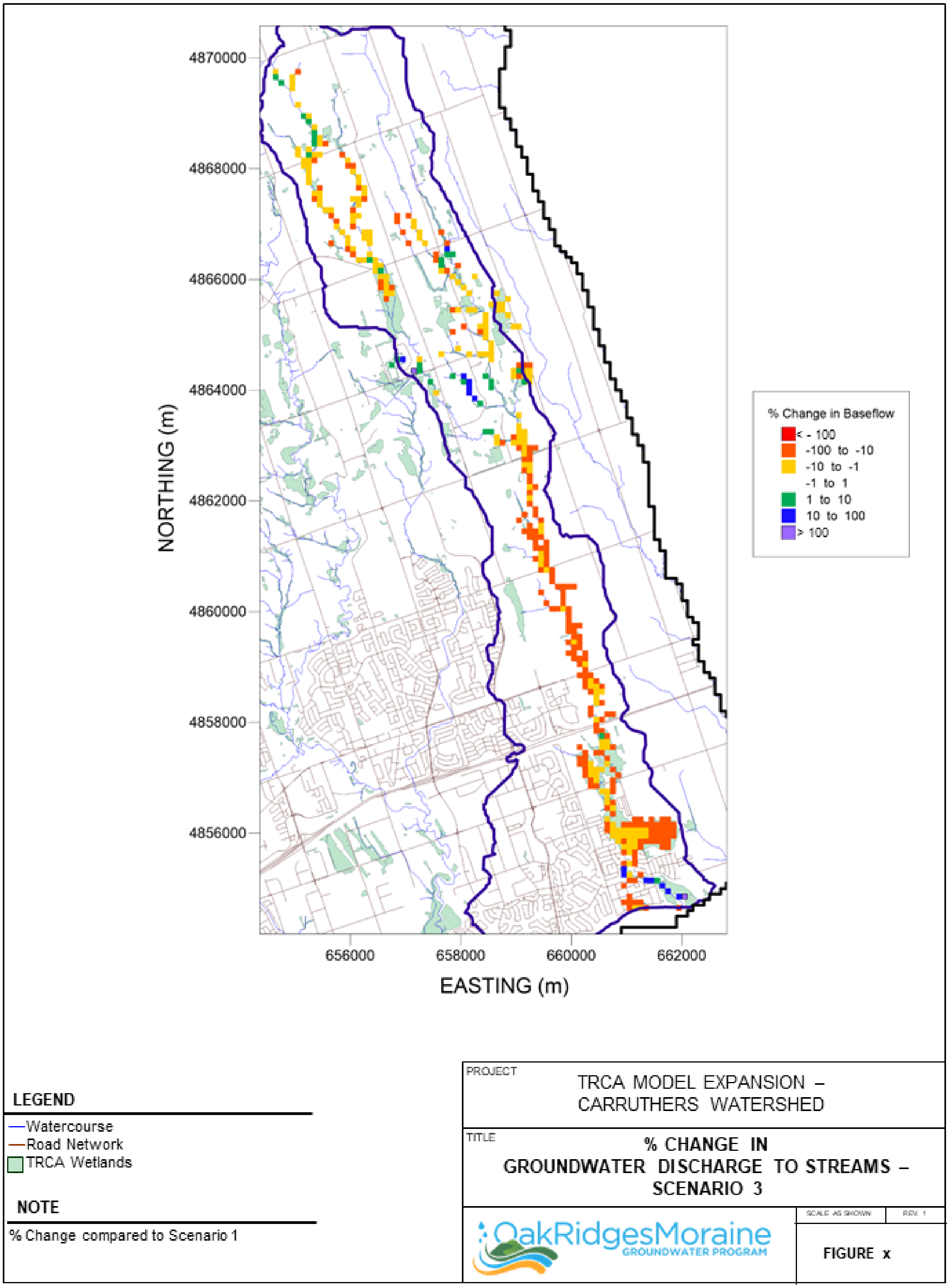

Figure 20: Change in scenario 3 groundwater exchange to streams relative to the base case (Scenario 1).

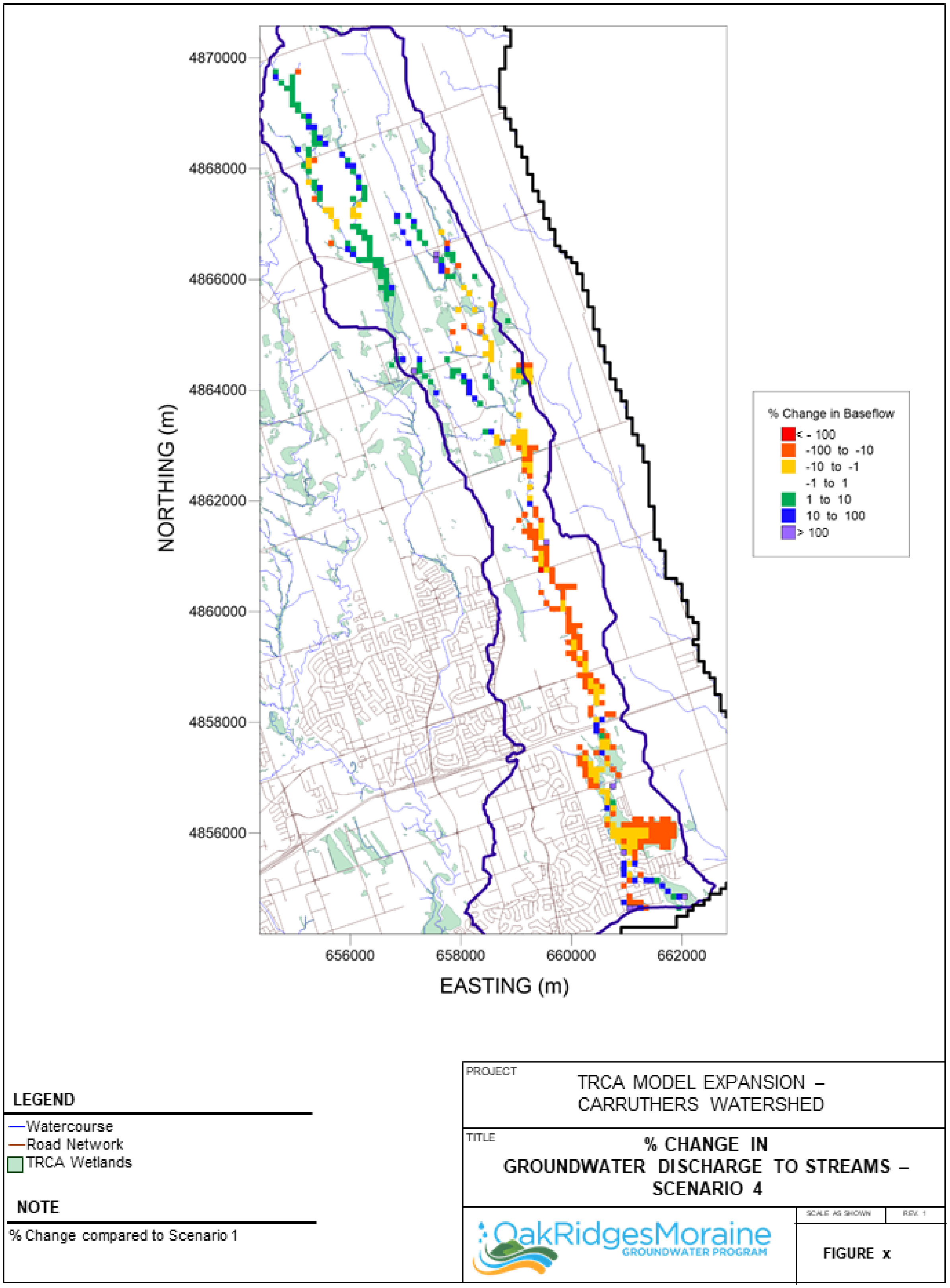

Figure 21: Change in scenario 4 groundwater exchange to streams relative to the base case (Scenario 1).

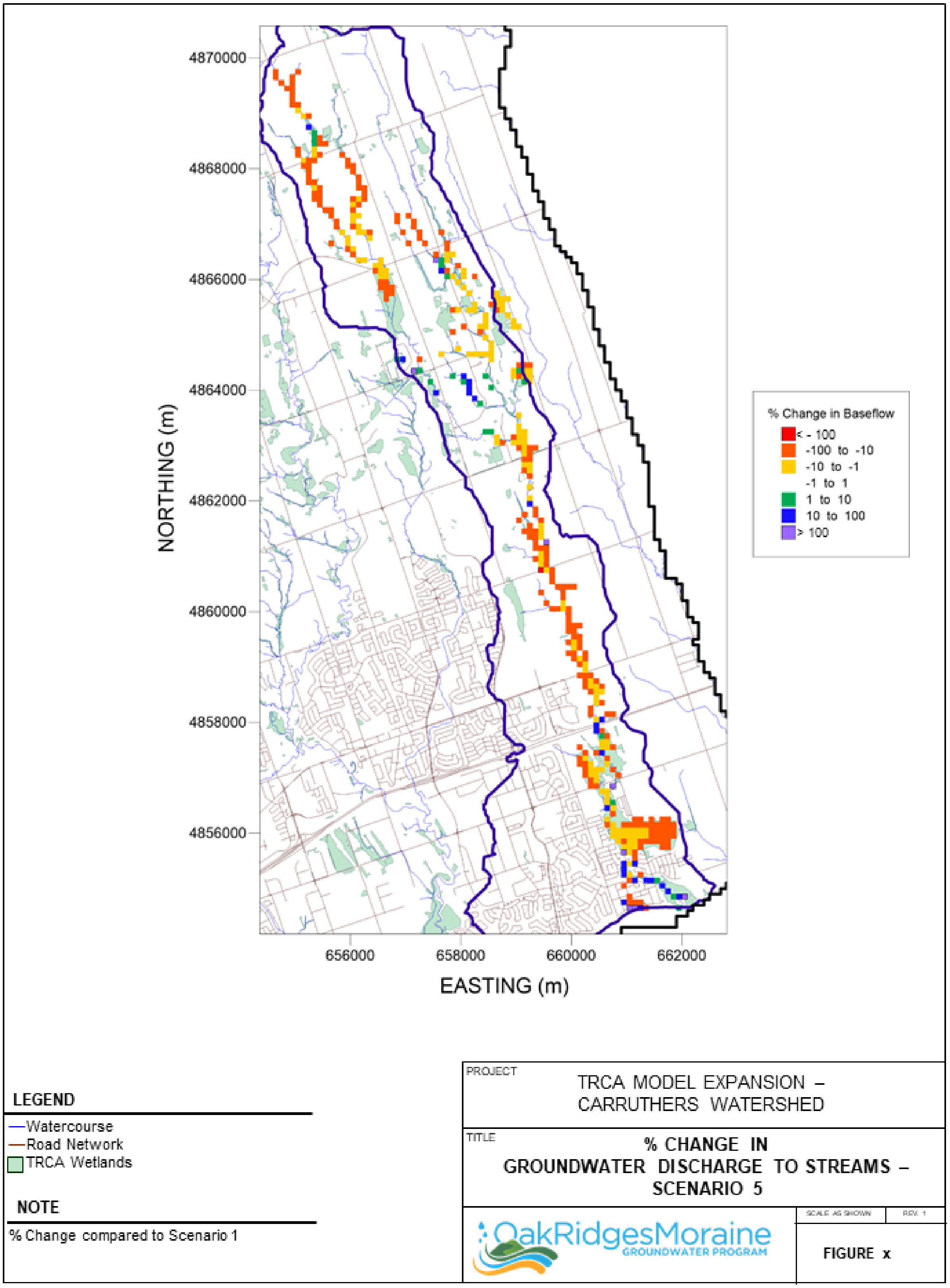

Figure 22: Change in scenario 5 groundwater exchange to streams relative to the base case (Scenario 1).

MEMORANDUM

Date: Thursday 22nd November, 2018

To: Ms. Laura Del Giudice, B.Sc., M.F.C., Senior Manager, Watershed Planning & Reporting
Ms. Namrata Shrestha, Ph.D., Senior Research Scientist, Research & Knowledge Management
Watershed Strategies
Mr. Gary Bowen, Watershed Specialist, Duffins Carruthers Petticoat and Great Lakes Advisor
Toronto Region Conservation Authority

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

Re: TRCA expanded groundwater flow model development

Background

In preparation for Municipal Comprehensive Reviews and Watershed plans, the TRCA has requested ORMGP staff to assist in providing support by utilizing existing numerical groundwater flow models. With a longer term goal of providing TRCA staff with a path for making effective use of existing groundwater flow models, the ORMGP staff have agreed to assist with the necessary tasks.

At the time of TRCA's request, no singular existing numerical groundwater flow model encompassed the entirety of the TRCA's jurisdiction with the necessary spatial discretization for the requested tasks. Three main tasks requested by the TRCA included:

1. Develop a jurisdiction-wide map of Ecologically-Significant Groundwater Recharge Areas (ESGRAs, see Marchildon et. al., 2016). ESGRA delineation is required in the Growth Plan for the Greater Golden Horseshoe (2017);
2. Entertain a possible methodology to address Significant Surface Water Contribution Areas (SSWCAs) as required in the Growth Plan for the Greater Golden Horseshoe (2017); and
3. For the Carruthers Creek Watershed Plan, to investigate the implications of proposed development to the groundwater system in the northerly reaches of the watershed.

The purpose of this memo is to briefly outline the setup of the model used to address the above needs. The model to be discussed below, is not a newly developed model per se, but is an amalgamation of three existing models developed in the past by hired consultants to address Source Water Protection requirements of the Clean Water Act, 2008. It should be noted that the models used in the creation of the "TRCA Expanded Groundwater Flow model" were not originally intended for focused use within the TRCA's jurisdiction. Should the TRCA plan to further understand the local groundwater system, particularly within the City of Toronto, then it is recommended that investments be made in model refinement, similar to ongoing projects within the regions of Peel and Durham.

ORMGP modelling staff are available to meet and discuss the modelling results in the context of the Municipal Comprehensive Review and the Carruthers Watershed Plan as documentation is being prepared. Documentation on the original three models used in this exercise are available from the ORMGP and must be used as reference for the modelling results presented here.

Outline

The structure of this memo is as follows:

1. outline the work performed in setting-up the structure of the TRCA Expanded Groundwater Flow Model (TEGWFM);
2. detail the recharge extrapolation to areas where estimated groundwater recharge was unavailable;
3. comparison of model outputs to:
   (i) existing models;
   (ii) groundwater monitoring data; and,
   (iii) estimated baseflow discharge.

Model Setup

The TEGWFM is an amalgamation of three existing models (listed in order of priority):

1. York Region Tier 3 (steady-state) Groundwater flow model (Earthfx Inc., 2013);
2. Core West Model (Earthfx Inc., 2007);
3. Core East Model (Earthfx Inc., 2014).

Although the York Tier 3 (YT3) model was focused on York Region groundwater issues, it was largely based on the Core Model developed under the ORMGP between 2002 and 2006. The south side of the moraine was given less attention during the Tier 3 work; however, the original Core Model was calibrated across the entire model domain and reflects reasonable groundwater conditions within the TRCA's jurisdiction. No attempt was made to improve calibration as it is beyond the scope of this work. Should this be an issue moving forward, the ORMGP will gladly assist in developing a strategy to improve numerical groundwater modelling products across the TRCA's jurisdiction.

A primary requirement for this model set-up was to expand the existing geographical model extent along the east side of the Carruthers Creek Watershed to capture part of the adjacent Lynde Creek Watershed and to the west beyond TRCAs boundary to include the Etobicoke Creek watershed that was excluded from the original YT3 model. This expansion beyond the TRCA's border ensured that model boundary conditions were sufficiently distant that they did not unduly influence the groundwater system within TRCA's watersheds (see Figure 1).

Each of the three models were developed using overlapping 100 m×100 m finite difference grids. While the YT3 model consisted of 10 model layers, in which the Newmarket Till was subdivided into three distinct layers (Earthfx Inc., 2013), the Newmarket layer in both the Core east and west models was represented as a single layer, resulting in both being 8-layer models. The Core east and west models were first converted into 10-layer models by subdividing their Newmarket layers into three layers of equal thickness.

From within the expanded boundary shown in Figure 1, a 10-layer×100 m×100 m grid was constructed using the material properties from the existing models in the order of priority listed above. 86% of the resulting model originated from the YT3 model, while the remaining 12.6% and 1.4% was derived from the Core West and East models, respectively.

Boundary Conditions

Boundary conditions set for the model was as follows:

- Constant head of 218.9 metres above sea level (masl) along the Lake Simcoe shoreline;
- Constant head of 74.7 masl along the Lake Ontario shoreline;
- Watercourses were handled differently according to the task:

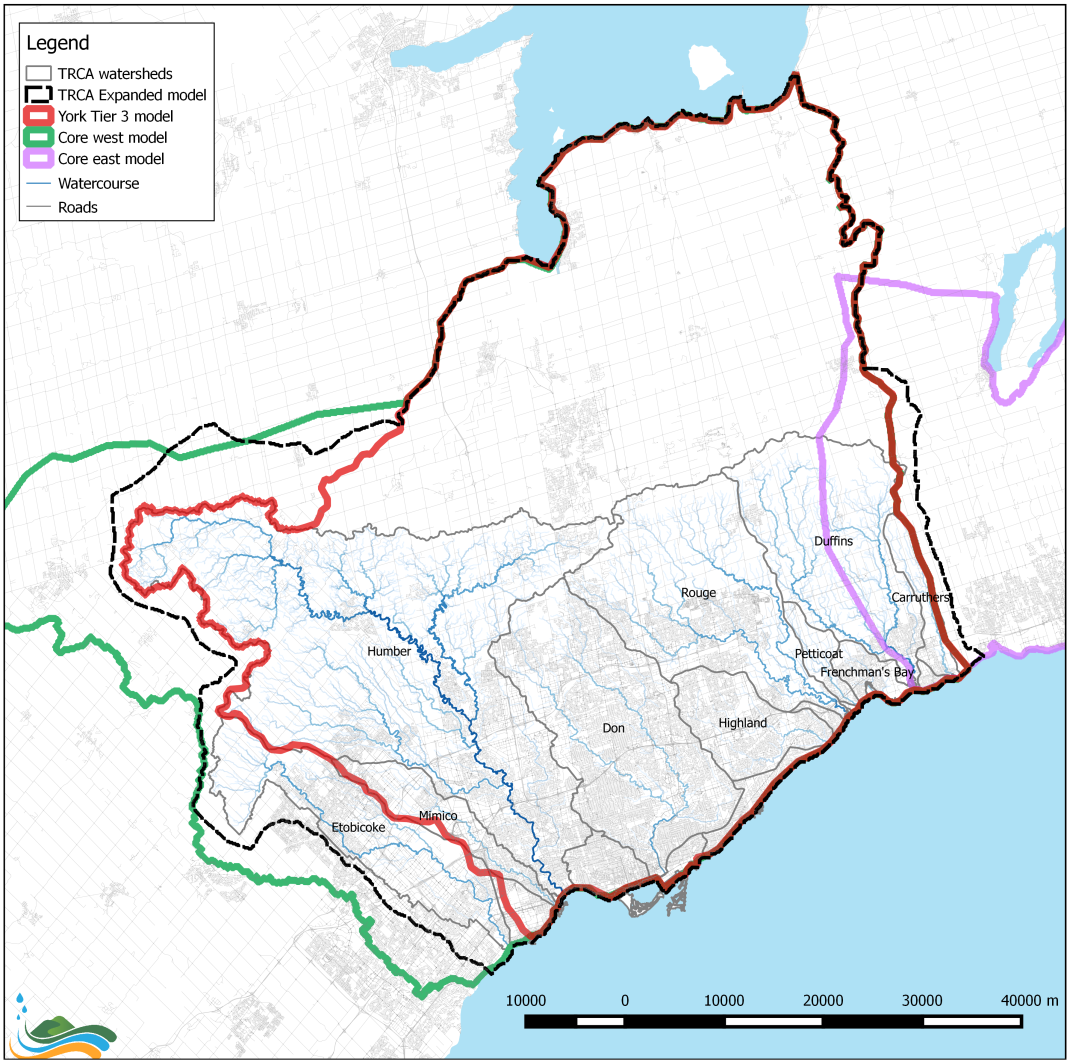

Figure 1: TRCA Expanded Groundwater Flow Model (TEGWFM) boundary relative to existing models used in its amalgamation.

  - ESGRAs: SFR-package (Niswonger and Prudic, 2005) employed for all TRCA streams;
  - Carruthers Creek watershed plan:
    - "River" (Harbaugh, 2005) boundary conditions set for TRCA streams of Strahler (1952) class greater than and equal to 3, with flow depths ranging from 0.2 to 1.0m, dependent on Strahler class; and,
    - "Drain" (Harbaugh, 2005) boundary conditions set for TRCA streams of Strahler class less than 3.
  - In all cases, Drain boundary conditions were set for all watercourses outside of the TRCA jurisdiction.

- Drain boundary conditions were set for all cells intersecting a mapped wetland (as provided by the TRCA), with the ground surface elevation used as the reference elevation.

- Long-term average groundwater pumping rates of Earthfx Inc. (2013) applied.

- Steady recharge rates based on Earthfx Inc. (2013) and extrapolated to TEGWFM extents (see below).

Groundwater Recharge Extrapolation

The distributed long-term steady groundwater recharge rates applied to the YT3 model (Earthfx Inc., 2013) was aggregated according to land use and surficial geology combinations. A spatial analysis of land use and surficial geology combinations using SOLRIS (OMNR, 2008) and OGS (OMNDM, 2010), respectively, was used to classify recharge estimated by the YT3 model. Both land use and surficial geology (more specifically permeability, as it determines percolation rates) are the primary drivers of simulated groundwater recharge. Topography also has an influence, however consideration of topography would require the explicit modelling of its influence, which was beyond the scope of the present work. The final recharge estimates assigned to the newly incorporated model areas were deemed to be reasonably similar to those used in the YT3 model and thus suitable for the current work.

For brevity, Table 1 lists the top 76% of land use and surficial geology combination coverage within the original YT3 model domain, and its associated groundwater recharge rates. Figure 2 shows the final recharge estimates used for the model, note the similarity in recharge outside of the original YT3 model domain.

Table 1: Land use and surficial geology combinations found within the York Tier 3 model domain and the average recharge simulated.

SOLRIS land use class	Relative permeability[1] (of underlying material)	Areal coverage	Average GW recharge (mm/yr)	standard deviation
Tilled	low	10%	158.7	151
Built Up Area–Impervious	low-medium	10%	47.3	33
Built Up Area–Impervious	low	10%	86.6	105
Agriculture[2]	low	9%	193.2	163
Agriculture[2]	high	8%	384.2	375
Agriculture[2]	low-medium	6%	97.8	110
Tilled	low-medium	6%	83.0	60
Built Up Area–Impervious	high	5%	117.9	163
Tilled	high	4%	348.9	146
Treed Swamp	high	2%	368.8	185
Deciduous Forest	high	2%	402.7	258
Treed Swamp	organic material	2%	24.9	101
Mixed Forest	high	2%	397.3	372

[1] as per OMNDM (2010)

[2] SOLRIS land class “Undifferentiated” has been renamed here as “Agriculture”

Model Performance

Comparison of Results to the YT3 model

Although the majority of the model was based on the YT3 model, certain differences in the model setup were required in order to undertake the TRCA work. In particular, representation of wetland features had to be included for the sake of ESGRA generation. This required that model cells covered by mapped wetlands (as provided by the TRCA) had to be converted into drain-type boundary conditions (Harbaugh, 2005), thus allowing for the wetlands to be represented in the model as groundwater sinks, where water drains from the groundwater system to wetlands.

The YT3 steady-state model did not explicitly represent the wetlands in this way as it was beyond the needs of that model. Instead, wetlands where omitted from the steady-state model and thus no drainage to these features was allowed to occur.[1] This increased drainage into wetlands in the TEGWFM caused

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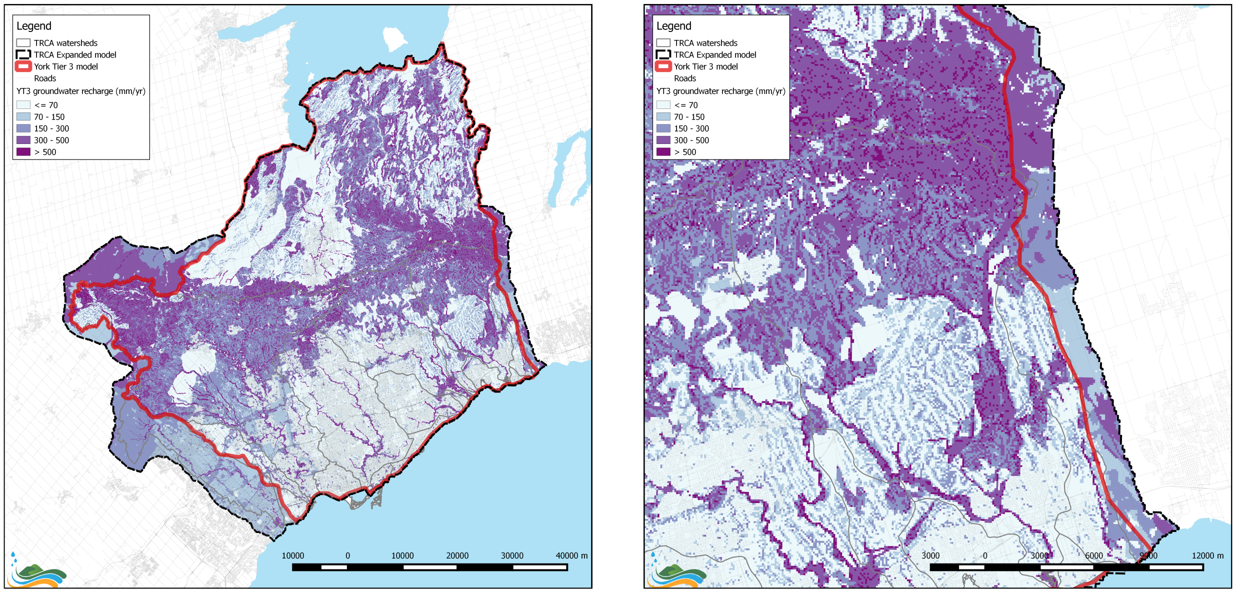
[1] It should be noted that the YT3 model came also in the form of an integrated/transient model, which would adequately represent wetland function; however, a steady-state model is required for ESGRA analysis.



(a) full extent

(b) eastern boundary close-up

Figure 2: Recharge distribution extrapolated from within the YT3 model boundary.

some changes to the resultant steady-state water levels solved by the model. Figure 3 shows a comparison of resulting head by numerical model layer. Overall, there is a 0.67 m bias to the YT3 relative to the TEGWFM (meaning that the TEGWFM steady-state heads are, on average, 0.67 m lower than the heads simulated by the YT3 model). This was expected as there exists more opportunity for groundwater to drain. In comparing the results, the root mean squared error (RMSE) is 5.77 m over the model domain where the TEGWFM overlaps the YT3.

As discussed in the following section, RMSE between either the TEGWFM and YT3 models and measured data do not differ, and are far above the 5.77 m RMSE calculated between the models. This suggests that, differences found between the models should be mostly attributed to model and data uncertainty, and not tied to the model alteration procedure outlined in this memo.

Figure 4 shows model head comparison between YT3 and TEGWFM for the three major aquifer complexes: Inter-Newmarket Sediments (INS), the Thorncliffe aquifer complex (TAC), and the Scarborough aquifer complex (SAC). These figure were generated simply to illustrate the similarities between modelled heads and the prevailing gradients, which are perpendicular to the contours.

Comparison of Results to Groundwater Monitoring

As discussed above, the TEGWFM does exhibit some difference to the YT3. Here, the results from both models are compared to field measurements. Figure 5 shows the models performance against measured data. The model's performance achieves an RMSE, globally, of 16.5 m, well above the RMSE determined between the YT3 and TEGWFM model results, yet comparable to the values reported in Earthfx Inc. (2013). Similarly, Figure 6, taken from Earthfx Inc. (2013), has been included to illustrate no notable difference in model performance between the YT3 and TEGWFM model.

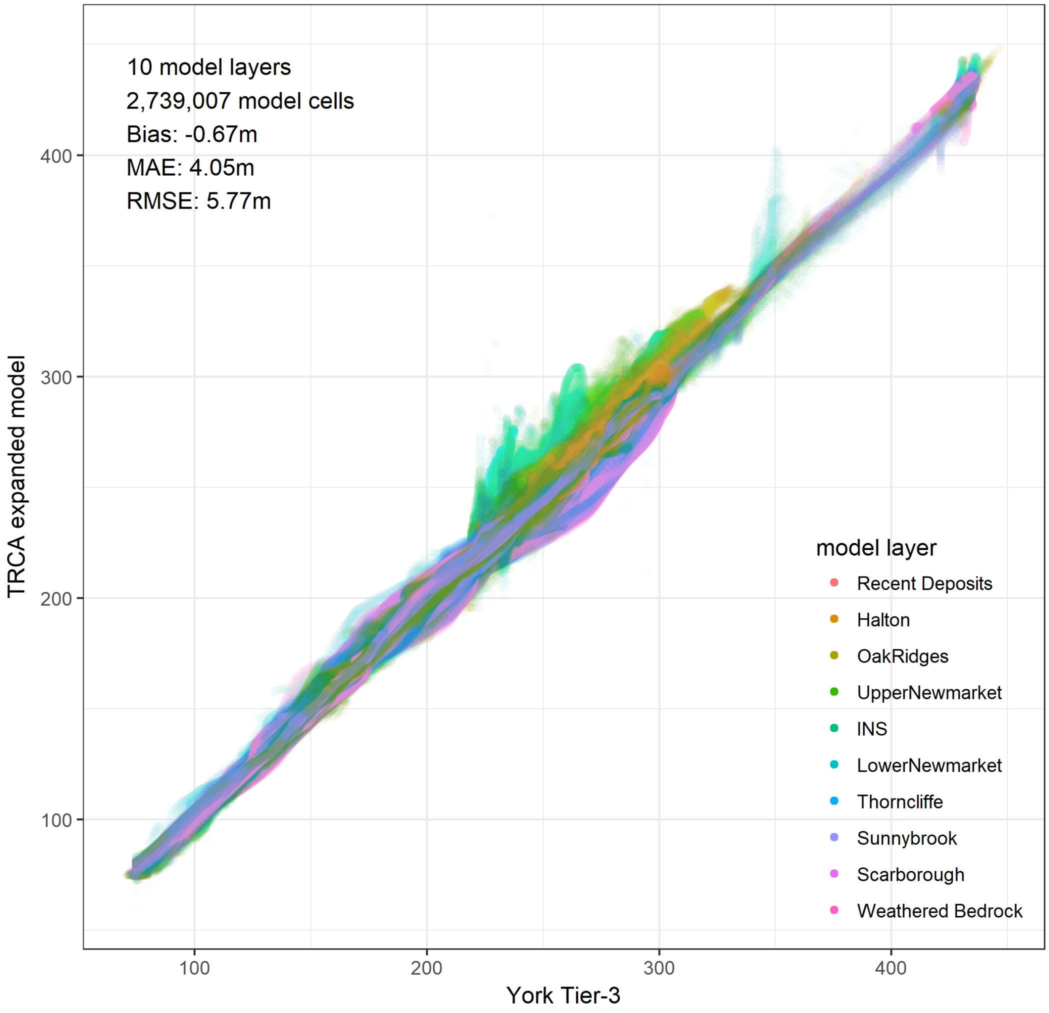


Figure 3: Layer-by-layer scatter comparison of steady-state heads (masl) between TRCA Expanded Groundwater Flow Model and the York Region Tier-3 model.

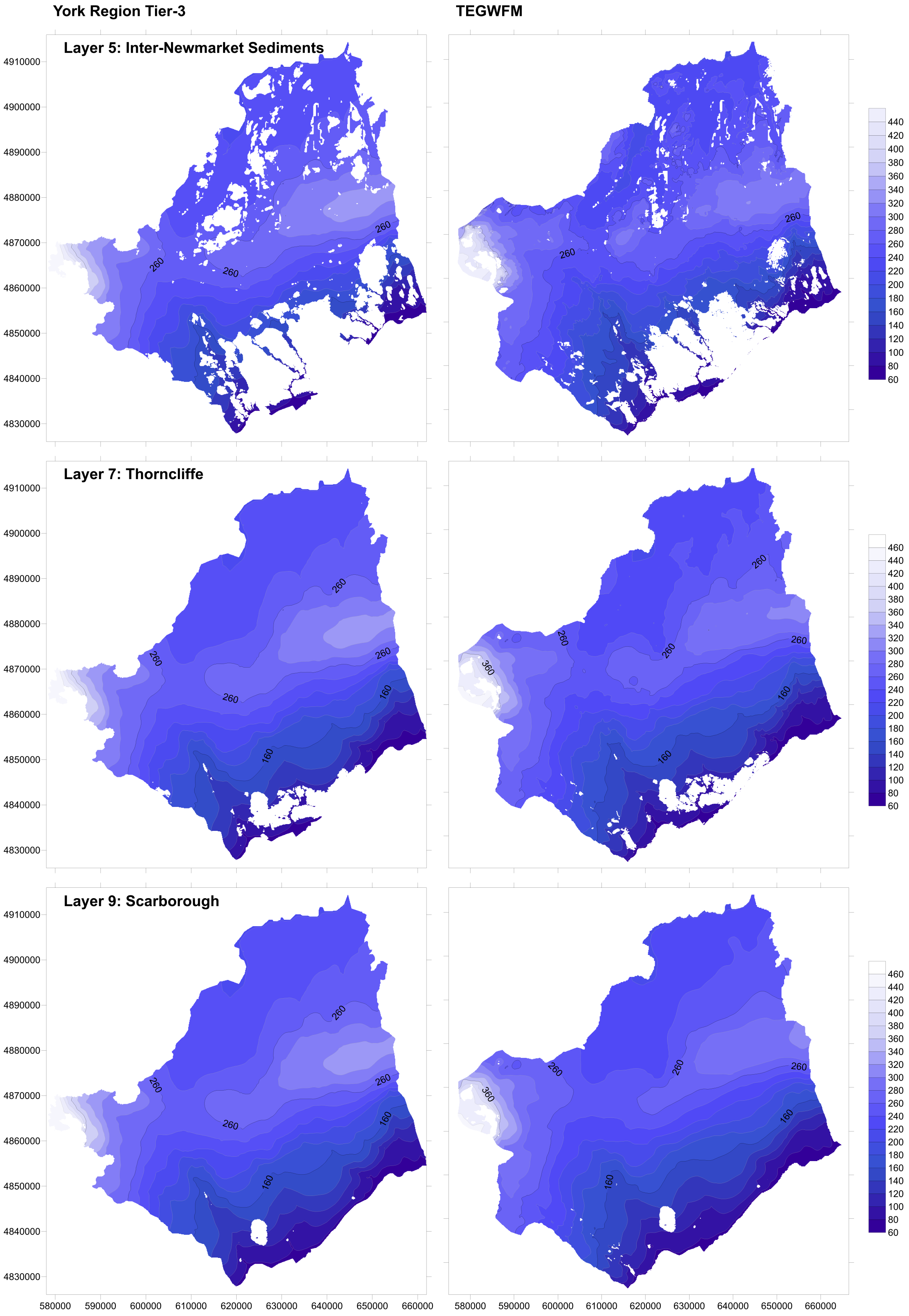
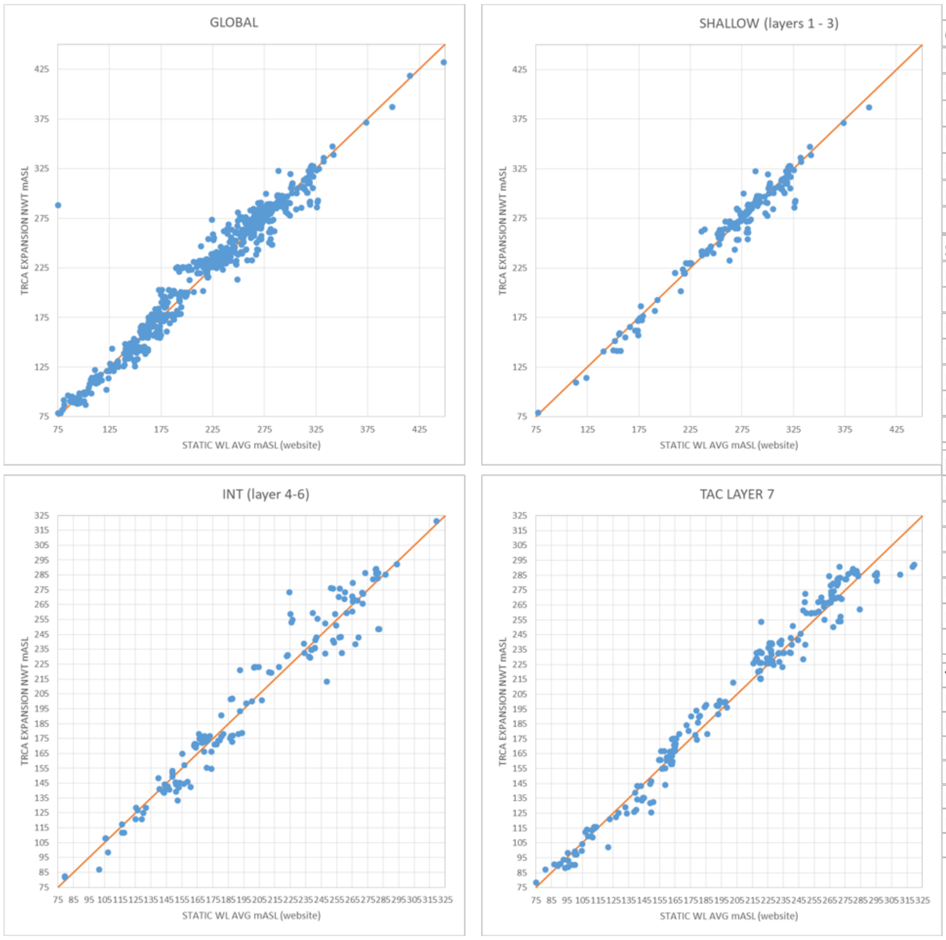
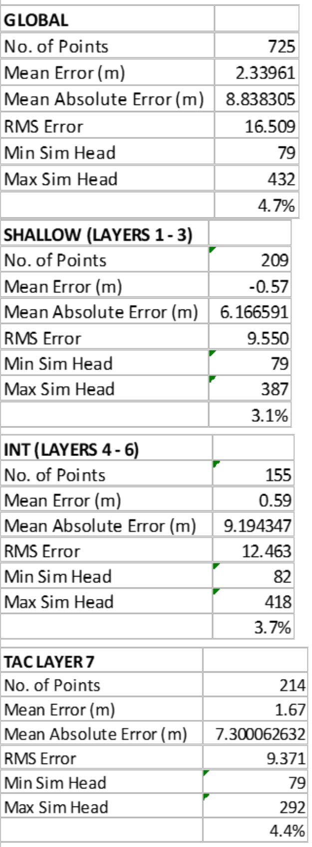


Figure 4: Comparison of aquifer steady-state heads (masl) between TRCA Expanded Groundwater Flow Model and the York Region Tier-3 model.





GLOBAL	
No. of Points	725
Mean Error (m)	2.33961
Mean Absolute Error (m)	8.838305
RMS Error	16.509
Min Sim Head	79
Max Sim Head	432
	4.7%

SHALLOW (LAYERS 1 - 3)	
No. of Points	209
Mean Error (m)	-0.57
Mean Absolute Error (m)	6.166591
RMS Error	9.550
Min Sim Head	79
Max Sim Head	387
	3.1%

INT (LAYERS 4 - 6)	
No. of Points	155
Mean Error (m)	0.59
Mean Absolute Error (m)	9.194347
RMS Error	12.463
Min Sim Head	82
Max Sim Head	418
	3.7%

TAC LAYER 7	
No. of Points	214
Mean Error (m)	1.67
Mean Absolute Error (m)	7.300062632
RMS Error	9.371
Min Sim Head	79
Max Sim Head	292
	4.4%

Figure 5: Scatter-plot comparison of steady-state heads (masl) between TRCA Expanded Groundwater Flow Model and measured observed heads.

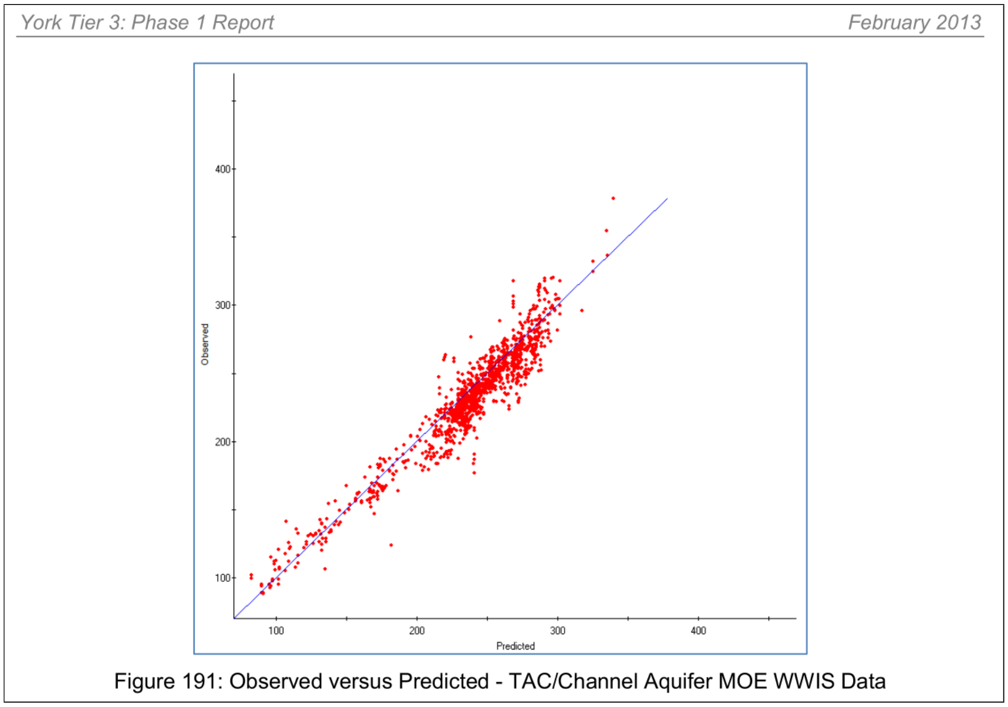


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Figure 191: Observed versus Predicted - TAC/Channel Aquifer MOE WWIS Data

Figure 6: Scatter-plot comparison of steady-state heads (masl) between York Tier-3 model and measured observed heads (from Earthfx Inc., 2013).

Comparison of Results to Baseflow Discharge

A total of 11 Water Survey of Canada (WSC) gauges where selected to compare the performance of the model (Figure 7). These particular gauges were selected based on their period of record and their overall coverage of TRCA's jurisdiction. Streamflow records are first processed by extracting baseflow estimates using automated hydrograph separation techniques. In total, 13 variants of hydrograph separation were used as there is no clear distinction as to which method is most representative of actual baseflow, here deemed as total groundwater discharge to streams. The methods include:

1. The Wallingford (UKIH) method (Institute of Hydrology, 1980)

2–4. Three modified/extended Wallingford methods: sweeping minima, sweeping maxima, sweeping mean (Piggott et. al., 2005)

5. The Clarifica method (Clarifica, 2002)

6–8. The USGS Hydrograph Separation (HYSEP) method, three methods: fixed interval, sliding interval, local minimum (Sloto and Crouse, 1996)

9. The PART method (Rutledge, 1998)

10. The Lyne and Hollick digital filter (Nathan and McMahon, 1990)

11. The Chapman digital filter (Nathan and McMahon, 1991)

12. The Chapman and Maxwell digital filter (Chapman and Maxwell, 1996)

13. The Eckhardt digital filter (Eckhardt, 2005)

The set of hydrograph separation results were then summarized according to their annual maximum and minimum discharge rates, and normalized by contributing area. These bounding values, given in mm/yr, were then compared to the modelled steady-state groundwater discharge to streams occurring within the same contributing areas (Figure 8). Here, it is evident that the model, for the most part, remains bounded by the baseflow estimates, with the exception of Black Creek (WSC gauge 02HC027) and Highland Creek (02HC013), which are both highly urbanized relative to the remaining catchments and thus understandably not well represented in the model. Typically, urbanized catchments exhibit a sustained drainage (from sewers, culverts, etc., exhibiting groundwater inflow and infiltration) that artificially increases effective "baseflow." Without the consideration of urban drainage systems and their interaction with the shallow groundwater system, groundwater models tend to under predict baseflow discharge.

Figure 7: Location of stream-flow gauge contributing areas used in determining baseflow discharge to streams.

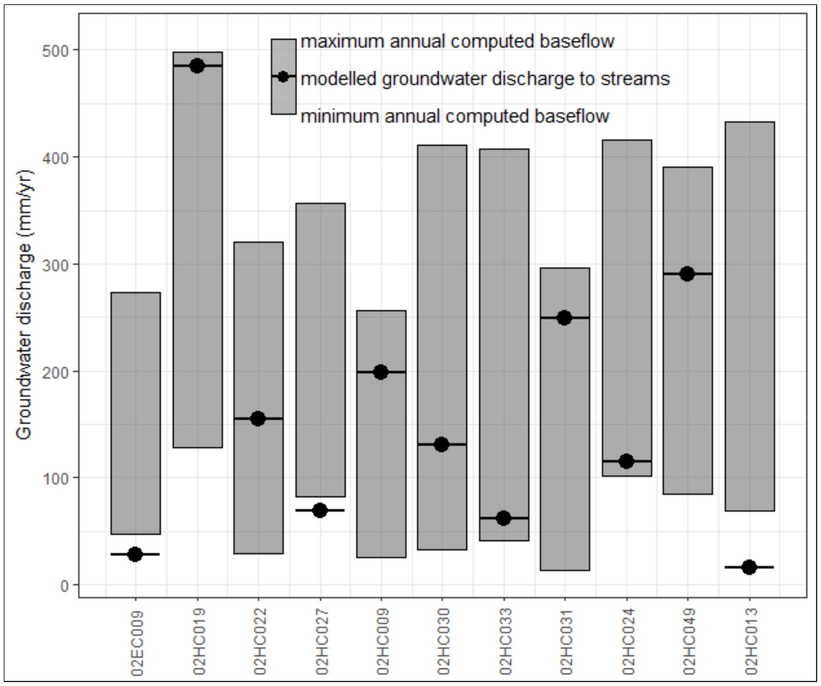

Figure 8: Comparison of modelled groundwater discharge to streams versus estimated annual baseflow range.

Summary

The TRCA Expanded Groundwater Flow Model (TEGWFM) was built to address a variety of modelling requirements needed by the TRCA to fulfil their Municipal Comprehensive Reviews and Watershed plan needs. The model was built upon previous models that, at the time of their development, incorporated significant geological and hydrogeological syntheses. In the absence of other guiding information, it is put forward that the results can be relied upon and used to assist TRCA staff in making informed decisions. That said, the existing models used in constructing the TEGWFM were neither intended for ESGRA and land use analysis requested by the TRCA as they were not built with a specific focus on the Toronto region. For this reason, this TEGWFM should be considered as preliminary in nature and it is recommended that in the future, it should form the basis for a more rigorous model development project for which the ORMGP staff would be available to assist.

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,

Mason Marchildon P.Eng, M.A.Sc
Hydrologist
Oak Ridges Moraine Groundwater Program
mmarchildon@owrc.ca

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MEMORANDUM

Date: Thursday 29th November, 2018

To: Ms. Laura Del Giudice, B.Sc., M.F.C., Senior Manager, Watershed Planning & Reporting
Ms. Namrata Shrestha, Ph.D., Senior Research Scientist, Research & Knowledge Management
Ms. Angela Wallace, M.Sc., Project Manager, Watershed Planning & Reporting
Mr. Neil Taylor, M.Sc., Research Analyst, Research & Knowledge Management
Mr. Jonathan Ruppert, Ph.D., Research Scientist, Research & Knowledge Management
Watershed Strategies, Toronto Region Conservation Authority

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.

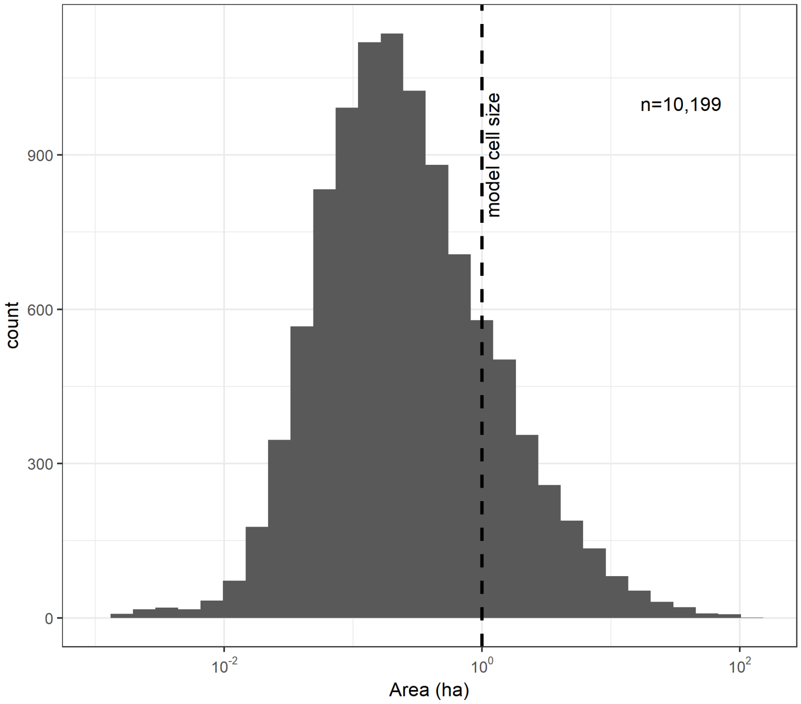

Figure 1: Distribution of areal extent for wetlands used in the model (n=10,199).

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

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

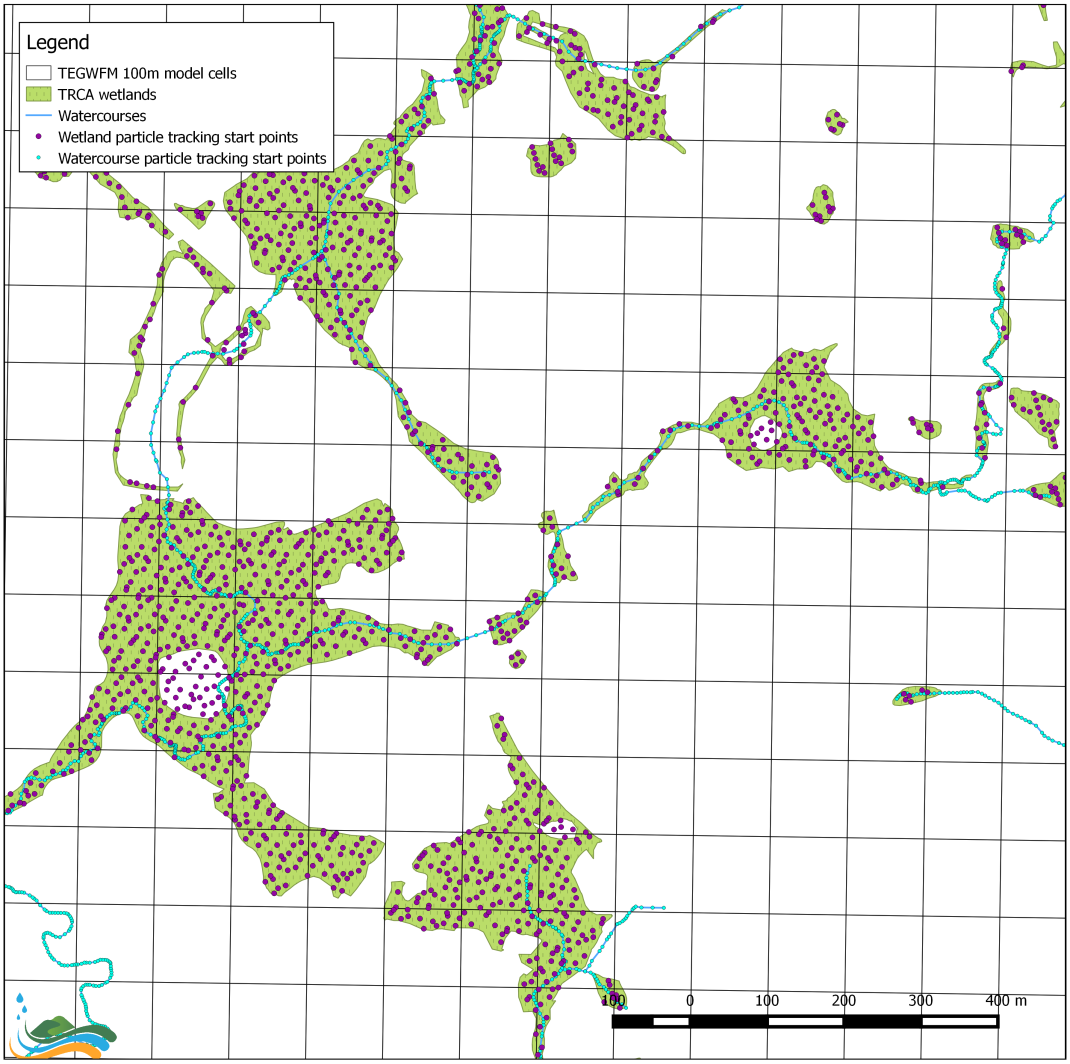

Figure 2: Distribution reverse particle tracking startpoints used in producing ESGRAs.

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

The cluster analysis was then projected onto a $25\,\mathrm{m}\times25\,\mathrm{m}$ 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

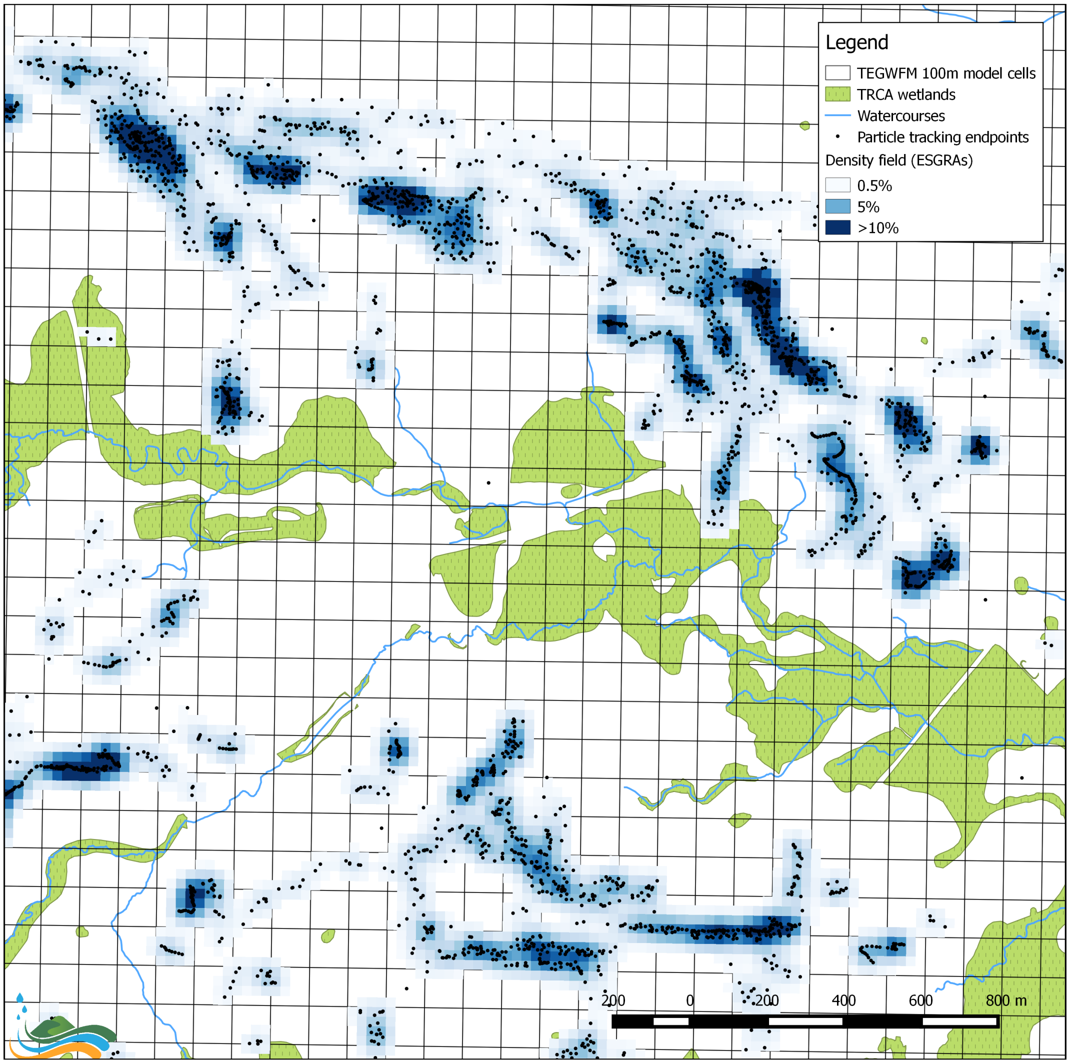

Figure 3: Distribution reverse particle tracking endpoints used in defining ESGRAs for the TRCA.

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

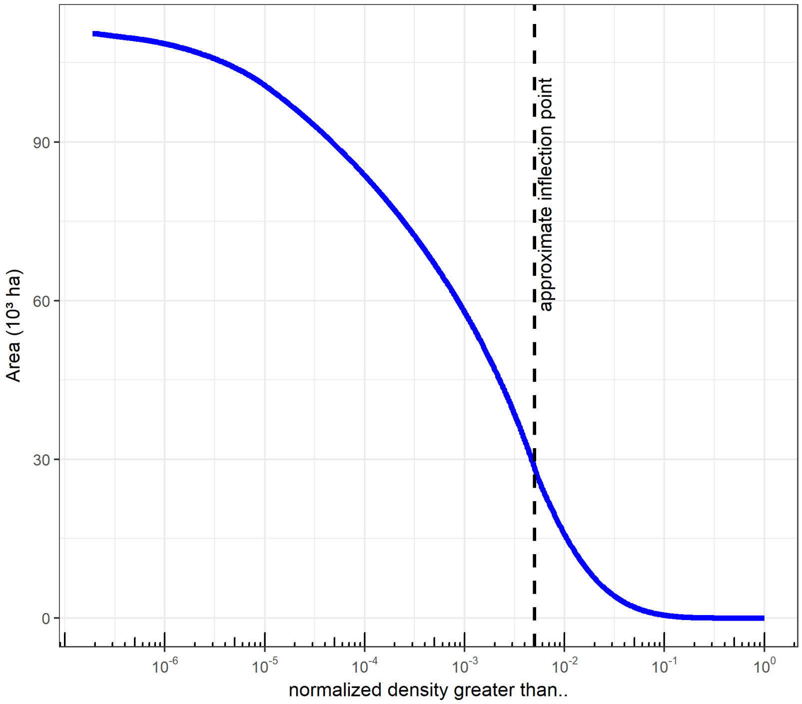

Figure 4: ESGRA cumulative density plot.

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

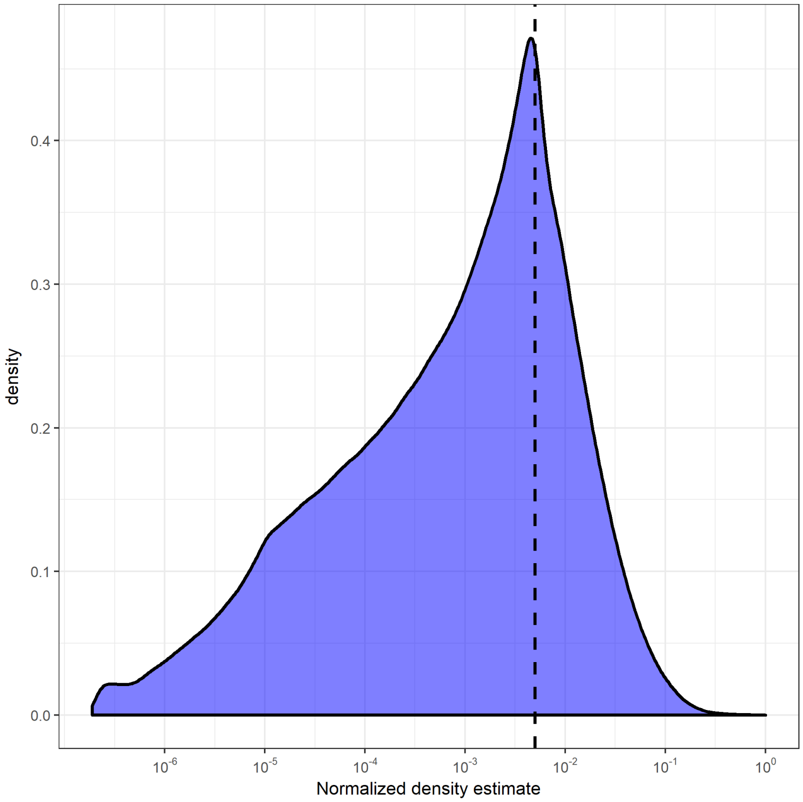

Figure 5: Kernel density distribution. (Hashed line placed at the density of 0.005.)

> 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

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[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.

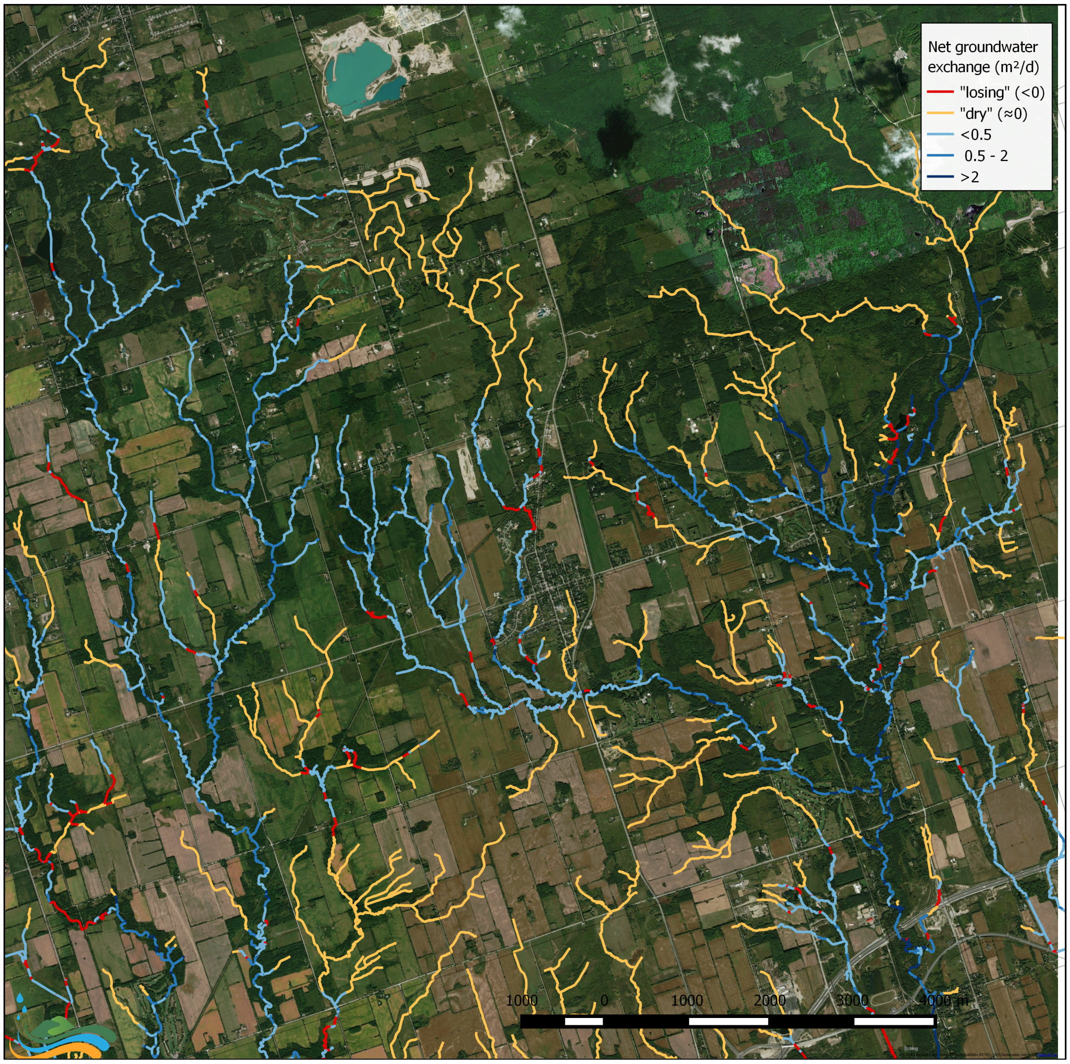

Figure 6: Significant Surface Water Contribution Features. Reaches shaded a darker blue "contribute to baseflow volumes which are significant to the overall surface water flow volumes within a watershed" (OMMAH, 2017)

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

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[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,

Mason Marchildon P.Eng, M.A.Sc
Hydrologist
Oak Ridges Moraine Groundwater Program
mmarchildon@owrc.ca

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.

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[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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