Natural Systems Climate Change Vulnerability Assessment in the Durham Region

Prepared by Toronto and Region Conservation Authority for The Regional Municipality of Durham

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EXECUTIVE SUMMARY

The impacts of climate change on natural systems in the Greater Toronto Area (GTA), including in Durham Region, have been well-documented over the past decade. There are numerous reports of extreme events that have affected terrestrial and aquatic ecosystems along with the well-being of local communities across the GTA. Examples include severe ice storm and flood damages to vegetation in natural areas and urban areas, drought impacts to climate sensitive vegetation and wildlife, water level fluctuations in wetlands, and invasive species infestations.

Recent work conducted as part of the Region of Durham's Community Climate Adaptation Plan (DCCAP) recognized that with future climate projections, these impacts will likely worsen and intensify. Natural Heritage System (NHS) planning as part of the Region's Municipal Comprehensive Review (MCR) provides a strategic, proactive, and timely opportunity to address these impacts by considering the climate change vulnerabilities of natural systems.

Key actions in the DCCAP relating to the natural environment include the need to define a connected natural heritage system across Durham Region that integrates targeted systems and ensures natural adaptation to climate change. The Natural Environment Climate Change Collaborative (NECCC), which oversees implementation of these actions, has identified the MCR process as the logical and most appropriate means to implement them.

To support this, TRCA has applied a rapid assessment framework to complete a Natural System Climate Change Vulnerability Assessment (NS-CCVA) for Durham Region in 2021-2022. This initiative identifies the natural heritage features and areas that may have higher vulnerability to future climate conditions using a set of criteria and methodology based on earlier studies completed by TRCA (TRCA 2017, TRCA 2020). The results of NS-CCVA are expected to inform identification and implementation of Durham Region's Natural Heritage System (NHS) from science, policy, and planning aspects.

The key objectives of the NS-CCVA are to complete (1) a rapid assessment to compare differences in predicted climate futures between Peel and Durham, (2) NS-CCVA for the Durham Region using available data, and (3) an assessment of the alignment of NS-CCVA results with Durham's proposed Official Plan Natural Heritage System (NHS) and Enhancement Opportunity (EO) areas as well as the known future development areas.

Firstly, we conducted a rapid comparison between Peel Region (a previous NS-CCVA) and Durham Region climate projections to identify whether there are similarities and/or discrepancies in future climate scenarios under the RCP 8.5 (high emissions) and RCP 4.5 (moderate emissions) scenarios. While the magnitude of change between RCP 8.5 and RCP 4.5 scenarios differs for climate outcomes, the differences between regions is limited. Thus, we find that the NS-CCVA methods developed and applied in Peel Region are suitable for use in Durham Region and differences do not warrant modifications to the NS-CCVA approach.

Secondly, we undertook the NS-CCVA using the same five vulnerability indicators of natural systems as we had used in previous assessments to identify the areas that are most vulnerable to climate change impacts. These indicators include habitat patch score, sensitive vegetation, wetland vulnerability, soil drainage and ground surface temperature. Each individual indicators and their additive overlay show higher vulnerability in both the southern and northern portions of the region. Overall, we find that most of the higher vulnerability areas align with more urbanized and agricultural landscapes, where the natural cover patches are of lower quality and/or may be exposed to higher heat island effects.

Lastly, we undertook an overlay analysis between the results of the NS-CCVA and Durham's proposed Official Plan NHS and EO areas to identify the extent of protection and enhancements provided to vulnerable areas. While Durham's proposed Official Plan NHS and EO areas include most of the natural features and areas including some highly vulnerable areas, there are still number of features that remain outside these areas. We also completed overlay analysis between the results of the NS-CCVA and potential buildout areas (whitebelt). Generally, we find that the coverage of the NHS and EO areas is consistent within the potential buildout areas.

Altogether, actions that either include natural system features within NHS/EO areas (by expanding the NHS/EO footprint) or lead to the implementation of enhancements in developed areas (e.g., green infrastructure, urban tree canopy) will undoubtedly help to mitigate future climate vulnerability.

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1. INTRODUCTION

The main goal of this project is to equip the Durham Region with the results of a natural system climate change vulnerability assessment that will identify the features and areas in the region that are most vulnerable to climate change impacts. This data and related information will help to inform and support the Municipal Comprehensive Review (MCR) process and strengthen Envision Durham's objectives and policies around Natural Heritage System (NHS) as well as climate adaptation and resilience. Specifically, the main objectives of the work, includes:

1. In partnership with the other Conservation Authorities (CAs), undertake a rapid comparison between Peel climate projections and those recently developed through the Durham Climate Modeling Update Project to ensure no major deviances.
2. Collaborate and coordinate with the Durham Region and partner CAs to acquire and QA/QC natural feature data and information for analysis.
3. Undertake the rapid, broad scale assessment using the TRCA Natural System Climate Change Vulnerability Assessment (NS-CCVA) framework (TRCA 2019) in partnership with the other CAs and apply this approach to the entirety of the Durham Region, with any modifications as needed (see below for further details).
4. Provide a summary report and climate vulnerability mapping for Durham Region to inform the MCR process and the OCC-Durham-GLISA project (to support the training workshop module for natural systems).

Completing the proposed objectives will directly support Durham Region's Official Plan Environment Goal 2.1.1 *to ensure the preservation, conservation, and enhancement of the Region's natural environment for its valuable ecological functions and for the enjoyment of the Region's residents.* Further, the Provincial Policy Statement (2020) requires that an NHS be protected for the long-term, which includes ensuring that NHSs are resilient to the effects of a future climate. The results of this study will help to inform NHS development by providing a climate lens as discussed previously.

The proposed project will also support implementation of the Durham Region's Community Climate Adaptation Plan (DCCAP), including its natural environment sector objectives and programs *to enhance natural capital and build climate resilience in the natural environment (NE1)*. The results of the proposed project will provide spatially explicit information on strategic areas to invest in and plan for management and adaptation actions to increase the resilience of natural systems.

In addition, the proposed project will provide additional benefits to Durham Region by:

a) Collecting and conducting QA/QC on ecological data to ensure that data are in the standard digital format, which can be easily transferable to Durham Region environmental databases;
b) Building and sharing the knowledge base and data to develop long-term capacity to incorporate a climate lens in NHS planning and implementation;

c) Increasing efficiencies (time and budget) by conducting and streamlining analysis that will serve multiple initiatives, including the MCR process, OCC-Durham-GLISA project, development and infrastructure planning processes, and various restoration and adaptation initiatives;
d) Providing regular access to a high level of expertise in natural system and climate impacts;
e) Building a network of long-term partnerships with Durham Region, the research community, and Conservation Authorities that will continue to promote Durham Region as a leader in integrating climate information into natural systems planning and design.

To conduct this work, TRCA has applied a rapid, high-level assessment framework to complete the Natural System Climate Change Vulnerability Assessment (NS-CCVA) for Durham Region in 2021-2022. This initiative identifies the natural heritage features and areas (or Terrestrial Natural Features) that may have higher vulnerability to future climate conditions using a set of criteria and methodology based on earlier studies completed by TRCA (TRCA 2017, TRCA 2020). The results of NS-CCVA are expected to help inform identification and implementation of Durham Region's Natural Heritage System (NHS) from science, policy, and planning aspects. The key objectives of this NS-CCVA study are to:

1. Complete a rapid assessment to compare differences in predicted climate futures between Peel and Durham,
2. Undertake a rapid, broad scale NS-CCVA for the Durham Region using available data, and
3. Complete an overlay analysis between NS-CCVA results with Durham's proposed Official Plan Natural Heritage System (NHS) and Enhancement Opportunity (EO) areas as well as the potential future development areas (whitebelt areas).

Altogether, the results will equip the Durham Region with science-based information to support the implementation of the NS-CCVA through planning processes and lend strong support for the development of policies to guide future work and planning in this area.

2. CLIMATE PROJECTIONS

Climate change is currently impacting natural systems in the Durham Region and future projected climate change will intensify these impacts. Notably, climate change projections predict an increased frequency and magnitude of precipitation events as well as temperature extremes in the Great Lakes region (Magnuson et al. 1997). Improving natural systems planning requires the consideration of factors that influence the function and resilience of natural systems. A better understanding of climate change resiliency is related to the hydrological links between terrestrial and aquatic systems, the vulnerability of natural system components to climate change, and the contribution of the urban forest and other components of the urban matrix to the natural system.

Here, we provide a rapid analysis to compare the climate projections developed for the Region of Peel in 2016 (Auld et al. 2016) and those recently developed for the Durham Region in 2020 (Ontario Climate Consortium 2021) by TRCA and partners. This comparison is part of the project scope of the Durham Region Natural System Climate Change Vulnerability Assessment (NS-CCVA) and serves to identify any major deviances. Such deviances would suggest that the responses of natural systems and their vulnerability to climate change in Peel and Durham would differ, which would in turn suggest that methods may need to account for these deviances.

2.1. Climate Projection Comparison Methods

This comparison focused on a subset of climate variables under the RCP 8.5 (high emissions) and RCP 4.5 (moderate emissions) scenario, which is most relevant to the NS-CCVA. This includes key climate variables important to natural systems, such as:

- Annual mean temperature
- Annual mean maximum temperature
- Annual mean minimum temperature
- Total annual precipitation
- Number of days above 30˚C
- Number of days below -15˚C
- Maximum 1-day total precipitation

In this report, climate projections were compared across the short-, medium-, and long-term timelines. In both the projections, the same future periods (2020s, 2050s, and 2080s) were used, however, the historical projections were different between Peel and Durham (Table 1). For the comparison, absolute values were used rather than differences against the historical period between two regions. It is also notable that different methods were used to develop the climate projections for Peel and Durham, so there may be other factors that contribute to the deviances between the projections, not just geographical differences. Recognizing this limitation, we utilized data for the high emission scenario (RCP 8.5) from climatedata.ca, which was downloaded and analyzed for Peel and Durham as a cross-reference, using the same historical period (1971-2000) for consistency with the Durham projections. Data from climatedata.ca are available in the following formats: median, 10th percentile (low range), and 90th percentile (high range). To estimate the ensemble, mean, we used the average between the low and high-range values, and then averaged across each future period.

Table 1. Differences between approaches applied to the Peel and Durham climate projections developed by TRCA and partners.

	Peel	Durham
Historical Period	1981-2010	1971-2000
Future Periods	2020s (2011-2040) 2050s (2041-2070) 2080s (2071-2100)	2020s (2011-2040) 2050s (2041-2070) 2080s (2071-2100)
Historical Data	Environment Canada and Climate Change (ECCC) station and gridded time series data from the CANGRD product developed by McKenney et al. (2011)	ECCC's climate normal website
Climate Stations	1. Toronto Lester B Pearson Int'l A 2. Orangeville MOEs	1. Bowmanville Mostert 2. Burketon McLaughlin 3. Oshawa WPCP 4. Tyrone 5. Cobourg STP 6. Richmond Hill 7. Frenchman's Bay
General Circulation Models (GCMs) or Regional Climate Models (RCMs)?	Ensemble of GCMs; for certain variables, higher resolution climate modeling output was available from the most recent Canadian regional climate model (CanRCM4)	Ensemble of RCMs
Number of Climate Models	41	7
Downscaling and Bias Correction Method	No-bias correction (Statistical Downscaling)	Delta bias correction method (Dynamic Downscaling)
Output Scale	10km by 10km	25km by 25 km
Consideration for the influence of the Great Lakes	Not all GCMs incorporate or simulate influence of the Great Lakes	Part of the model selection criteria so all models include some representation of the Great Lakes

2.2. Climate Projection Comparison Findings

Overall, the same climate trends are projected for Peel and Durham for RCP 8.5 based on the climate projections developed by TRCA and partners (see last column of Table 2). Warmer temperatures, more precipitation, and more extreme heat days are anticipated in both regions. As temperature rises, the number of extreme cold days (i.e., days below -15˚C) are also anticipated to decrease in the future. The similar trends were found in our analysis of the data from climatedata.ca (see last column of Table 3).

Our comparison also found that the projected values for most of the climate variables analyzed are similar between Peel and Durham, including annual mean temperature; maximum temperature; minimum temperature; days below -15˚C, and maximum 1-day total precipitation (Table 2). Differences were noted for annual total precipitation and days above 30˚C, especially by the end of the century. Based on the climate projections developed by TRCA and partners, Durham is anticipated to see more annual total precipitation compared to Peel, while Peel is anticipated to see more extreme heat days by the end of the century.

This pattern is corroborated by the projections from climatedata.ca, although this projection suggests there is a smaller difference in annual total precipitation between the regions. Meanwhile, data from climatedata.ca also suggests that the number of extreme heat days could be higher for both regions by the end of the century, compared to the projections developed by TRCA and partners. Additionally, data from climatedata.ca also indicates that more extreme precipitation (i.e., maximum 1-day total precipitation) can be expected for Peel compared to Durham under the high emission scenario (Table 3).

Table 2. Summary of the projected ensemble mean values and overall trends for Peel and Durham under RCP 8.5 emission scenario based on the projections developed by TRCA and partners.

Climate Parameter	Historical 1981-2010 and 1971-2000		Short-Term 2011-2040		Medium-Term 2041-2070		Long-Term 2071-2100		Trend
	Peel	Durham	Peel	Durham	Peel	Durham	Peel	Durham	
Annual mean temperature (˚C)	7.4	7.1	8.8	8.6	9.4	10.1	12.3	12.1	↑
Maximum temperature (˚C)	12.3	11.6	13.7	12.9	14.2	14.5	17.1	16.4	↑
Minimum temperature (˚C)	2.5	2.5	4.0	4.1	4.5	5.7	7.6	7.9	↑
Annual total precipitation (mm)	851	952	885	1075	928	1118	953	1232	↑
Days above 30˚C (days)	12	8	17	16	26	27	62	47	↑
Days below -15˚C (days)	19	23	14	13	8	8	4	3	↓
Max 1-day total precipitation (mm)	37	34	39	35	40	40	45	44	↑

Table 3. Summary of the averages of the projected ensemble low- and high-range values and overall trends for Peel and Durham under RCP 8.5 emission scenario based on climatedata.ca.

Climate Parameter	Historical 1971-2000		Short-Term 2011-2040		Medium-Term 2041-2070		Long-Term 2071-2100		Trend
	Peel	Durham	Peel	Durham	Peel	Durham	Peel	Durham	
Annual mean temperature (˚C)	7.0	6.8	8.8	8.6	10.8	10.6	13.0	12.8	↑
Maximum temperature (˚C)	12.0	11.6	13.8	13.4	15.7	15.4	17.9	17.6	↑
Minimum temperature (˚C)	2.1	2.0	3.8	3.7	5.8	5.7	8.0	8.0	↑
Annual total precipitation (mm)	842	864	861	874	898	913	928	940	↑
Days above 30˚C (days)	9	5	26	19	46	39	72	67	↑
Days below -15˚C (days)	23	27	14	17	6	8	3	3	↓
Max 1-day total precipitation (mm)	39	38	48	44	50	45	54	47	↑

Table 4. Summary of the projected ensemble mean values and overall trends for Peel and Durham under RCP 4.5 emission scenario based on the projections developed by TRCA and partners.

Climate Parameter	Historical 1981-2010 and 1971-2000		Short-Term 2011-2040		Medium-Term 2041-2070		Long-Term 2071-2100		Trend
	Peel	Durham	Peel	Durham	Peel	Durham	Peel	Durham	
Annual mean temperature (˚C)	7.4	7.1	8.7	9.7	9.1	10.9	10.2	11.3	↑
Maximum temperature (˚C)	12.3	11.6	13.6	14.3	14.0	15.5	15.1	15.9	↑
Minimum temperature (˚C)	2.5	2.5	3.8	5.1	4.3	6.4	5.4	6.8	↑
Annual total precipitation (mm)	851	952	894	943	919	960	928	1009	↑
Days above 30˚C (days)	12	7.6	15	25.3	23	35.1	35	42.7	↑
Days below -15˚C (days)	19	22.7	14	6.9	10	2.6	9	3.2	↓
Max 1-day total precipitation (mm)	37	34	40	35	41	61	41	38	↑

2.2.1. Temperature and Precipitation

Based on the climate projections developed by TRCA and partners, the annual mean temperature is expected to rise by approximately 5˚C in Peel and Durham by the end of the century in the RCP 8.5 emission scenario, compared to their respective historical periods (i.e., 1981-2010 and 1971-2000) (Figures 1, 2). There is a slight difference between the projections for the medium-term, with a more moderate increase anticipated for Peel between the short and medium-term, along with a steeper increase anticipated between the medium and long-term (Figure 2). Meanwhile, data from climatedata.ca suggests that annual mean temperature could rise by approximately 6˚C in Peel and Durham by the end of the century (Table 3) in the high emission scenario (RCP 8.5). However, under the moderate emission scenario (RCP 4.5), Durham is likely to see a higher mean annual temperature than Peel by 2100. With that, the mean annual temperature is expected to rise by approximately 4˚C in the Durham region and 2.8˚C in the Peel region by the end of the century, compared to their respective historical periods (Figures 1, 2) as projected by the TRCA and partners.

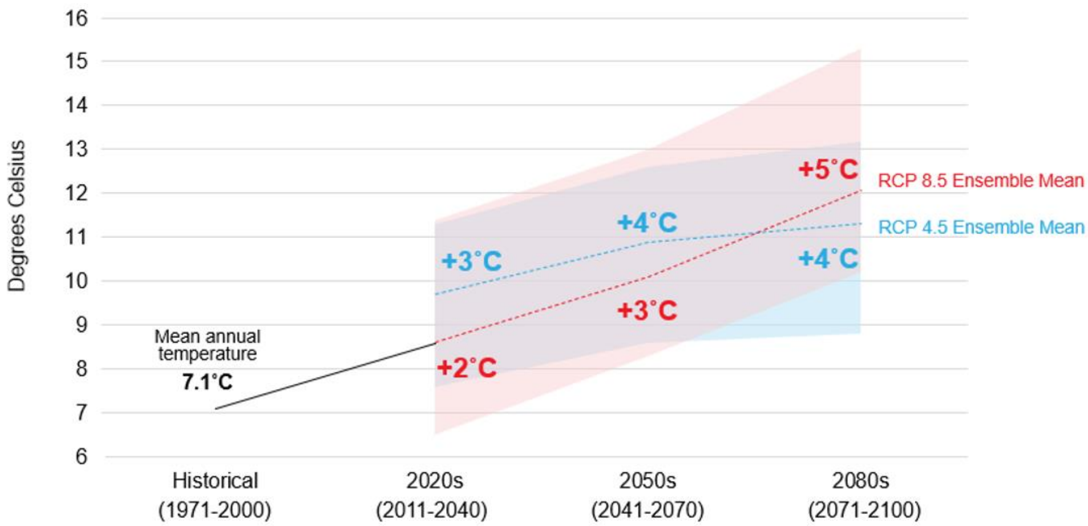

Figure 1. Historical (observed mean) and projected annual mean temperature for Durham based on climate projections developed by TRCA and partners. Shaded areas demonstrate the 10th and 90th percentiles, the red dotted line represents the ensemble mean of 16 model runs under RCP 8.5 and the blue dotted line represents the ensemble mean of 3 model runs under RCP 4.5 emission scenario.

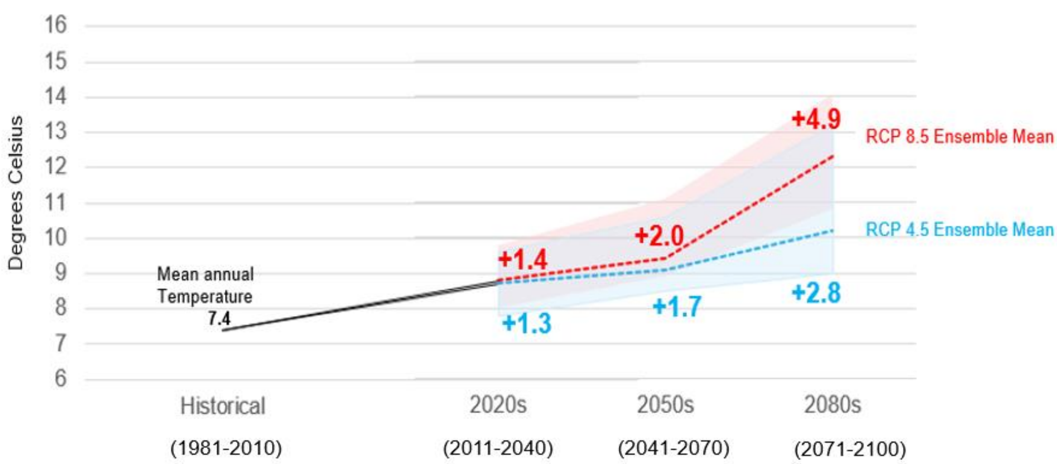

Figure 2. The observed mean and projected annual mean temperature for Peel based on climate projections developed by TRCA and partners. Shaded areas demonstrate the 10th and 90th percentiles, the red dotted line represents the ensemble mean of 16 model runs under RCP 8.5 and the blue dotted line represents the ensemble mean of 3 model runs under RCP 4.5 emission scenario.

As noted earlier, more annual total precipitation is anticipated in Durham compared to Peel based on the climate projections developed by TRCA and partners (Figures 3, 4). Based on TRCA's climate projections, annual total precipitation is expected to increase by 29% in Durham compared to 1971-2000 (Figure 3) in the RCP 8.5

emission scenario, while an increase by 12% is expected for Peel compared to 1981-2010 (Figure 4). Meanwhile, annual total precipitation data from climatedata.ca suggests a similar trend where Durham can expect to see more precipitation than Peel across all climate periods. However, with the percent change from historical time (1981-2010) to the long-term (2071-2100), Peel is anticipated to see a higher increase (10%) than Durham (9%) in climatedata.ca projections. A similar trend was found for annual precipitation change in the RCP 4.5 emission scenario, developed by TRCA and partners, where a percent increase in annual total precipitation is likely to increase more in Peel than in Durham by 2100. Under the moderate emission scenario (RCP 4.5), annual total precipitation is expected to rise by 6% in the Durham region and 9% in the Peel region by the end of the century, compared to their respective historical periods (Figure 3, 4).

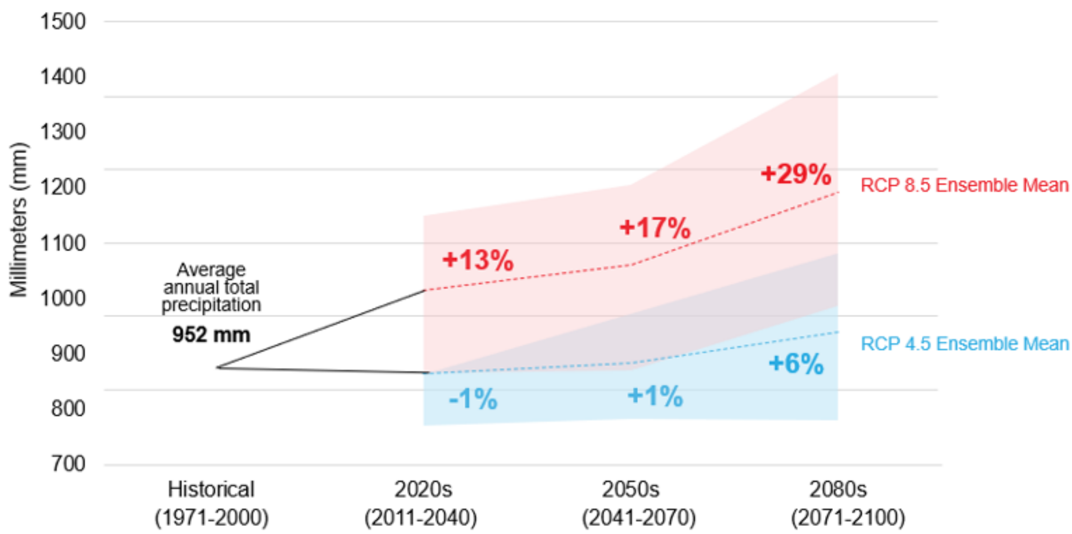

Figure 3. Historical (observed mean) and projected annual total precipitation for Durham based on climate projections developed by TRCA and partners. Shaded areas demonstrate the 10th and 90th percentiles, the red dotted line represents the ensemble mean of 16 model runs under RCP 8.5 and the blue dotted line represents the ensemble mean of 3 model runs under RCP 4.5 emission scenario.

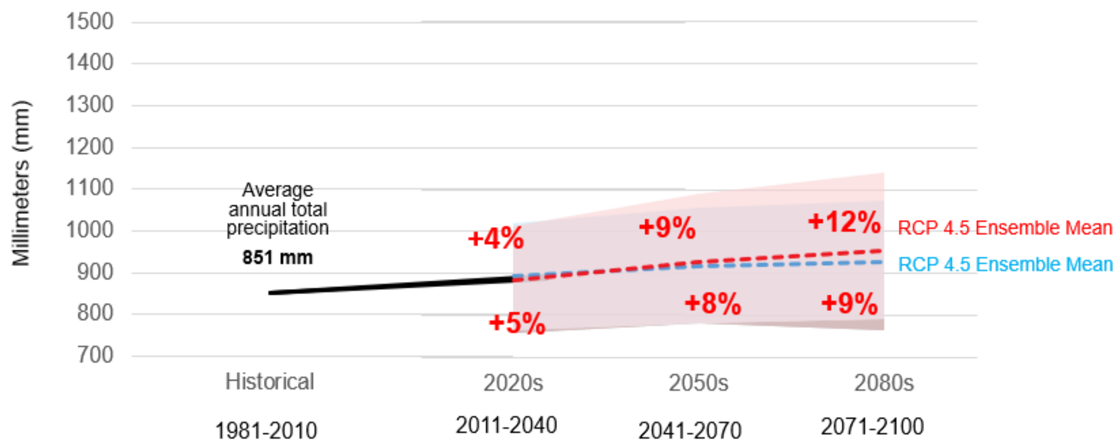

Figure 4. Historical (observed mean) and projected annual total precipitation for Peel based on climate projections developed by TRCA and partners. Shaded areas demonstrate the 10th and 90th percentiles, the red dotted line represents the ensemble mean of 16 model runs under RCP 8.5 and the blue dotted line represents the ensemble mean of 3 model runs under RCP 4.5 emission scenario.

2.2.2. Extreme Heat, Cold, and Precipitation

The number of days with temperatures above 30˚C is anticipated to increase dramatically in Peel and Durham under the high emission scenario (RCP 8.5) based on the climate projections developed by TRCA and partners (see Table 2). In Durham, the number of extreme heat days is expected to see a six-fold increase compared to 1971-2000, rising to 47 days in a year by the end of the century. Meanwhile, in Peel, an eight-fold increase is anticipated compared to 1981-2010, with the number of extreme heat days rising to 62 days in a year by the end of the century. As noted previously, data from climatedata.ca suggests that the number of extreme heat days could rise even more in both regions in the RCP 8.5 emission scenario, to 67 days in Durham and 72 days in Peel by the end of the century compared to their respective historical period (see Table 3). A similar trend was found for the trend in extreme heat days for both Durham and Peel under the moderate emission scenario (RCP 4.5) as projected by the TRCA and partners see Table 4).

As temperature increases, the number of days with temperatures below -15˚C is expected to decline in both regions. In Durham, the number of extreme cold days is expected to reduce by 13% compared to 1971-2000, representing a reduction by nearly 3 weeks' time in a year by the end of the century. Meanwhile, in Peel, the number of extreme cold days is expected to reduce by 21% compared to 1981-2010, representing a reduction by nearly 2 weeks' time in a year by the end of the century. A similar trend was found in our analysis of the data from climatedata.ca. Under the moderate emission scenario, change in extreme cold days will follow the same trend as projected by the TRCA and partners (see Table 4).

Extreme precipitation, as measured by a maximum of 1-day total precipitation, is expected to increase in both regions under the high emission scenario (RCP 8.5). In Durham, a maximum of 1-day total precipitation is expected to increase by nearly 30% compared to 1971-2000, rising to 44mm by the end of the century in the RCP 8.5 emission scenario (Table 2). Meanwhile, in Peel, an increase by 22% is anticipated compared to 1981-2010, rising to 45mm by the end of the century. Data from climatedata.ca suggests that an increase by 24% is expected for Durham and 38% is expected for Peel compared to 1971-2000, with maximum 1-day total precipitation rising to 47 and 54mm, respectively. This suggests that Peel is expected to receive more maximum 1-day total precipitation compared to Durham, but the projections by TRCA and climatedata.ca differ by how much precipitation can be expected. Under the RCP 4.5 emission scenario, both regions are expected to see a slight increase in maximum 1-day precipitation (roughly 4 mm for each region) by the end of the century compared to their respective historical period as projected by the TRCA and partners (Table 4).

This analysis demonstrates that the climate trends anticipated for Peel and Durham are similar under both high and moderate emission scenarios. Since the RCP 4.5 climate change scenario is used less frequently by planners and practitioners than the RCP 8.5 scenario (a more likely scenario), there is much less data available for the RCP 4.5 scenario. This study compared data from 3 model runs for the RCP 4.5 scenario and 16 model runs for the RCP 8.5 scenario and therefore the results associated with the RCP 4.5 scenario should be used with cautions. The projected values are similar between the two regions for most of the climate variables that were analyzed. Differences were found for some variables in terms of the rate and magnitude of change between the two regions, including annual total precipitation and the number of extreme heat days. Some differences between the projections developed by TRCA and those available from climatedata.ca were also found, illustrating the uncertainties with future climate projections, and these uncertainties increase as we project further into the future.

Overall, given the results of this rapid comparative analysis, the methods developed and applied in Peel Region are suitable for use in Durham Region, and that the differences identified do not warrant significant modifications to the NS-CCVA approach.

3. METHODS

Based on previous versions of NS-CCVA from Peel (Tu *et al.* 2017) and TRCA (TRCA 2020), we use this blueprint for the data, methods, and analysis for the calculation of vulnerability indicators and the overlay analysis. In line with previous work, we calculated five vulnerability indicators for the climate change vulnerability assessment:

A. Habitat patch score
B. Sensitive vegetation
C. Wetland vulnerability
D. Soil drainage
E. Ground surface temperature

Each indicator was scored with low, medium, or high vulnerability with corresponding scores of zero, one, or two, respectively. Indicators were summarized as 100 m x 100 m raster cells based on the majority value of the indicator in a cell. Below we provide a summary of methods and analysis for each indicator, please refer to Tu *et al.* (2017) and TRCA 2020 for further details.

3.1. Vulnerability Indicators

3.1.1. Habitat patch score

Habitat patch score is a strong indicator of ecosystem vulnerability because of its relationship with other vulnerability factors. For example, the degree of connectivity of a habitat patch with the surrounding natural system is a strong predictor of the ability of native species to find suitable habitat for the completion of lifecycle requirements. Habitat patch score is also likely to be positively correlated with the regulation of erosion, water quality, and other elements of the hydrological cycle (e.g., gradual reduction of excess runoff and high evapotranspiration), as well as moderating air temperatures. Habitat patch score represents the quality of habitat patch based on its size, shape, and influence of the surrounding matrix using the TRCA Landscape Analysis Model (See TRCA (2007; Appendix E), for further detail on the Landscape Analysis Model). Here the Landscape Analysis Model (LAM) assesses each discrete habitat patch and scores three landscape ecology measures (size, shape, and matrix influence) for each patch to assign a vulnerability rank. The reason for using these measures is that they are widely utilized in the field of landscape ecology for the assessment of fragmented landscapes (Fahrig et al. 2022). Briefly the LAM assesses three criteria, the amount of area (size), the edge-to-area ratio (shape), and landscape condition within 2km, which are aggregated to produce ranks from L1 to L5 for each patch, where L1 is the highest quality (TRCA 2007). Habitat patch types were classified as beach/bluff, forest, meadow, and wetland. These scores were aggregated into vulnerability scores (Table 5).

3.1.2. Climate sensitive vegetation

As certain species will be more impacted by increasing seasonal temperatures and increasing variability in precipitation than others, a list of all terrestrial ecosystems in the Durham Region were categorized by broad Ecological Land Classification (ELC) communities. Specific climate sensitive vegetation patches were derived from ELC using the following broad community types: FOC (coniferous forest), FOM (mixed forest), CUP (plantations), SWC (coniferous swamp), SWD (deciduous swamp; TRCA 2021). Each of these vegetation community types represent a broad association to increased vulnerability to wind or ice damage, drought, or further vulnerability due to diseases that are exacerbated by climate change (Sauer 1998, Saad *et al.* 2017, Aubin *et al.* 2018, Wyka *et al.* 2018). Here, we applied the LAM analysis to each of the ELC patches designated as a sensitive type (FOC, FOM, CUP, SWC and SWD) and applied the same criteria as the habitat patch indicator to each of these ELC patches (see above). These scores were aggregated into vulnerability scores (Table 5 for details).

3.1.3. Wetland vulnerability

To distinguish wetland vulnerability, we first used natural cover classified from ELC data as a wetland community (bog, fen, marsh, swamp). Further data to identify areas where there was a high potential for groundwater discharge based on the depth-to-water-table data layer from the Oak Ridges Moraine Groundwater Program. Wetlands within 30 m of a permanent watercourse were less vulnerable regardless of community type. Overall, wetlands without potential groundwater discharge or more than 30 m from a permanent watercourse were considered highly vulnerable due to only being precipitation-fed (Table 5).

3.1.4. Soil drainage

The surficial soils within the natural system also interact with the biotic elements of the system to produce vulnerability to climate change. The approach applied here assumes that tight soils with poor drainage will produce shallower root networks and increased potential for localized inundation, contributing to higher relative vulnerability given that future climate will have precipitation events that are more extreme and episodic in nature. However, it is noted that the interaction between soil drainage properties and changes in different climatic variables is very complex, and in certain respects soils with higher drainage ratings will be more vulnerable (e.g., to erosion resulting from extreme precipitation events). Further, it is possible that under future climate, higher vulnerabilities in soil drainage may lead to the conversion of natural features that may be perceived as positive (e.g., from forest to wetland), however, it does make the current natural system vulnerable, which is what we are assessing in this study.

To assess soil drainage, we use the OMAFRA dataset to classify this vulnerability indicator which classifies soils by drainage rating, considering both texture and slope, into six classes ranging from well drained to very poorly drained, as well as categories for urban land covers and open water. These drainage categories were classified into vulnerability scores (Table 5). While the OMAFRA layer was derived from soil surveys conducted in the 1950s and 1960s, it is important to incorporate this layer as it complements the more urban based climate vulnerabilities. The age of the data will introduce some uncertainty with respect to resolution, land cover and land use changes, but it remains the most comprehensive soils data layer available for the region.

3.1.5. Ground surface temperature

The ground surface temperature measured by satellite remote sensing in mid-afternoon close to the summer solstice is a good proxy for the distribution of potential heat and drought stress throughout the natural system during summer and early fall. As this data is remotely sensed, it will account for the observed variability in ground temperature throughout Durham Region, including accounting for any influence of large lake systems. Higher air temperatures, for which ground surface temperature is a proxy, could lead to enhanced drying of soil and forest understories, plant heat stress, reduction in natural system thermal regulation, and loss of thermal refuges for heat-intolerant species. This in turn could lead to degradation or loss of local flora and fauna communities and reduced capacity of natural cover to provide localized cooling.

No specific numerical vulnerability thresholds emerged from the literature review for Peel, and any thresholds would inevitably also be dependent upon the presence of other vulnerability factors. Therefore, to determine vulnerability class thresholds, the data covering the area of the TRCA watershed jurisdiction was divided into three classes of equal abundance. This translated into a low vulnerability class consisting of cells reporting less than 20.3˚C, a high vulnerability class of cells greater than 25.6˚C, and medium vulnerability class cells falling between these two thresholds (Table 5).

3.2. Additive Vulnerability Indicator

The additive vulnerability layer was based on the sum of the maximum possible score within each cell and the number of layers with data available for that cell (Table 5). For example, a cell with all the five vulnerability indicators would have a maximum possible score of 10 (with a maximum possible score of 2 in each individual layer). By contrast, a cell with only two vulnerability indicators (e.g., only soil drainage and ground surface temperature) would have a maximum score of 4. Thus, in areas where there is natural cover is present (e.g., natural cover type or ELC) the maximum potential score will be higher, whereas outside of natural cover, only soil drainage and ground surface temperature are available and will have a lower maximum potential score. To reconcile this difference, we used the maximum potential score for each cell (100m x 100m resolution) and rescaled the final value, so it ranged from 0 (no vulnerability) to 1 (high vulnerability) for the entire jurisdiction.

Table 5. Summary of climate change vulnerability indicators for their methodology and interpretation.

Indicator	Methodology	Interpretation
Habitat patch	Habitat patch score represents the quality of habitat patch based on its size, shape, and influence of the surrounding matrix using the TRCA Landscape Analysis Model (TRCA 2007). TRCA's LAM analysis ranks patches from L1 to L5, where L1 is the highest quality (TRCA 2007). The lower quality habitat patches (L4, L5) have smaller sizes, linear shape with high edge effects, and are situated in areas with higher levels of urbanization. These lower quality patches are expected to be stressed and thus more vulnerable to climate change impacts.	Score 0: Low vulnerability (L1, L2) Score 1: Moderate vulnerability (L3) Score 2: High vulnerability (L4, L5)

Indicator	Methodology	Interpretation
Sensitive vegetation	The climate sensitive vegetation was derived from Ecological Land Classification (ELC) using broad community types: FOC (coniferous forest), FOM (mixed forest), CUP (plantations), SWC (coniferous swamp), SWD (deciduous swamp). A LAM analysis was applied to these ELC patch boundaries with the same criteria as the habitat patch indicator (see above). These community types are more impacted by increasing seasonal temperatures and increasing variability in precipitation will be negatively affected by climate change due to disrupting functional processes.	Score 0: Low vulnerability (L1, L2) Score 1: Moderate vulnerability (L3) Score 2: High vulnerability (L4, L5)
Wetland vulnerability	Wetland sensitivity to climate change based on receiving inputs of water only from precipitation and local catchment runoff were more vulnerable than wetlands receiving additional water inputs from groundwater or from larger riparian systems. Number of potential water sources (riparian = within 30 m of permanent watercourse; groundwater ≤ 1 m depth to estimated water table).	Score 0: Low vulnerability Score 1: Moderate vulnerability (Riparian or groundwater) Score 2: High vulnerability (Precipitation only (no riparian on groundwater))
Soil drainage	Soil drainage relating to poor drainage will produce shallower root networks and increased potential for localized inundation, contributing to higher relative vulnerability. Scoring for climate vulnerability was based on the soil surveys (OMAFRA) from well drained to poorly drained or no drainage (e.g., urban) classification.	Score 0: Low vulnerability Score 1: Moderate vulnerability (imperfect drainage) Score 2: High vulnerability (poor drainage)

Indicator	Methodology	Interpretation
Ground surface temperature	Ground surface temperature using LANDSAT imagery (2017) represents the potential heat and drought stress throughout the natural system leading to the drying of soil and forest understories, plant heat stress, reduction in natural system thermal regulation, and loss of thermal refuges for heat-intolerant species. The data represent general urban areas or lower canopy cover that may increase ground surface temperatures. Scoring was based on ground surface temperatures under three data percentiles of equal thirds.	Score 0: Low vulnerability (14.6 – 20.3̊ C) Score 1: Moderate vulnerability (20.3 – 25.6̊ C) Score 2: High vulnerability (25.6 – 33.0̊ C)
Additive total	The additive vulnerability score for the five vulnerability indicators in the Durham Region (total score 1 is the highest vulnerability) as a 100-m grid unit. Additive score is a summary of all five vulnerability indicators wherein each indicator is added together, and the overall scoring is rescaled from 0 to 1.	Score 0 (lowest vulnerability) to 1 (highest vulnerability): Low vulnerability (≤ 0.33) Moderate vulnerability (> 0.33 and < 0.66) High vulnerability (≥ 0.66)

4. RESULTS AND DISCUSSIONS

Using the five vulnerability indicators, including habitat patch score, sensitive vegetation communities, wetland hydrological stability, soil drainage rating, and ground surface temperature, as well as their additive scores, we provide a high-level assessment of climate change vulnerability for the Durham Region. Here, we break down the results by indicator and provide an overall summary of results with an additive analysis. Table 6 and Figures 5-10 provide an overview of the results that are discussed in the subsequent sections 4.1 and 4.2.

Table 6. Summary of low, moderate, and highly vulnerable areas in hectares (ha) within the Durham Region using five vulnerability indicators of habitat patch score, climate sensitivity of vegetation, wetland hydrological stability, soil drainage rating, and ground surface temperature, as well as their additive scores.

Climate Vulnerability Indicators	Vulnerability level	Area (ha)	Percentage*
Habitat Patch	Low	45323	50%
	Mod	38867	43%
	High	6950	8%
Climate Sensitive Vegetation	Low	14446	50%
	Mod	12843	45%
	High	1570	5%
Wetland Vulnerability	Low	11844	78%
	Mod	2513	17%
	High	826	5%
Soil Drainage	Low	216367	85%
	Mod	26257	10%
	High	11570	5%
Ground Surface Temperature	Low	8268	3%
	Mod	225871	89%
	High	20054	8%
Additive	Low	162182	64%
	Mod	79425	31%
	High	12586	5%

* Percentages represent the total vulnerability in each climate vulnerability indicator tier (low, moderate, and high vulnerability). Percentages of climate sensitive vegetation and wetland vulnerability are a subset of natural cover.

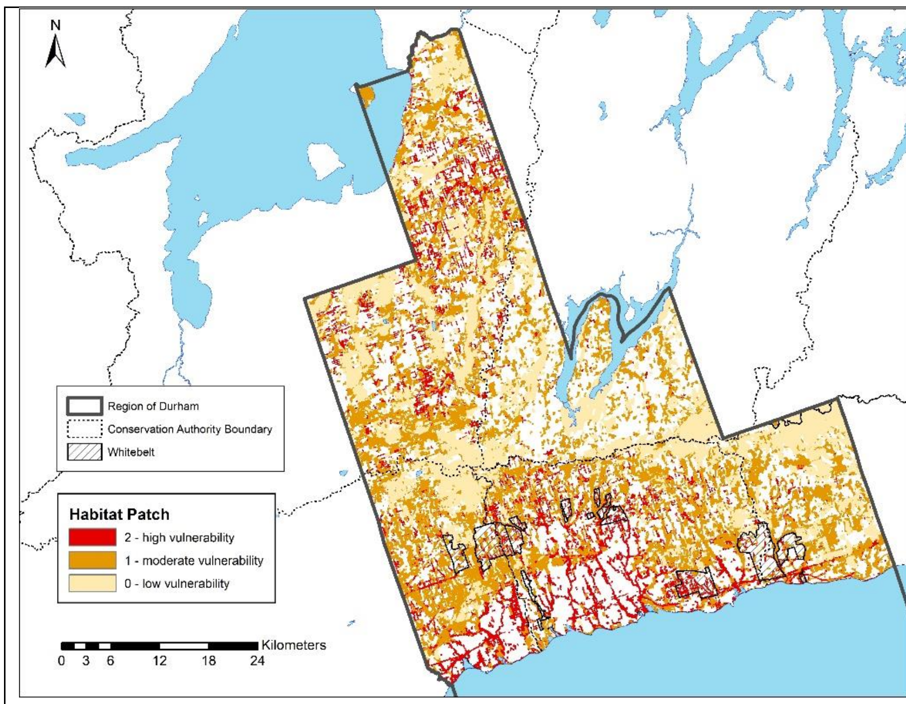

Figure 5. Vulnerability scores for the habitat patch vulnerability indicator using the Landscape Analysis Model (LAM) with future build out areas shown (whitebelt; hashed lines).

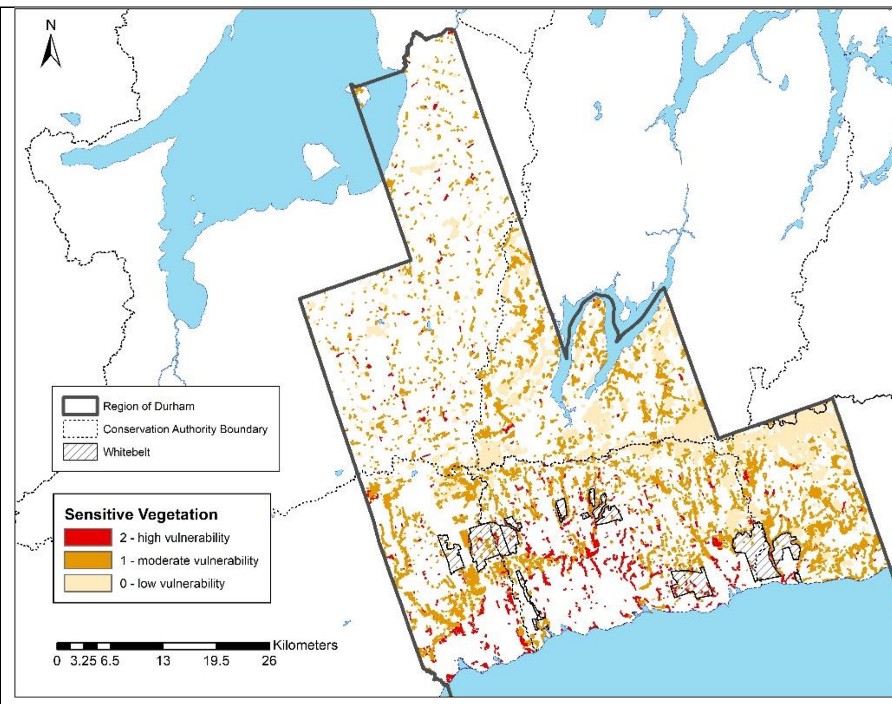

Figure 6. Vulnerability scores for the sensitive vegetation vulnerability indicator with future build out areas shown (whitebelt; hashed lines).

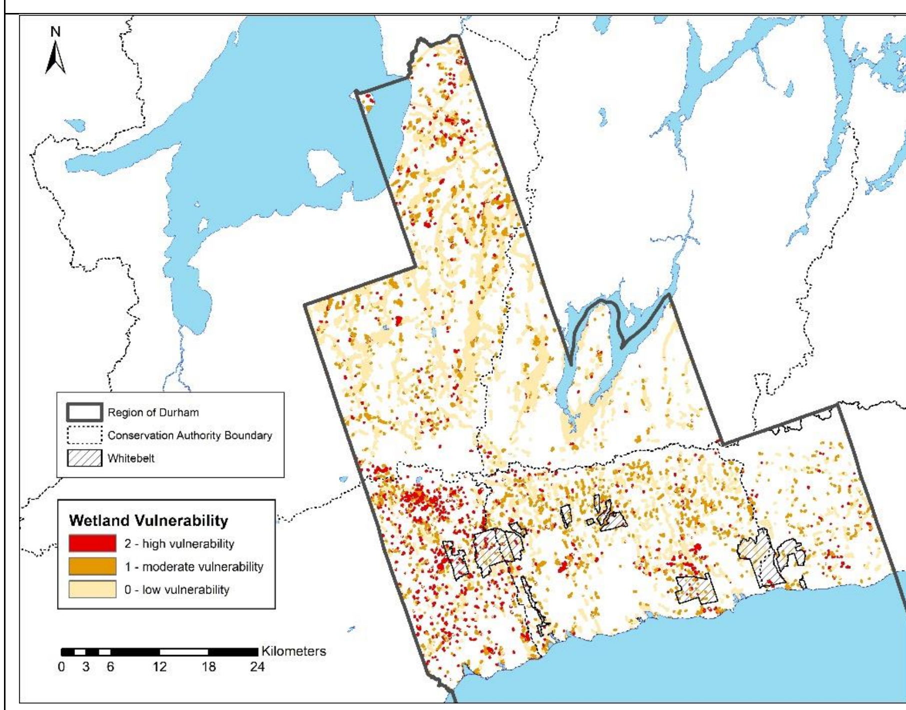

Figure 7. Vulnerability scores for the wetland vulnerability indicator with future build out areas shown (whitebelt; hashed lines).

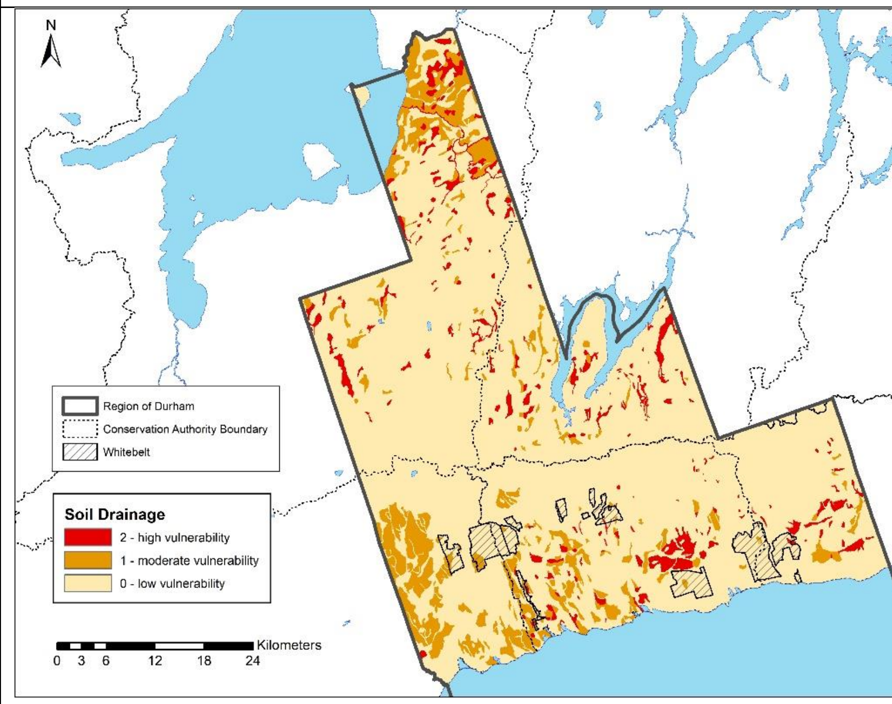

Figure 8. Vulnerability scores for the soil drainage vulnerability indicator with future build out areas shown (whitebelt; hashed lines).

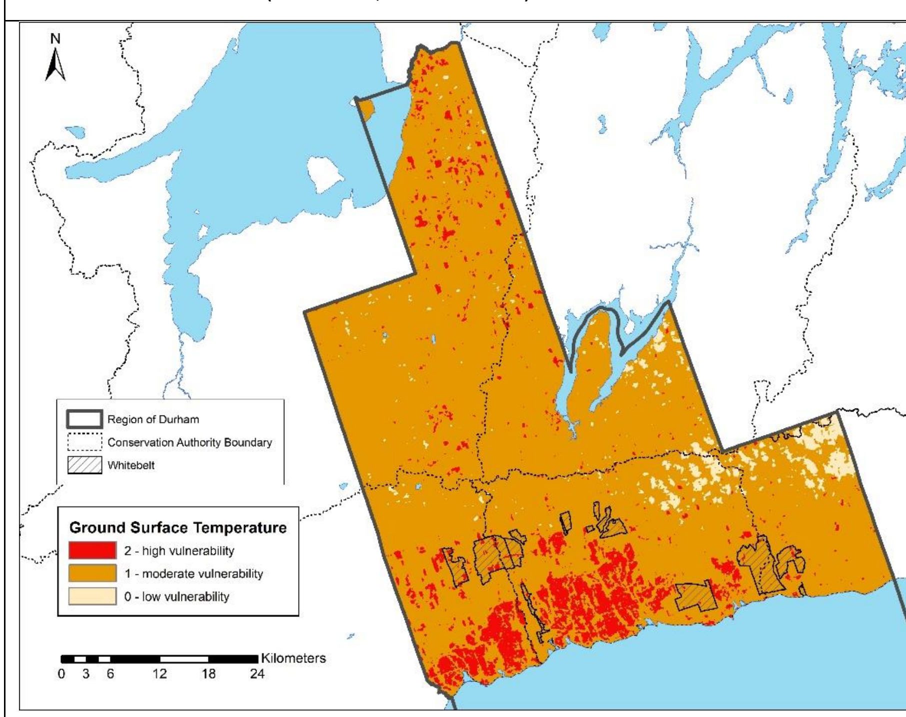

Figure 9. Vulnerability scores for the ground surface temperature vulnerability indicator with future build out areas shown (whitebelt; hashed lines).

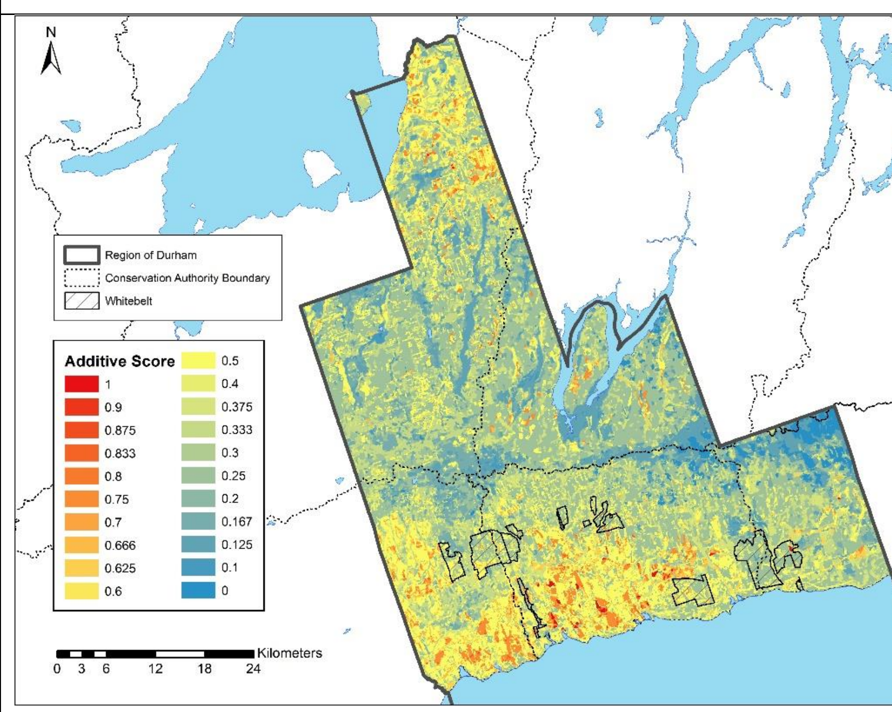

Figure 10. Additive total vulnerability scores for the Durham Region in 100-m grids with future build out areas shown (whitebelt; hashed lines).

4.1. Vulnerability Indicators

4.1.1. Habitat patch

The habitat patch score is a strong indicator of ecosystem vulnerability because of its interrelations with multiple vulnerability factors. Here, the habitat patch score considers several factors, such as patch size, shape, and influence of the surrounding matrix using the approach outlined by the TRCA Landscape Analysis Model (TRCA 2007). Table 6 highlights that about 8% of natural cover (6,950 ha) in Durham is highly vulnerable under future climate change and 43% vulnerable (38,867 ha) is moderate. Figure 5 shows that there tends to be highly vulnerable areas associated with urban areas in the Durham Region as this type of surrounding matrix will have an impact on patches (Figure 5). Further, the rural surroundings of patches (e.g., agriculture) in the northern areas of the Durham Region have less matrix influence, but patches tend to be small and fragmented increasing their climate vulnerability (Figure 5). Lastly, we also find that vulnerable areas include meadow habitats as they tend to have lower ecological function by being located around highway medians that are heavily influenced by impervious surfaces and the surrounding urban matrix (Figure 5).

These results also highlight that in addition to smaller patch sizes, there are some less than ideal shapes that increases edge effects on habitat patches, where the surrounding land use will have a high influence on the quality of the habitat patch and their vulnerabilities to stressors like extreme events (e.g., drought periods) or continuous climate stress (e.g., exposure to chronic higher temperature). Thus, to address these vulnerabilities related to habitat quality it is important to consider protection and restoration of natural cover as well as managing areas currently outside of natural cover for climate adaptation. This includes measures to increase natural areas as well as implementation of green infrastructure such as urban tree canopy in urban landscapes can help natural systems to adapt to the effects of climate change.

4.1.2. Climate sensitive vegetation

Climate sensitive vegetation is more impacted by increasing seasonal temperatures and increasing variability in precipitation, which will be at increased risk of impacts from climate change. Here these vegetation communities include coniferous forest, plantations, mixed forest, coniferous swamp, and deciduous swamp.

Results indicate that the highly vulnerable or most climate sensitive vegetation communities are found in 1,570 ha or 5% of natural cover, which represents a small subset of the habitat patches (Table 6 and Figure 6). Whereas a larger portion of sensitive vegetation is found to be moderately vulnerable, amounting to 12,843 ha (45%) of natural cover (Table 6 and Figure 6).

Again, we find that the sensitive vegetation has an increased vulnerability that is associated with the urban matrix and urban areas tend to have high vulnerability scores (Figure 6). Further, while the northern areas of Durham Region are primarily rural, it shows several smaller and fragmented patches of sensitive vegetation communities which increase their climate vulnerability (Figure 6). Like the habitat patch indicator above, because the species that make up these patches are more impacted by climate change this means they will be more impacted under future climate (Ordóñez and Duinker 2014, Aubin et al. 2018). To address these vulnerabilities related to habitat quality, consideration for the protection and restoration of natural cover as well as managing areas currently outside of natural cover for climate adaptation would be desirable in both rural and urban environments. This includes measures to increase natural areas as well as implementation of green infrastructure such as urban tree canopy in urban landscapes can help natural systems to adapt to the effects of climate change.

4.1.3. Wetland vulnerability

Wetland vulnerability increases where soils have a higher potential for remaining dry for extended periods of time and as a result tend to be more vulnerable to colonization by upland vegetation and invasive species leading to potential adverse impacts. Highly vulnerable wetlands are found within 826 ha (5% of natural cover) of the Durham Region (Table 6 and Figure 7). Moderately vulnerable wetlands cover 2,513 ha (17% of natural cover) of the Durham Region under future climate change (Table 6 and Figure 7). Despite wetlands comprising 15,223 ha of the Durham Region, the combined total of moderately and highly vulnerable wetlands results in 32% as moderately to highly vulnerable in the region under future climate. Identifying potential natural cover adjacent to highly vulnerable wetlands may be areas that could be targeted for restoration to reduce the vulnerability to climate change.

4.1.4. Soil drainage

Poor soil drainage will produce shallower root networks and increased potential for localized inundation, contributing to higher relative vulnerability. However, soil drainage is a climate change vulnerability indicator that cannot lead to actual actions to reduce the negative effects of climate change as it is a landscape condition. Yet, identifying areas of poor soil drainage can focus on areas that are at greater risk to climate change. Highly vulnerable soil drainage areas are comprised of 11,570 ha (5% of Durham Region) throughout the Durham Region (Table 6 and Figure 8). Moderately vulnerable soil drainage areas (26,257 ha, 10% of Durham Region) are also found throughout the Durham Region, but with larger areas concentrated in the southwest and northern parts of the region (Table 6 and Figure 8). The influence of the urbanized portion of Durham Region has not been fully captured with an updated soil drainage information due to the age of the soil information, particularly in the built areas. Therefore, the vulnerability outside of natural cover is particularly underrepresented.

4.1.5. Ground surface temperature

Ground surface temperature represents the potential heat and drought stress throughout the natural system which can contribute to the drying of soil and forest understories, plant heat stress, reduction in natural system thermal regulation, and loss of thermal refuges for heat-intolerant species. Notably, the highly vulnerable ground surface temperature areas are limited in areas with natural cover (8,268 ha, 8% of Durham Region) due to its effect to mediate ground surface temperature (Table 6 and Figure 9). Most of Durham Region (225,871 ha, 89%) is considered to have moderate vulnerable ground surface temperature under future climate change (Table 6 and Figure 9). This vulnerability is reflective of the greater imperviousness and the urban heat island effect. Essentially, the greatest opportunity in urban areas to reduce climate change vulnerability of ground surface temperature is to increase urban forest canopy by increasing vegetation cover and reducing impervious surfaces.

4.2. Additive Vulnerability across Durham Region

Altogether the additive vulnerability reflects the patterns of all the indicators combined (Table 6 and Figure 10). We find that 32% (29,408 ha) of areas within Durham region have a moderate to high vulnerability under future climate (Table 6). Specifically, we find that both northern and southern portions of Durham Region have a larger share of moderately and highly vulnerable areas (Figure 10). These areas tend to be associated with largely agricultural and urban areas meaning that the broader landscape condition is poorer for natural systems in these areas. Specifically, we find that there are many moderate to highly vulnerable habitat patches, sensitive vegetation patches, poorer soil drainage, and higher ground surface temperatures that are contributing to increases in the additive vulnerability in these areas. It is the smaller and more fragmented natural cover patches (which increases vulnerability) combined with higher vulnerability of soil drainage and ground surface temperature that creates this increased risk. Increasing the landscape condition in these areas, through increases in the implementation of urban canopy, green infrastructure and natural heritage system would be seen as beneficial.

5. MANAGEMENT IMPLICATIONS

Climate change impacts are often exacerbated by changes in land use and intensity, which in turn will contribute to increase natural system vulnerabilities. This often results from natural cover loss and degradation as well as an increase in impervious surfaces surrounding natural areas. However, some of these impacts can be mitigated using natural heritage protection, restoration, and enhancements. In this analysis, we completed a rapid overlay analysis between the NS-CCVA results and (i) Durham's proposed Official Plan Natural Heritage System (NHS) and Enhancement Opportunity (EO) areas as well as an overlay of (ii) potential future urban expansion areas where increases to imperviousness may occur (hereafter referred to as the Whitebelt). Together these results will provide Durham Region with science-based information that can inform implementation of the NS-CCVA through policies and planning processes.

5.1. Overlay Analysis with Durham's NHS and Enhancement Areas

We completed an overlay analysis of NS-CCVA results with Durham Region's proposed Official Plan NHS and EO areas (April 2022; see both the viewer here and pdf version here). Specifically, we compared the overall additive climate vulnerability and each of the CCVA indicators within the region with the proposed NHS and EO areas to identify whether high and moderate vulnerability areas are included within the proposed NHS and EO areas. Table 7 and Figures 11-18 provides an overview of the results, and the subsequent sections highlights the key messages.

Table 7. Summary of low, moderate (mod), and highly vulnerable areas in hectares (ha) within the Durham Region Natural Heritage System (NHS) and enhancement opportunities (EO) using five vulnerability indicators of habitat patch, climate sensitivity of vegetation, wetland hydrological stability, soil drainage rating, and ground surface temperature, as well as additive score.

Vulnerability Indicator	Vulnerability Level	Natural Heritage System (NHS)	*Percentage*	Enhancement Opportunities (EO)	*Percentage*	Outside NHS and EO	*Percentage*
Habitat Patch	Low	42566	*46.7%*	528	*0.6%*	2229	*2.4%*
	Mod	31822	*34.9%*	1006	*1.1%*	6039	*6.6%*
	High	4697	*5.2%*	141	*0.2%*	2113	*2.3%*
Sensitive Vegetation	Low	13781	*47.8%*	112	*0.4%*	553	*1.9%*
	Mod	11813	*40.9%*	209	*0.7%*	821	*2.8%*
	High	1444	*5.0%*	9	*<0.1%*	117	*0.4%*
Wetland Vulnerability	Low	11353	*74.6%*	42	*0.3%*	490	*3.2%*
	Mod	2161	*14.2%*	40	*0.3%*	313	*2.1%*
	High	688	*4.5%*	7	*<0.1%*	131	*0.9%*
Soil Drainage	Low	106599	*41.9%*	8004	*3.1%*	101764	*40.0%*
	Mod	11444	*4.5%*	1770	*0.7%*	13079	*5.1%*
	High	9123	*3.6%*	175	*0.1%*	2281	*0.9%*
Ground Surface Temperature	Low	6348	*2.5%*	217	*0.1%*	1704	*0.7%*
	Mod	119066	*46.8%*	9346	*3.7%*	97459	*38.3%*
	High	1753	*0.7%*	386	*0.2%*	17915	*7.0%*
Additive	Low	83770	*33.0%*	5961	*2.3%*	72452	*28.5%*
	Mod	39689	*15.5%*	3452	*1.4%*	36283	*14.3%*
	High	3708	*1.4%*	536	*0.2%*	8343	*3.3%*

* Percentages represent the total amount for each type of climate vulnerability indicator score (low, mod, high) within NHS, EO or neither.

5.1.1. Additive vulnerability

Table 7 highlights that Durham's proposed Official Plan NHS includes areas with mostly low to moderate vulnerability. The additive score map (Figure 11B) highlights the distribution of these vulnerabilities across the proposed NHS. Most low vulnerability areas dominate the middle portions of the Region, while moderate and high vulnerabilities are present in the northern and the southern portions of the Region.

This is not surprising given that most of the middle portions of the Region have large amount of natural cover that are included in the NHS and are situated in relatively rural landscapes. This ensures that the vulnerability indicators such as habitat patch quality or ground surface temperature have low vulnerability scores, which brings down the overall vulnerability scores. In contrast, the northern and southern portions of the Region have smaller and more fragmented habitat patches and/or are mostly situated in urban landscapes. In these areas the multiple vulnerability indicators amalgamate to increase the overall vulnerability score (e.g., climate sensitive vegetation in combination with low habitat quality and high temperature).

In these high to moderate vulnerability areas within NHS, adapting to climate change may require multi-prong approach. This includes protecting existing natural cover and restoring potential natural cover where possible through NHS and EO areas. In addition, the focus should also be on improving other urban portions through green infrastructure and low impact development measures to decrease the ground surface temperature, improve habitat quality, and improve drainage conditions. The EO areas highlighted in Figure 11 include some high to moderate vulnerability areas, which can provide additional coverage to vulnerable natural systems and should be given strong consideration for inclusion in the NHS.

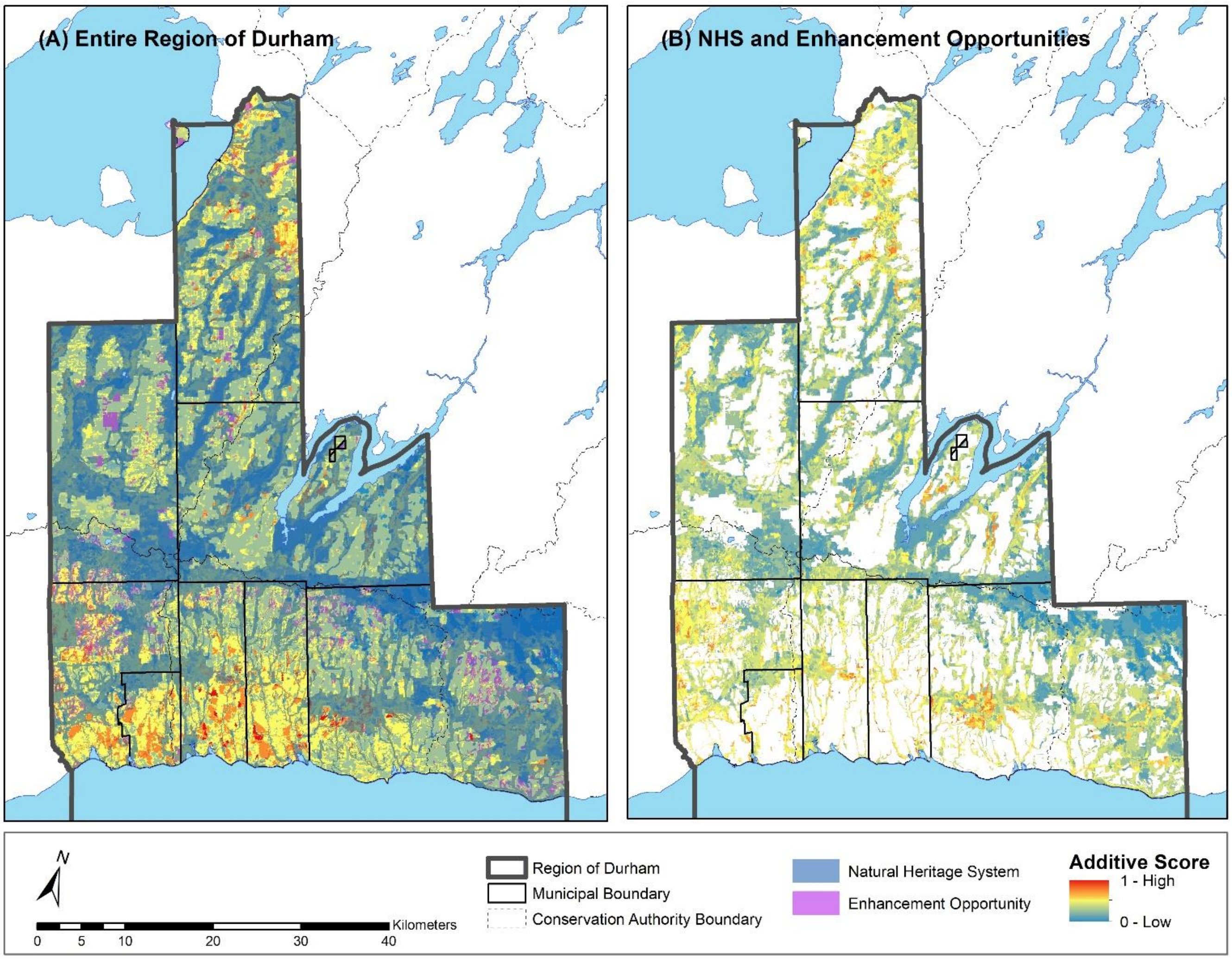

Figure 11. Summary of climate vulnerability additive score for the (A) entire Durham Region with the Natural Heritage System and Enhancement Opportunity overlay and (B) only within the Durham Region’s Natural Heritage System and Enhancement Opportunities areas.

5.1.2. Individual vulnerability indicator scores

In addition to the overall vulnerabilities, individual vulnerability indicators distribution within and outside of the NHS and EO areas provide important insights on areas that could be considered for the NHS planning and implementation.

For the habitat patch score, Table 7 highlights that most natural cover or habitat patches are found within the NHS (79,085 ha or 87% of natural cover) or EO areas (1,675 ha or 2% of natural cover). However, a substantial portion of natural cover remain outside of NHS/EO areas (10,318 ha or 11% of patches). Focusing only on the natural cover with high vulnerability to climate change, most of them are largely within the NHS (4,697 ha or 5% of highly vulnerable areas of natural cover) and some are identified in the proposed EO areas (141 ha, 0.2% of highly vulnerable areas of natural cover; Table 7 and Figure 12A). The remaining high vulnerability patches (2,113 ha and 2% of patches) are generally in urban and agricultural areas where the landscape condition (being not natural cover) is one of the main driving factors of higher scores outside of the NHS (Figure 11, 12A and Table 7).

For vulnerable sensitive vegetation communities, most are found within the NHS (27,038 ha or 94%) or EO (331 ha or 0.4%) areas, however, good number remain outside of either NHS/EO areas (1,491 ha or 5%; Table 7). As this indicator reflects current natural cover on the landscape, this means that a proportion of this feature is omitted from current natural heritage system plans. When reviewing highly vulnerable sensitive vegetation communities, we find that they are mainly found within the NHS (1,444 ha or 5% of sensitive vegetation patches; Figure 12B and Table 7). However, there are some also within the EO areas (9 ha and <0.1% of highly vulnerable areas) and outside of both the NHS and enhancements (117 ha and 0.4% of highly vulnerable areas; Table 7). As this indicator is based on current vegetation communities, this pattern likely reflects the notion that most current sensitive vegetation communities are being reflected within the natural heritage system mapping proposed by Durham Region. However, we note that a good portion of sensitive vegetation patches (5%) remain outside of the NHS and EO areas (Table 7).

Most wetlands are found within the NHS (14,202 ha or 93%) or EO (89 ha or 0.6%) areas, however, good portion of wetlands remain outside of either NHS/EO areas (934 ha or 6%; Table 7). Like the sensitive vegetation communities, this indicator reflects current natural cover on the landscape, given that some are outside NHS/EO areas, this means that a proportion of this indicator is omitted from current natural system plans. We find that most moderate to highly vulnerable wetlands are included within the NHS (2,849 ha, which is 19% of wetlands) as they are considered a natural feature as part of the NHS mapping (Figure 12C and Table 7). Further, the enhancement areas increase the number of highly vulnerable wetlands (47 ha and 0.3% of wetlands). However, there are moderate and highly vulnerable wetlands (444 ha and 3% of wetlands) that are excluded from both NHS and EO areas and can be found in largely urban or agricultural settings (Table 7). In these areas (and elsewhere), actions within wetland catchments that maintain the natural input of surface flow to wetlands would be desirable to maintain wetland water balance. Specifically, identifying potential natural cover adjacent to existing natural cover of highly vulnerable wetlands may be areas that could be targeted for restoration to reduce the vulnerability to climate change.

For soil drainage at a given location, the level of vulnerability here is not related to the current or future NHS or EO areas, but it does indicate where natural cover may be needed to reduce the overall climate change vulnerability of a given location. Most soils in Durham Region have a low vulnerability (216,367 ha or approximately 85%) under future climate change and there is a further 8% (20,568 ha) of moderate and highly vulnerable soils found within the NHS (Table 7 and Figure 12D). Additionally, the EO areas overlap with a further 1% (1,945 ha) of moderate to highly vulnerable soils (Table 7). However, there remains roughly 6% (15,314 ha) of moderate to highly vulnerable soils that do not overlap with either the NHS or EO areas (Table 7). These moderate to highly vulnerable soils that do not overlap with NHS or EO areas could be targeted for other enhancements such as urban tree canopy cover, low impact designed developments, green infrastructure or even be considered for inclusion in the NHS.

The ground surface temperature represents the potential heat and drought stress throughout the natural system and most ground surface temperatures are found to be at a moderate vulnerability (225,871 ha or 89%) throughout Durham Region (Table 7). There are a limited number of areas at a low vulnerability (8,268 ha or 3%), which are mostly located within the NHS (6,348 ha or 3%; Table 7). This is intuitive as NHS areas generally already include natural cover which will lower ground surface temperatures. Moderate to highly vulnerable areas are found within the NHS (120,819 ha or 48%) and EO (9,732 ha or 4%) areas, however, there remains a large amount outside of NHS/EO areas (115,374 ha or 45%; Table 7). Moderate to high vulnerabilities outside of NHS/EO areas represent areas that may be targeted for increasing natural cover patch sizes or areas that would benefit from planting opportunities for drought-tolerant and heat tolerant species. In urban areas, natural cover is inherently stressed and provide opportunities for mitigation through green infrastructure and urban tree canopy to offset the climate change vulnerability.

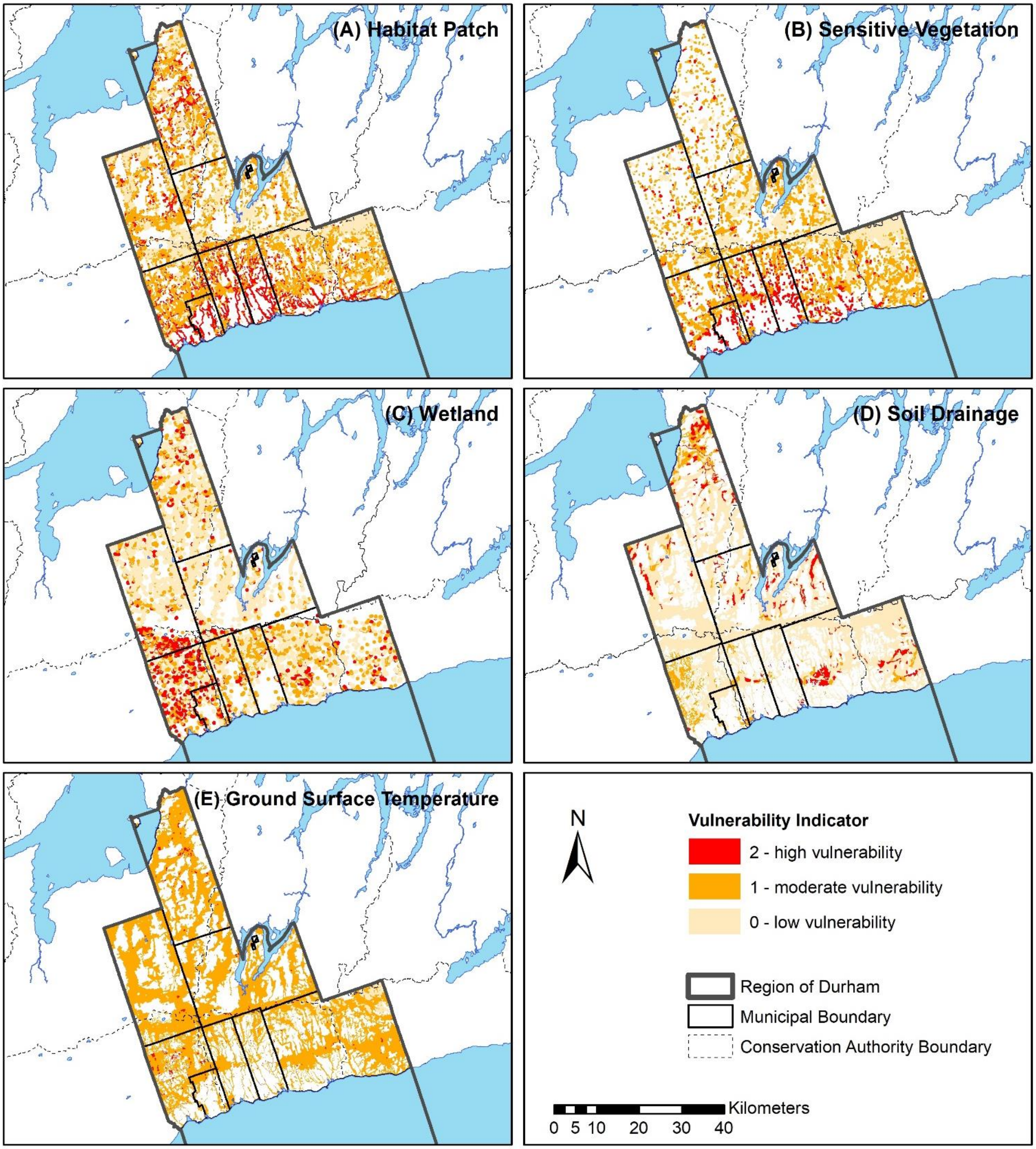

Figure 12. Summary of climate vulnerability indicators (A) habitat patch score, (B) climate sensitivity of native vegetation, (C) wetland hydrological stability, (D) soil drainage rating, (E) ground surface temperature in the Durham Region's Natural Heritage System and enhancement opportunities. Panels A-C have enhanced outlines for vulnerability indicators to increase visibility in the maps.

5.2. Future Development Assessment and NHS/EO Areas

One solution to adapt to future climate is to assess the vulnerability of natural systems within whitebelt areas in Durham Region to identify where impacts may be mitigated through the protection, maintenance, restoration, and enhancement of natural systems. The notion here is that natural systems will be more resilient than they are currently and may even have their vulnerabilities mitigated. This climate adaptation can be integrated into land use planning recommendations, but it requires identifying each vulnerability indicator within these whitebelt areas.

Table 8. Summary of low, moderate (mod), and highly vulnerable areas in hectares (ha) and percentage of each value within the defined areas within the whitebelt in the Durham Region. This is broken down by the (i) overall whitebelt coverage, as well as the tiered amount within the (ii) Natural Heritage System (NHS), (iii) enhancement opportunities (EO), as well as indicators found to be (iv) in neither NHS/EO areas in the whitebelt for each indicator. Shown are the five vulnerability indicators of habitat patch, climate sensitivity of vegetation, wetland hydrological stability, soil drainage rating, and ground surface temperature, as well as additive score. Percentages represent the total breakdown within the overall whitebelt and then the tiered percentage within (ii) NHS, (iii) EO, and (iv) neither, for each climate vulnerability indicator.

Vulnerability Indicators	Vulnerability Level	Whitebelt Overall	%	Whitebelt + NHS Overlap	%	Whitebelt + EO Overlap	%	Outside NHS + EO but within Whitebelt	%
Habitat Patch	Low	92	*8.3%*	75	*6.8%*	11	*1.0%*	5	*0.5%*
	Mod	649	*58.5%*	444	*40.0%*	33	*3.0%*	172	*15.5%*
	High	369	*33.3%*	249	*22.4%*	5	*0.4%*	116	*10.4%*
Sensitive Species	Low	0	*0.0%*	0	*0.0%*	0	*0.0%*	0	*0.0%*
	Mod	153	*72.3%*	139	*65.5%*	5	*2.3%*	10	*4.5%*
	High	59	*27.7%*	53	*25.0%*	0	*0.0%*	6	*2.7%*
Wetland Vulnerability	Low	90	*61.0%*	87	*57.5%*	0	*0.0%*	2	*1.5%*
	Mod	38	*25.8%*	33	*22.7%*	0	*0.1%*	4	*3.0%*
	High	19	*13.2%*	18	*12.1%*	0	*0.0%*	2	*1.0%*
Soil Drainage	Low	7979	*92.3%*	1413	*16.3%*	487	*5.6%*	6080	*70.3%*
	Mod	574	*6.6%*	83	*1.0%*	43	*0.5%*	449	*5.2%*
	High	95	*1.1%*	8	*0.1%*	9	*0.1%*	78	*0.9%*
Ground Surface Temperature	Low	5	*0.1%*	2	*0.0%*	0	*0.0%*	3	*0.0%*
	Mod	8149	*94.2%*	1453	*16.8%*	467	*5.4%*	6228	*72.0%*
	High	495	*5.7%*	48	*0.6%*	71	*0.8%*	375	*4.3%*
Additive	Low	5420	*62.7%*	658	*7.6%*	301	*3.5%*	4461	*51.6%*
	Mod	3000	*34.7%*	806	*9.3%*	210	*2.4%*	1984	*22.9%*
	High	229	*2.6%*	40	*0.5%*	27	*22.9%*	162	*1.9%*

5.2.1. Additive vulnerability

Altogether, whitebelt areas tend to have an overall lower climate change vulnerability compared to developed urban areas, because of the greater amount of pervious surfaces and natural cover present in its current form. In particular, the whitebelt areas in eastern Durham Region have the greatest proportion of low vulnerable areas as they are located furthest away from urban areas (Figure 13). By contrast, other whitebelt areas that are closer to the urban areas are inherently more vulnerable with greater urban matrix influence on natural cover patches and impervious cover which increases ground surface temperatures (Figure 13). Altogether, these patterns result from multiple climate change vulnerability indicators (described below) and further development would only increase the vulnerability of natural systems in whitebelt areas in the absence of implementing NHS/EO areas.

5.2.2. Individual vulnerability indicators

One of the biggest drivers of higher scoring in whitebelt areas is highly vulnerable patches based on the habitat patch vulnerability indicator (Figure 14). If left as is with no adaptation efforts, further development will increase the vulnerability of these patches. This is because most of the patches are small and highly fragmented and an increase in imperviousness in the landscape will consequently increase the vulnerability. Most habitat patches within the whitebelt areas have either moderate (649 ha or 59% of patches) or highly (369 ha or 33% of patches) vulnerable scores (Figure 14 and Table 8). There are only 8% of habitat patches that have a low vulnerability within the whitebelt (Table 8). Most moderate to highly vulnerable patches are found within the NHS (693 ha or 62% of patches within the whitebelt) and EO (38 ha or 3% of patches within the whitebelt) areas, but close to one quarter of patches remain outside this natural cover areas (288 ha or 26% of patches within the whitebelt; Table 8). Increasing NHS and EO coverage in these areas can conserve more habitat patches and potentially increase the size of individual patches to ultimately increase the climate change resilience. If increases in NHS or EO areas are not feasible then some solutions may be to use low impact development and increase the urban tree canopy in surrounding developments, which may mitigate against increasing the vulnerability of the remaining habitat patches.

The sensitive vegetation vulnerability indicator is like the habitat patch vulnerability indicator given that it is influenced by the size, shape, and matrix influence of each patch. Furthermore, it is based on a subset of vegetation community types – coniferous forest, mixed forest, plantations, coniferous swamp, or deciduous swamp. We find that most sensitive vegetation patches are either moderately (153 ha or 72% of patches within the whitebelt) or highly (59 ha or 28% of patches within the whitebelt) vulnerable within the whitebelt areas (Figure 15 and Table 8). None of sensitive vegetation patches have a low vulnerability within the whitebelt (Table 8). Most moderate to highly vulnerable patches are found within the NHS (192 ha or 91% of patches within the whitebelt) and EO (5 ha or 2% of patches within the whitebelt) areas, but close to 7% of patches remain outside NHS/EO areas (21 ha; Table 8). These patches are particularly small and fragmented, which will require restoration or enhancement opportunities as part of the future development, which could be supported through potential natural cover or urban tree plantings in surrounding areas.

For the wetland vulnerability indicator, although wetlands comprise 20,720 ha (8%) of Durham Region, only 147 ha of wetland habitat is found in whitebelt areas (Figure 16 and Table 8). Most of the wetlands are of low vulnerability (90 ha or 61% of wetlands) in the whitebelt, however, we find that a good portion are either moderate (38 ha or 26% of wetlands) to highly vulnerable (19 ha or 13% of wetlands) present as well (Figure 16 and Table 8). Most moderate to highly vulnerable wetlands are within the NHS (51 ha or 35%) areas. Lastly, there are approximately 6% of wetlands within the whitebelt areas remain outside or NHS and EO areas (low – 2%; mod – 3%; high – 1%; Figure 16 and Table 8). The omission of these wetlands from NHS and EO areas, especially low vulnerable wetlands, are a lost opportunity to conserving features that have a higher climate change resilience, since most will likely persist under future climate scenarios. Further, if increases in NHS or EO areas are not feasible, beyond conserving the feature itself (or alternatively through habitat compensation) than some solutions may be to use low impact development and increase the urban tree canopy in surrounding wetland catchments, which may mitigate against increasing the climate change vulnerability of wetlands.

Considering the soil drainage vulnerability and given that there are limited solutions, this does highlight that there will just be areas that are inherently more or less impacted by future climate. Most of the whitebelt areas have a low soil drainage vulnerability (7,979 ha or 92%), however, there remains some moderate to highly vulnerable areas (669 ha or 8%; Figure 17 and Table 8). We find that moderate to highly vulnerable soils in the whitebelt are represented in NHS (91 ha or 1%) and EO (52 ha or 0.6%) areas at lower amounts compared to those found outside of these areas (527 ha or 6%; Figure 17 and Table 8). These moderate to highly vulnerable soils should be considered for areas to target with increased natural cover enhancements such as increased urban canopy, low impact design and green infrastructure.

Lastly, ground surface temperature is going to be impacted through increases in impervious cover or bare soils. We found that there are a very limited number of low vulnerable areas (as low vulnerable areas are mainly restricted to the Oak Ridges Moraine – with higher elevation and higher natural cover) within whitebelt areas (Figure 18 and Table 8). Instead, whitebelt areas have a moderate and high vulnerability (8,644 ha or 99.9%) as they have surfaces that are predominantly bare of natural cover. While a portion of moderate to highly vulnerable areas are found within NHS (1,501 ha or 17%) and EO (538 ha or 6%) areas, most are found outside of these areas (6,603 ha or 76%; Figure 18 and Table 8). With further development in these whitebelt areas there should be an emphasis on solutions that enhance natural systems or contribute to increasing the amount of green infrastructure within and around areas of moderate and high vulnerability ground surface temperatures.

5.3. Conclusions

This study completed a rapid and high-level NS-CCVA to identify, mostly terrestrial natural system areas, which are vulnerable to future climate change across Durham Region. This was based on five key vulnerability indicators that were amalgamated into an additive vulnerability score. We also completed an overlay analysis that compared the climate vulnerable areas with Durham's proposed Official Plan NHS and EO areas as well as the whitebelt areas where potential future growth may occur. The combined result of these analysis is intended to provide the Region with the science-based information on climate vulnerable natural systems.

Firstly, we conducted a rapid climate change assessment, which shows that climate patterns will be largely similar between Peel and Durham regions, providing confidence that developed NS-CCVA methods will be applicable in both regions.

Secondly, our NS-CCVA results generally demonstrate higher vulnerabilities located in both the north and south of Durham Region in areas where the landscape is either dominated by agriculture or urbanized development

(Figure 10). Further, we find that the lowest risk is within the greenbelt or areas of the Oak Ridges Moraine, where there is a dominance of natural cover (Figure 10).

Lastly, our analysis supports the implementation of NHS enhancements that contribute to increasing the NHS footprint where existing natural cover is insufficient. These results also provide insight into what localized actions can be used to improve resilience. While most natural features are found to be included in NHS and EO areas, there are still number of features that remain outside these areas (Figure 11). We also find that this pattern is consistent within the whitebelt areas (Figure 13). Actions on the ground that either include these natural features within NHS/EO areas (by expanding the NHS/EO footprint) or lead to the implementation of enhancements in developed areas (e.g., green infrastructure, urban tree canopy) will undoubtedly help to mitigate future climate vulnerability.

In rapidly urbanizing landscapes proactive planning is critical to ensure a sustainable and resilient future for the Region and its residents. The results of the NS-CCVA provide a critical piece of information that helps to identify the strategic locations for climate adaptation measures that would ensure resilient natural systems, especially in the face of potential land use change. In this regard, this information may also be useful for strategic planning exercises beyond NHS planning, such as infrastructure, watershed, or restoration planning exercises. Specifically, these planning exercises aid in protecting, enhancing, and restoring watersheds, where healthy watersheds by virtue are more resilient to pressures from existing and future land use and climate change. Here the results from the NS-CCVA, provide a rapid, high-level assessment for the identification and implementation of Durham Region's NHS from science, policy, and planning aspects. The results can help to identify if the appropriate avoidance, mitigation, and compensation measures are in place such that the Region's natural systems and the services they provide are resilient to ongoing climate and land use change.

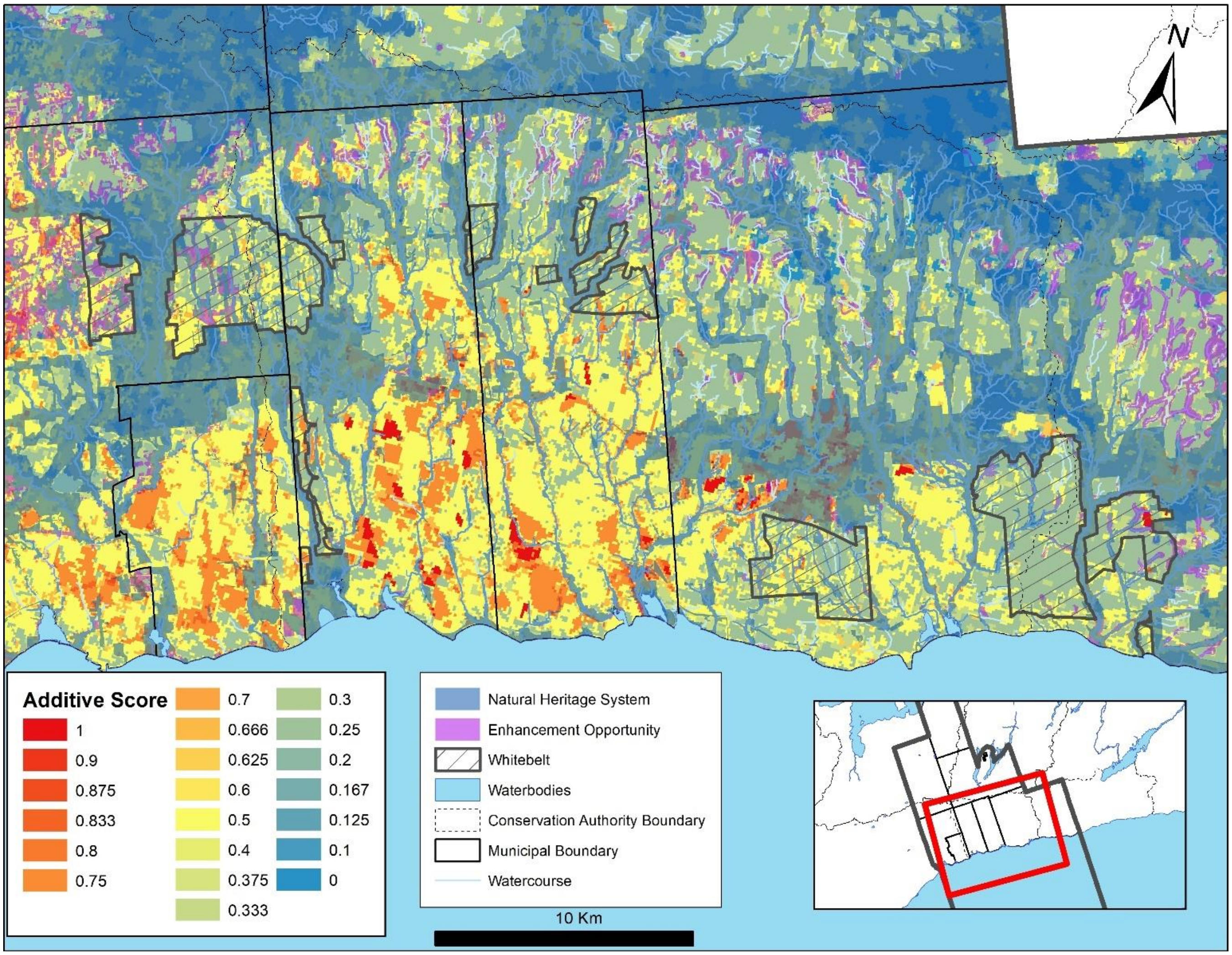

Figure 13. Additive climate change vulnerability scores for the Durham Region. Shown are the future buildout areas (whitebelt; hashed lines) alongside the natural heritage system and enhancement opportunity areas.

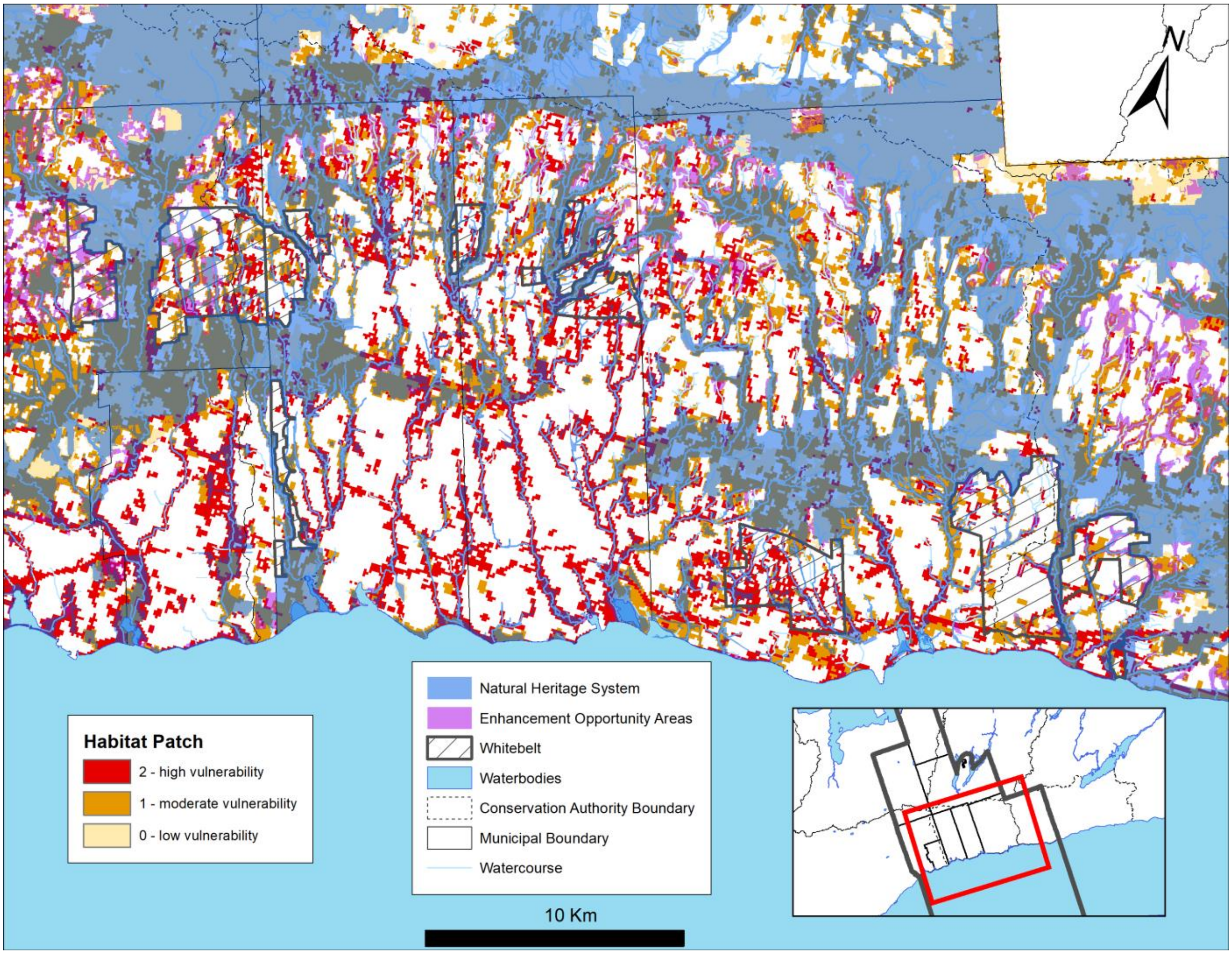

Figure 14. Climate change vulnerability scores for the habitat patch vulnerability indicator for the Durham Region. Shown are the future buildout areas (whitebelt; hashed lines) alongside the natural heritage system and enhancement opportunity areas.

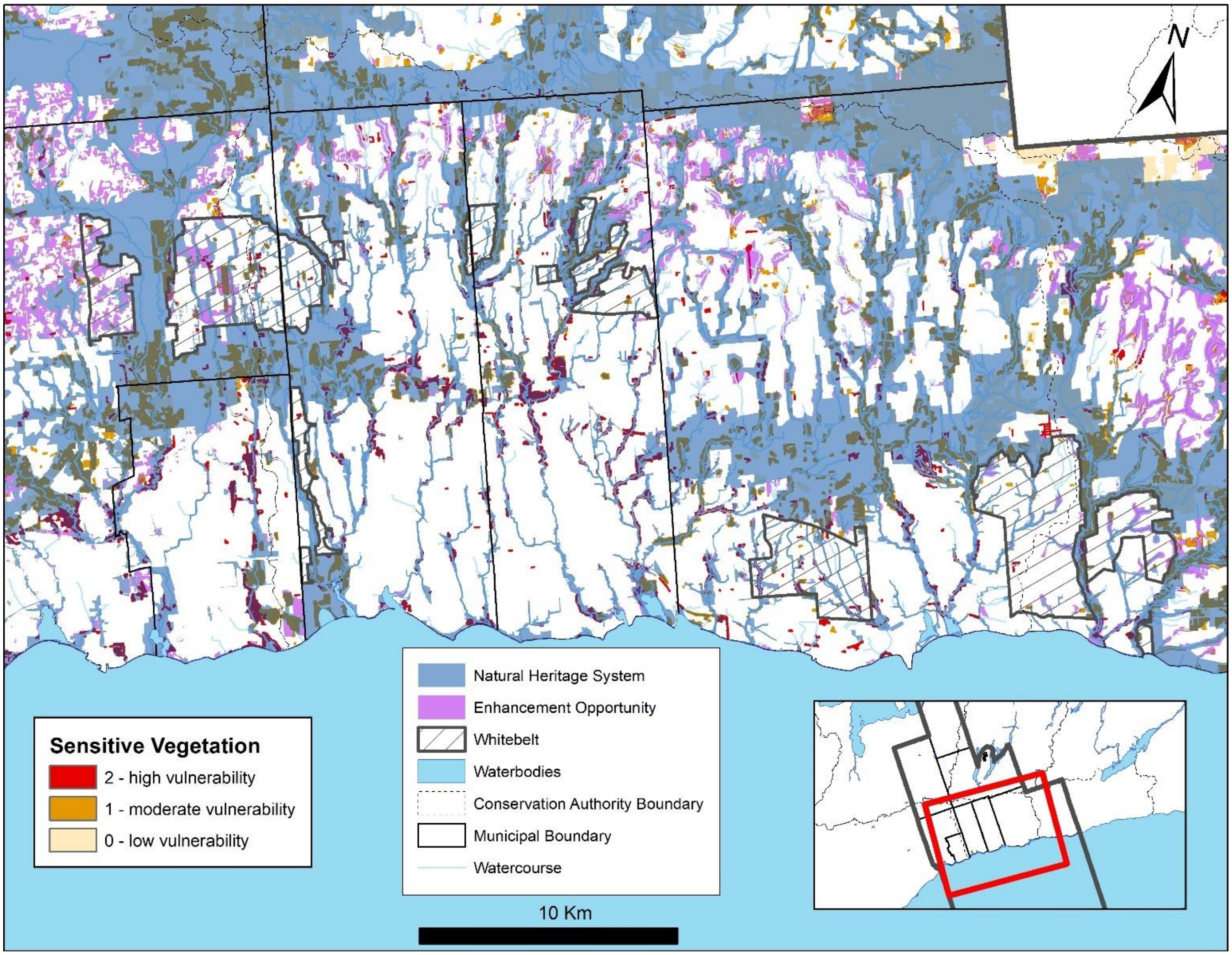

Figure 15. Climate change vulnerability scores for the sensitive vegetation vulnerability indicator for the Durham Region. Shown are the future buildout areas (whitebelt; hashed lines) alongside the natural heritage system and enhancement opportunity areas.

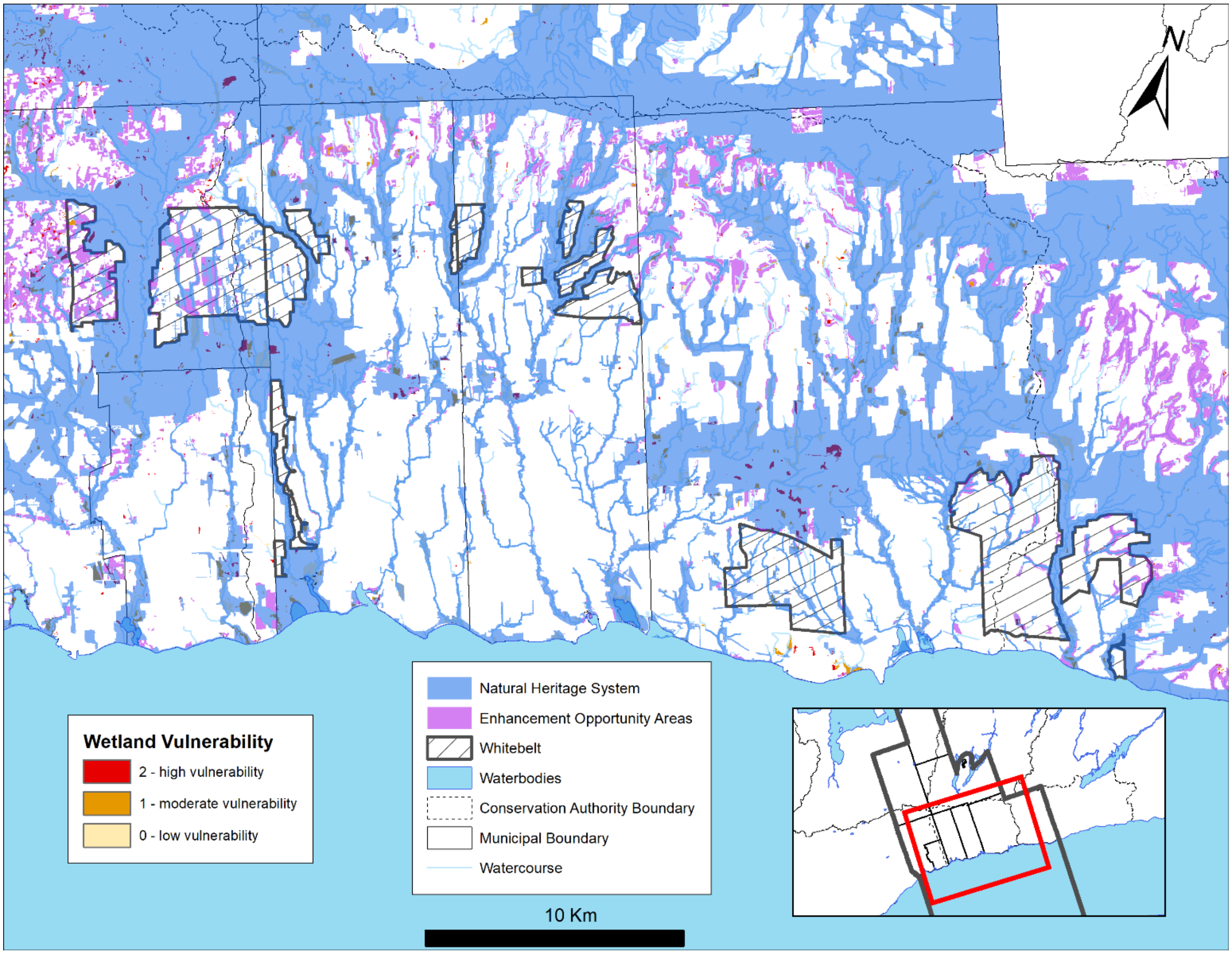

Figure 16. Climate change vulnerability scores for the wetland vulnerability indicator for the Durham Region. Shown are the future buildout areas (whitebelt; hashed lines) alongside the natural heritage system and enhancement opportunity areas.

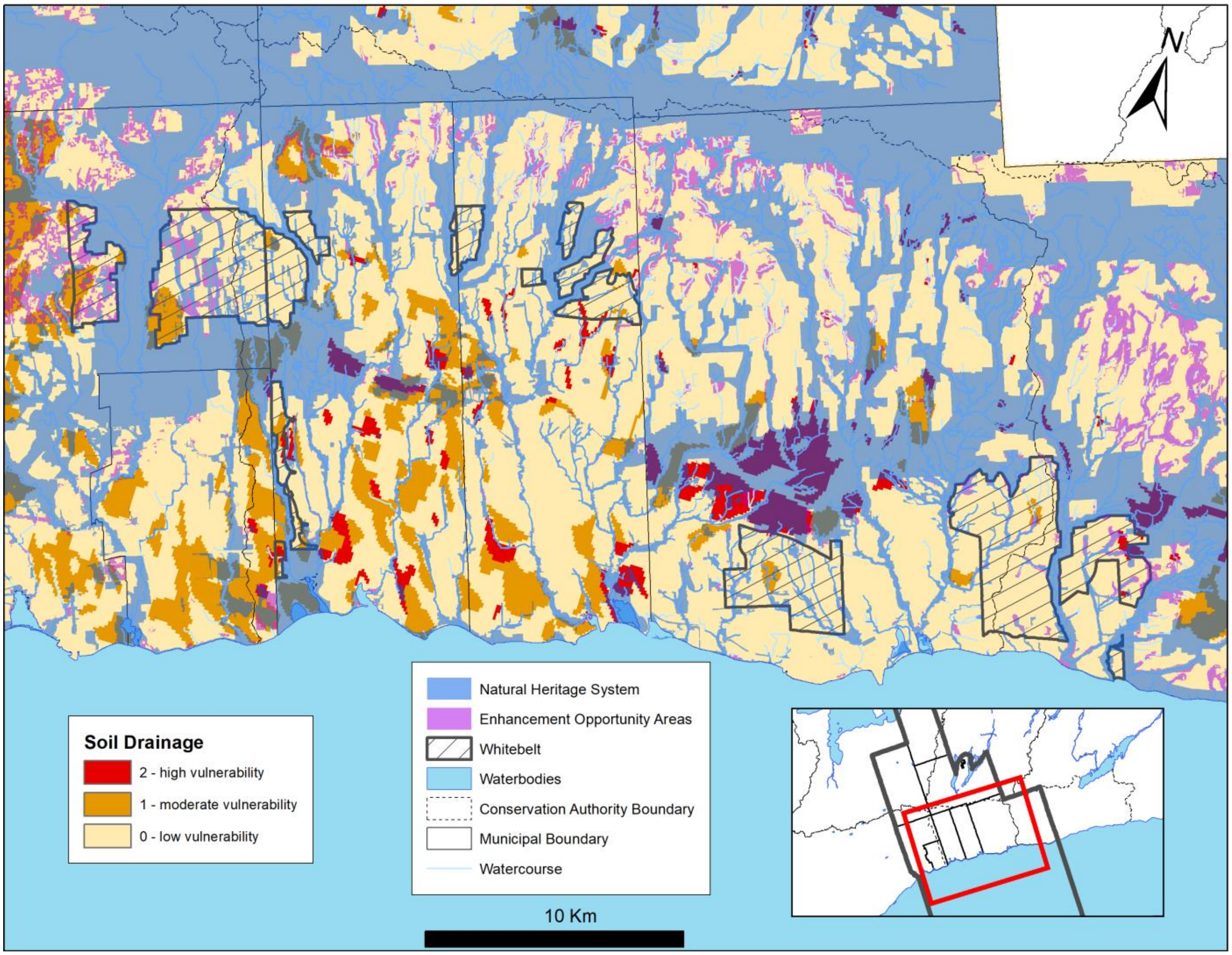

Figure 17. Climate change vulnerability scores for the soil drainage indicator for the Durham Region. Shown are the future buildout areas (whitebelt; hashed lines) alongside the natural heritage system and enhancement opportunity areas.

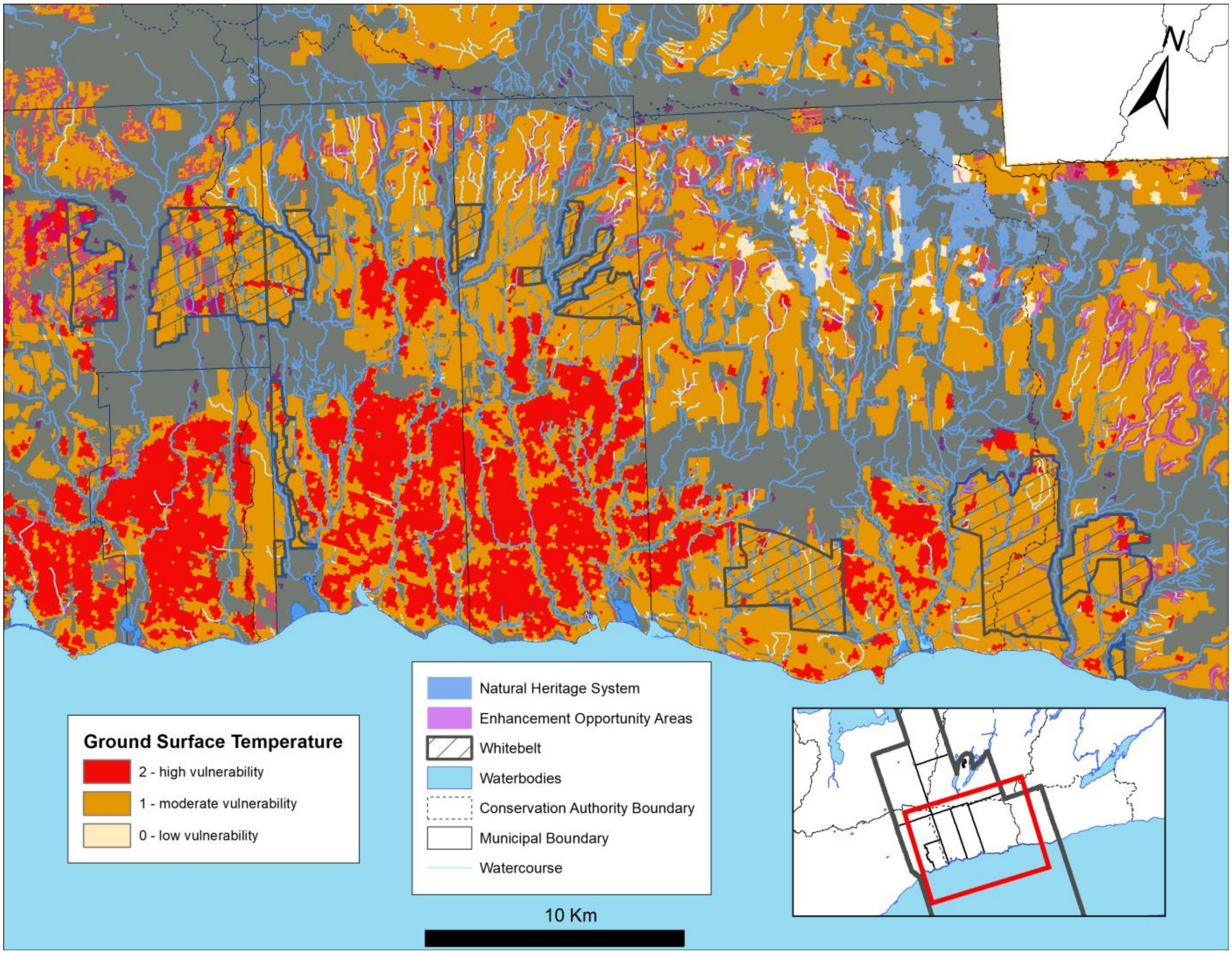

Figure 18. Climate change vulnerability scores for the ground surface temperature indicator for the Durham Region. Shown are the future buildout areas (whitebelt; hashed lines) alongside the natural heritage system and enhancement opportunity areas.

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