UNIVERSITY OF WATERLOO

COMPARISON OF METHODS FOR MAPPING SPATIAL PATTERN OF SETTLEMENTS

GEOG 481 – Individual Section

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Contents

1.0 Introduction

1.2 Morphological Measures

Different delineation methods are useful for achieving different planning goals, such as preserving ecological paths, improving access to infrastructures, maintaining ventilation of urban center, among others (Tannier, 2013). Another approach to delineating the boundary of an urban area is to use morphological measures, which uses the shape of elements such as streets, buildings and signs to delineate the boundary of a settlement area (Adel, 2002). In Adel's study, the distribution and the density of census tracts are used as morphological factors for urban boundary delineation. The study also implemented another 3 boundary delineation measures. They are population density, household density (density measure) and the layout of the road system (transportation measure). Using the four measures, four boundaries are generated, and the four layers are partly overlapped with each other. According to Adel (2002), the common overlapped area is the undisputed part of the city. For the area with differences, a buffer measure is used to delineate the urban boundary. The low accuracy of the input data is the limitation of the study, and the quality and the availability of data are the determiners of the accuracy of urban boundary.

Morphological methods involving dilation and erosion can also be used to delineate urban growth boundaries (Liang, 2018). After receiving potential urban area from future land use simulation model, the area is used for morphological delineation with dilation and erosion method. The dilation process and erosion process involve a structural element, which has a fixed shape and size. First, the urban area is dilated. As the structural element moves around the urban pixels, it transforms surrounding non-urban pixels to unban pixels, so the urban area is buffered, which refers to the process of dilation. Secondly, after the urban area is dilated, the same structural element moves around the urban pixels for erosion, and the boundary is shrunk with a distance. The dilation method makes the urban boundary less rectangular, and the gaps between urban clusters are filled. The erosion method removes small and isolated urban areas so that the noise of the delineation is reduced.

2.0 Methods

2.1 *Study Area*

Three study areas in Ontario were selected for this project because of both data availability for the region and because of our familiarity with the area. Data for Ontario and Canada is easily obtainable via open data sources, government websites, and research institutions. Our study area focuses on Ontario at three different scales. Southern Ontario in particular has been selected due to its unique urban development patterns. Many settlements in this region are experiencing rapid expansion and development due to a large influx of immigration and the region's growing economy. The Niagara escarpment and greenbelt initiative create physical and manmade barriers to the expansion and form of settlement boundaries in the region. These factors provide a unique perspective on the delineation of the urban-rural boundary.

One of the potential outcomes of this study is the influence of scale on the morphology of urban areas. This means that we want to focus on different areas in Ontario to reach a variety of settlement scales. On a large-scale, the entire southern Ontario region can give us an idea of results when we observe multiple urban regions at once, which may influence the result. Our main study area for this scale will be the tri-city area of Kitchener, Waterloo, and Cambridge (Figure X). Waterloo Region includes larger cities such as Kitchener and small settlements like St. Jacobs and Breslau.

For a medium-scale focus, individual settlement areas will be studied. Rather than including many cities and towns in one classification, we use one settlement as our focus area. This allows us to more accurately determine the characteristics of each individual settlement which may contribute to its definition as an urban area. Different towns in Ontario of various sizes have different characteristics. Smaller towns may lack certain services or transportation networks which are normally indicators of the presence of an urban area. Different cities have different growth patterns and natural characteristics. This means we may need to change our definition of settlement areas depending on the context. This study focuses on London (Figure X) for our individual city analysis due to its isolation as a city and its availability of data.

At the smallest scale, we can observe the rural-urban fringe along urban and suburban settlements. This allows us to focus clearly on the exact boundary between urban and rural areas. Effects at the rural-urban fringe may give us clues to what defines the boundary. The boundary of different settlements will be explored, which allows us to look at a variety of different types of urban fringe, whether it is located by newly constructed suburban subdivision, old housing developments, or in industrial areas and commercial plazas. Each of these land use types has a different land cover profile, so when compared to the land use maps we expect to see different results. It is important to consider the properties of the settlement when determining its boundaries. Markham (Figure X) is a city experiencing rapid suburban development and has plenty of land cover data available, so we will be focusing on this region for our small-scale fringe analysis.

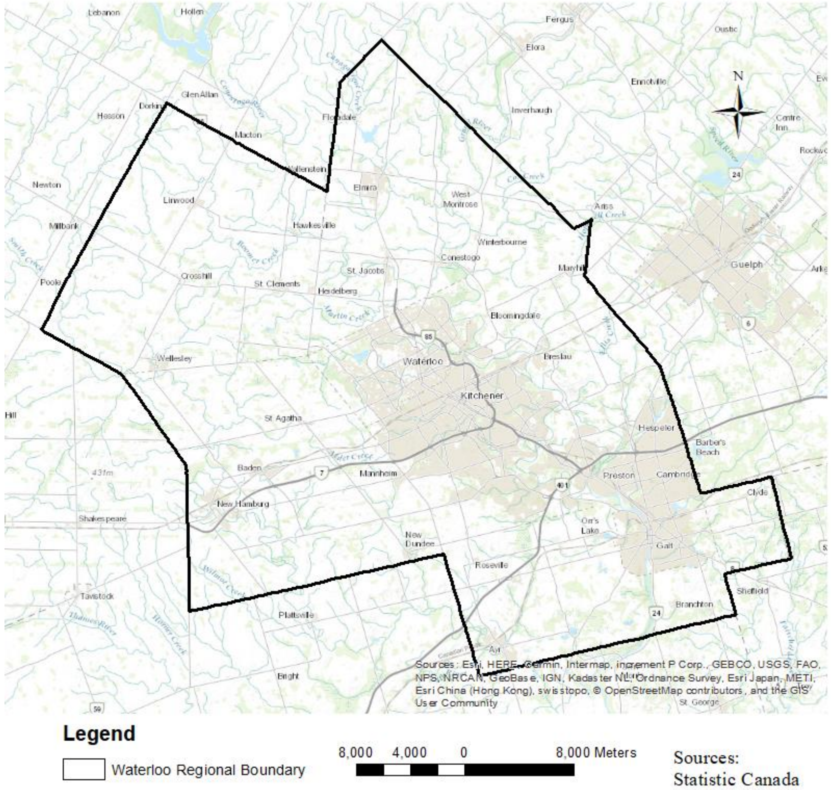

Figure 1: The Study Area of Waterloo Region, Ontario

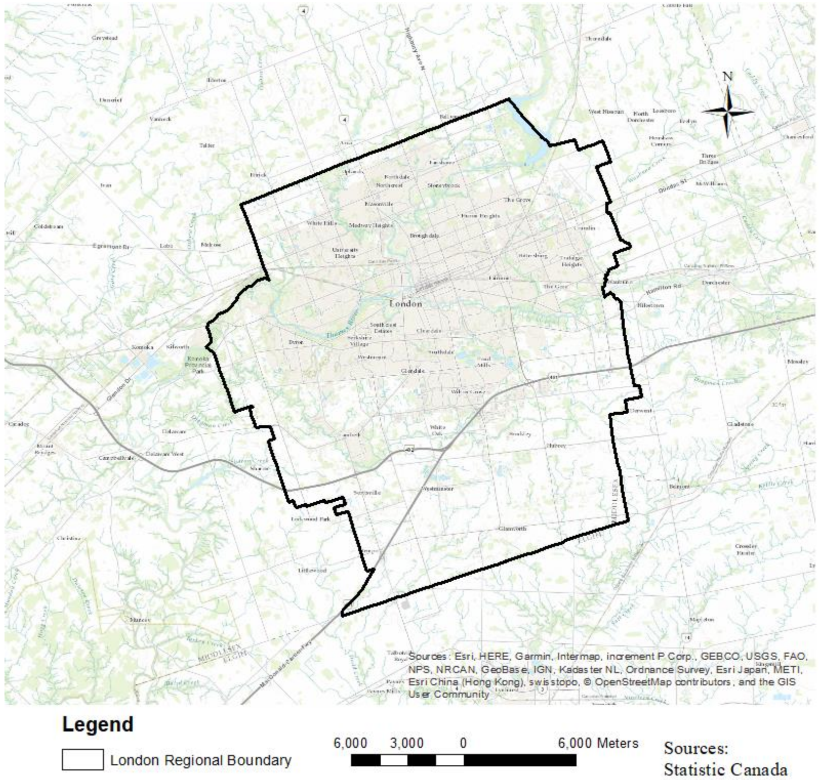

Figure 2: The Study Area of London, Ontario

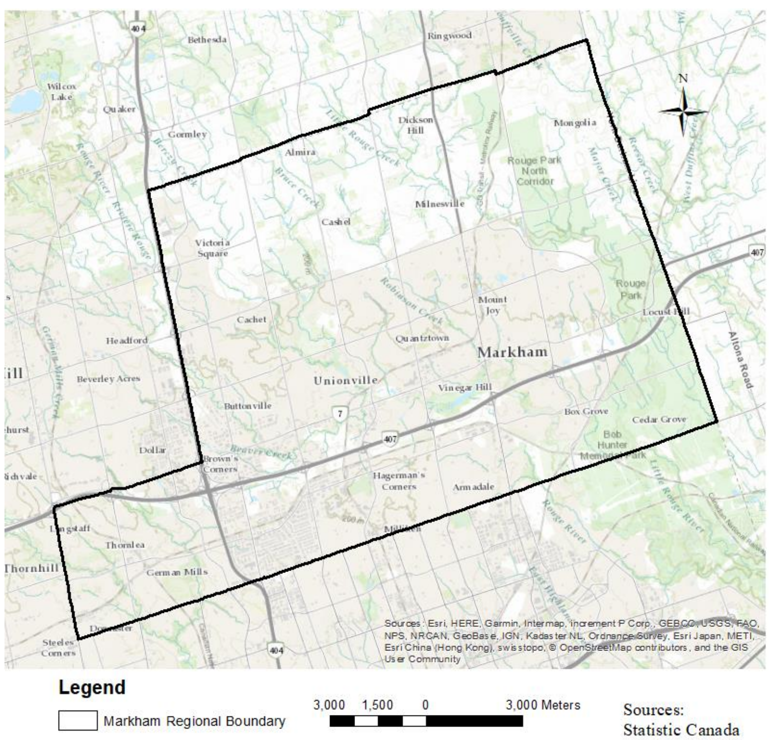

Figure 3: The Study Area of Markham, Ontario

2.3 *Morphological Measures*

Cellular automation (CA) is a morphological method for urban boundary delineation. The procedure of the morphological delineation method is derived from the CA model used in the study of Liang et al. (2018). The CA model uses dilation and erosion as the main geoprocessing operation. To settle the buffer size of dilation and erosion, the distance threshold calculation in the study of Tannier et al. (2013) is used for determining the buffer distance (Figure 6).

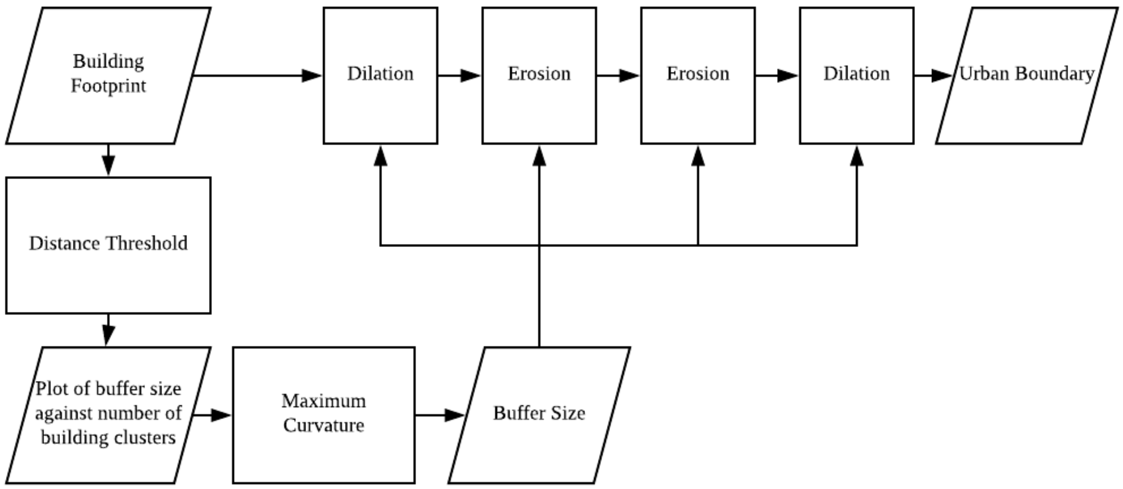

Figure 6: The Data Flow Diagram of Morphological Method

The CA delineation method consists of two main operations, which are the closing operation and the opening operation. The closing operation is performed before the opening operation. In the closing operation, the building footprint layer is dilated with a buffer size calculated with distance threshold method. Erosion comes after dilation. In the erosion step, the edge of the buffered boundary is shrunk with the same distance threshold. By this method, the gap between building footprints is filled (Figure 7). In the opening operation, the erosion method is performed before dilation. As erosion is perform earlier, the small and isolated patches of settlement area are removed (Figure 8).

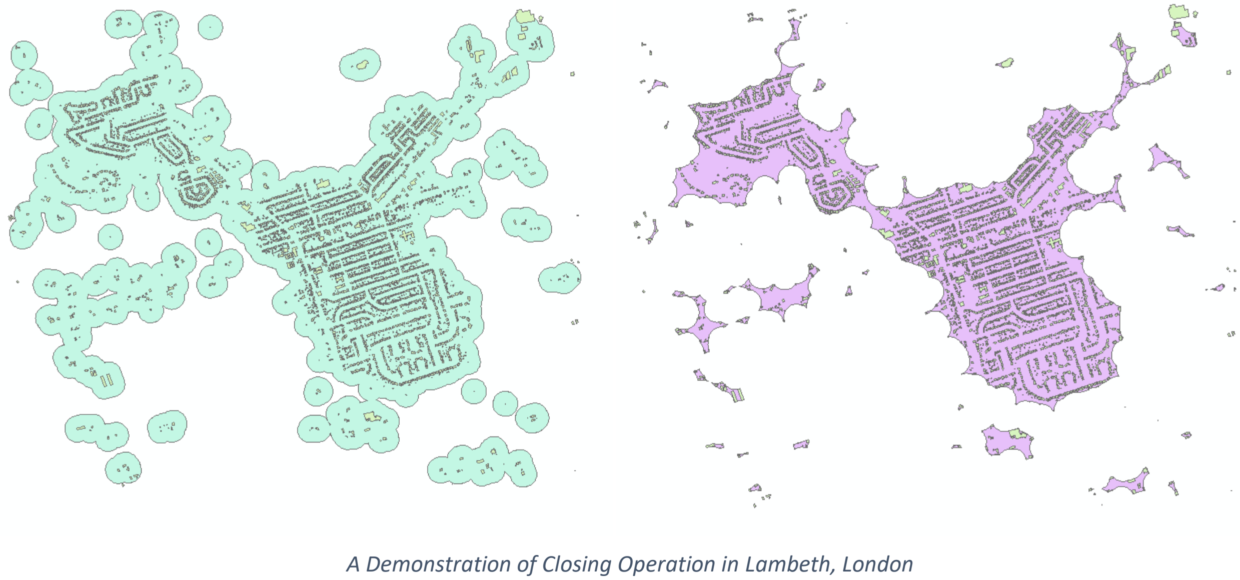

Figure 7: A Demonstration of the Closing Operation in Lambeth, London

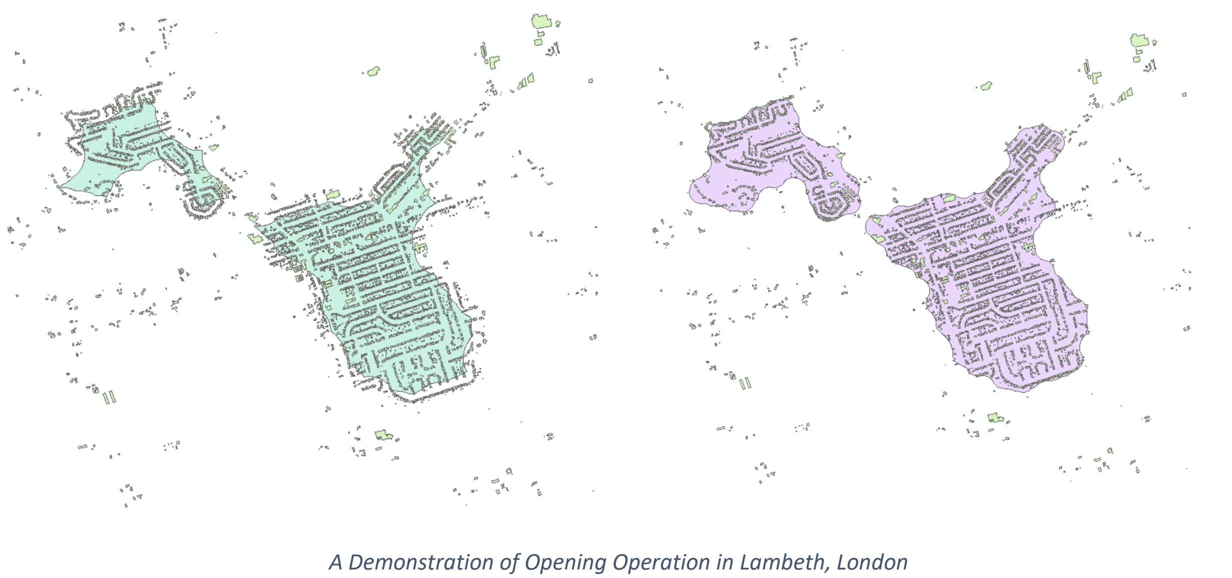

Figure 8: A Demonstration of the Opening Operation in Lambeth, London

The buffer size is derived from a plot where the X axis corresponds to the buffer distance, and the Y axis corresponds to the number of building clusters. As the buffer distance increases, the building footprint polygons merge together, so the number of polygons decreases as the buffer distance increases. The distance threshold is determined by the maximum curvature on the plot. The buffer size is set as the distance threshold. Because the number of polygons drop discretely, the log-log plot is scattered. Therefore, the maximum curvature is at the maximum elbow of the plot.

2.6 *Comparison Methods*

Two different methods of assessing the accuracy of each result were used. The first method compares the generated boundary from each method to 2010 Land Use Categories by Agriculture and Agri-Food Canada. These categories are used to determine areas of impervious surface versus non-impervious surface. The impervious surface is used to approximate the location of urban settlements in each of the study areas by clipping the raster image by the polygon representing each region. Pre-processing of the land use categories raster data was done on this result to ensure compatibility with our results. First, the raster cells representing land use categories were reclassified into two categories, which are impervious surface and non-impervious surface. Impervious surface includes settlement area category and road category. Secondly, the raster was converted to a polygon. Thirdly, the opening method, described earlier in section 2.3, was used to remove outspread roads outside the urban area in the resulting polygon with a distance threshold of 60 meters. The maximum road width of the study areas is around 120 meters, so the distance threshold is set to half of the width to ensure that every road outside the urban area will be removed (Figure 14). The output polygon approximates the urban boundary of each study area and is then used for accuracy assessment.

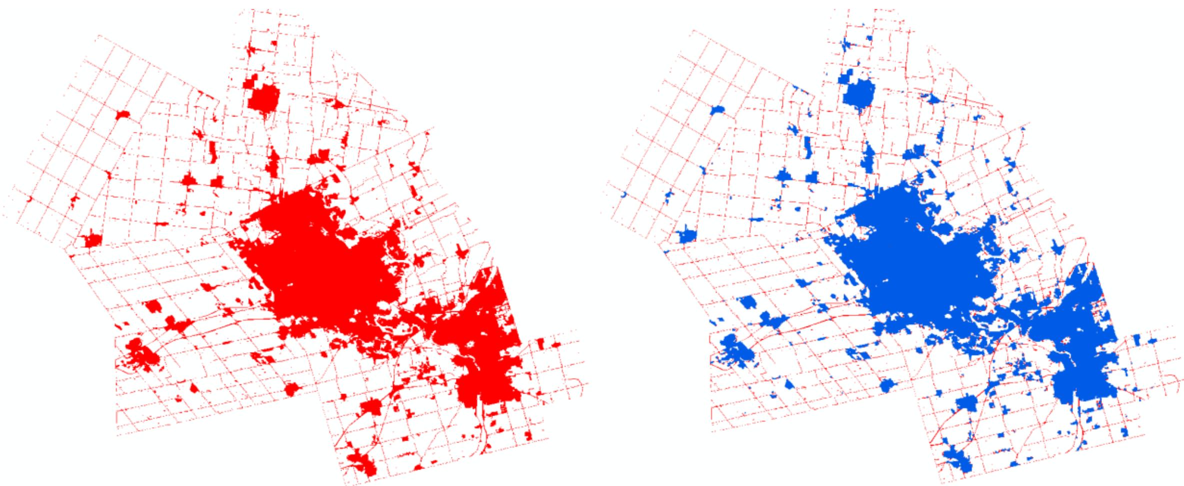

Figure 14: A demonstration of the opening operation performed on Land Use data with 60 m buffer size in Waterloo Region. Layer in red represents the original road category and settlement category. Layer in blue represents the result.

The second method involves creating a manually digitized boundary of each settlement area in our study areas which is based on a protocol for digitization. The protocol is built based on the Good Practice Guidance for Land Use, Land-Use Change and Forestry (LULUCF) and National Inventory Report Canada 2018 (NIR Canada, 2018). There are four elements to include in the urban boundary which are 1) developed land, which includes urban infrastructure, asphalt ground, and cement structures; 2) transportation infrastructure, which consists of roads, traffic facilities, and stations; 3) human settlements, which are defined as all buildings that are clustered together, forming a neighborhood or community; and 4) urban trees, which consist of three forms: street trees, vegetation in public and private gardens, and vegetation in city parks. According to the LULUCF guidance provided by Penman et al. (2003), the digitization of settlement areas includes developed land, transportation infrastructure, and different-sized human settlements. As the guideline assumes that urban trees are functionally and administratively associated to cities and towns, the digitized settlement area should include all forms of urban tree formations, which includes street trees, vegetation in public and private gardens, and vegetation in city parks. Using these criteria, a manually digitized polygon representing the boundary of each study area was created using the ArcGIS editor feature. USGS Glovis 2011 imagery was used as reference for the creation of these polygons.

Results from each of the four delineation methods were merged to compare the accuracy of combinations of results. For each study area, each combination of morphological measures, road networks, and land use results were combined using the *Merge* and *Dissolve* tools in ArcGIS. Combinations of each result are compared to the validation boundaries, which include both the land-use cover map and the manually digitized boundary, to obtain the accuracy result. Results from the population and employment density were omitted from this step and merged later due to the low resolution and accuracy of the results produced by this method (see sections 3.1 and 4.0).

To calculate the classification accuracy, a formula is used for quantifying the match level between produced boundary and validation boundary (Formula 1, Figure 15). The overlapping area between the produced boundary and validation boundary is used as the numerator of the division. The merged area of produced boundary and validation boundary is used as the denominator of the division. Therefore, both missing areas and producing extra areas will decrease the accuracy, and only two boundaries that are completely matched will achieve 100% accuracy.

$$Accuracy = \frac{Matched\ Area}{Matched\ Area + Unmatched\ Area} * 100\%$$

Formula 1: Classification Accuracy Calculation

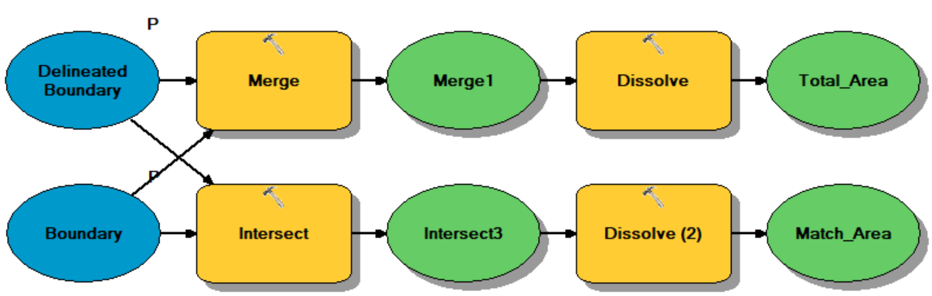

Figure 15: ArcGIS model used to calculate accuracy of results

The accuracy of each method and combination of methods is added to an error matrix which is used to determine sources of accuracy and errors. Six error matrices were created; three for the results of each study area compared to the land use polygon, and three for the results of each study area compared to the manually digitized boundary. The most accurate result in each error matrix was then joined with the result obtained from the population and employment density method (2.2) to determine if it increases the accuracy of the result by filling gaps or more closely matching the settlement boundary. Results were combined by using the same *Merge* and *Dissolve* tools as mentioned previously. The accuracy value obtained from this result was added below the error matrix to compare the value to the rest of the results.

3.0 Results

3.2 *Morphological Measures*

To determine the distance threshold for Cellular Automation, the building footprints are dilated with a series of distance, and then the corresponding number of building clusters are recorded. The data are shown in the plots below (Figure 17). According to the plots, the number of building clusters decreases significantly at the distance around 30 m, which indicates that most of the building footprints are merged together with a buffer distance of 30 m. Therefore, the gap distance between buildings are usually within 60 m. After the large drop, number of building clusters are reduced slowly as the buffer size increases, which indicates that shape and topology of building clusters are stabilized. Moreover, the shape of plots of different study area is similar. The plots are all drop significantly at the distance of 30 m, and they are all become stable after the drop around 30 m, which demonstrates that the building pattern of the three study areas is similar. Therefore, it is effective to use a union distance threshold for the three study areas.

The distance threshold is set to 35 m, which is around the maximum curvature point in the plots of buffer size against the number of building clusters, where the number of building clusters has been stabilized (Figure 18).

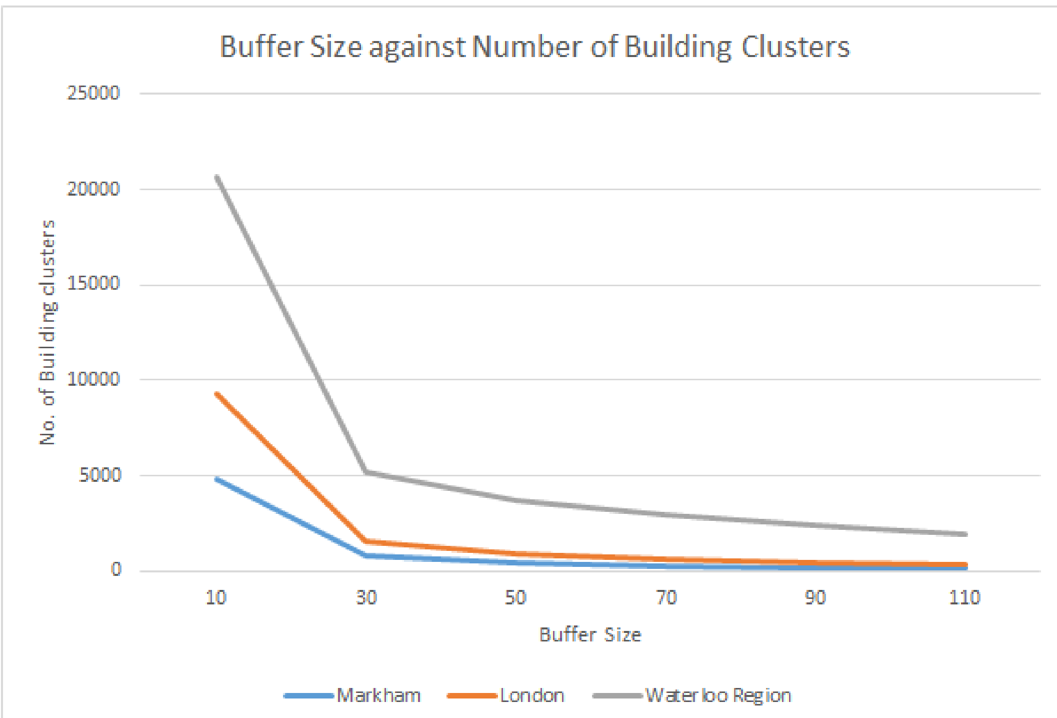

Figure 17: The Plot of Buffer Size against Number of Building Clusters (20 m Interval)

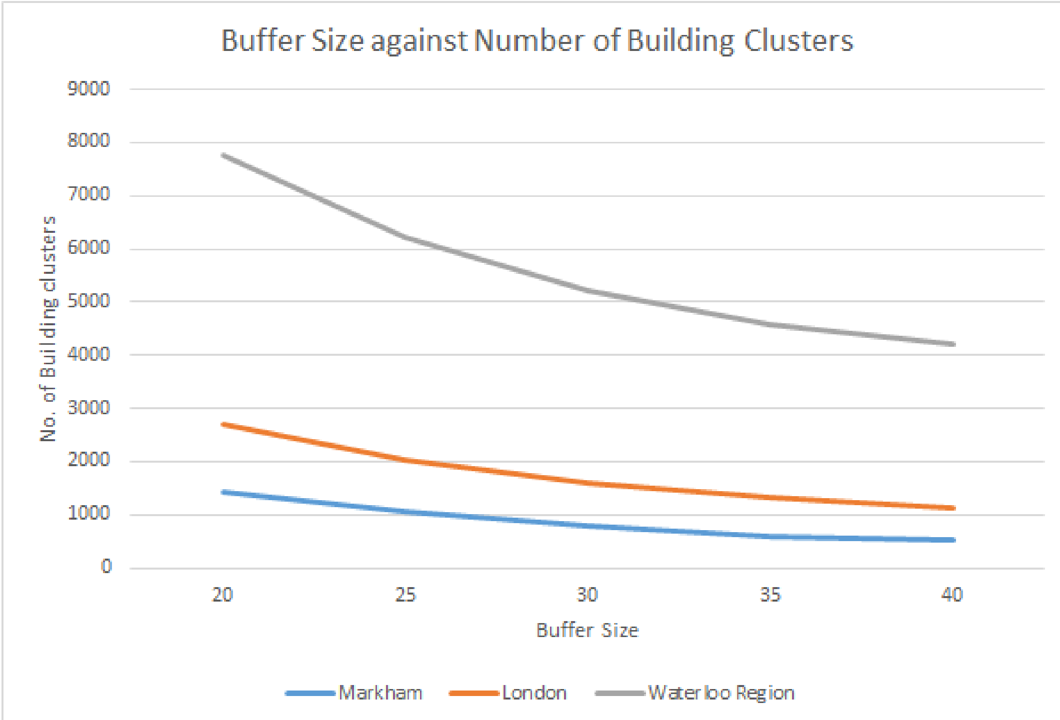

Figure 18: The Plot of Buffer Size against Number of Building Clusters (5 m Interval)

Using the distance threshold, Cellular Automation is performed using the building footprints data in the three study areas. The generated boundaries using morphological measures are shown in Figure 29, Figure 30 and Figure 31 in Appendix B.

According to the generated maps, in all the three study areas, the gaps between buildings within an independent neighborhood are merged together effectively, and the small and independent buildings that do not belong to a neighborhood are removed from the result. Therefore, it proves that opening and closing operations are effective for generating settlement boundaries. However, in the generated maps, the gaps between neighborhoods, which may represent roads, urban trees and developed lands, are not filled effectively, so the neighborhoods are scattered on the maps instead of being merged. Moreover, distortions in shape happen on the small-size neighborhoods (Figure 19), which is caused by the opening operation. The erosion method in opening operation over-shrinks the boundary of small-size neighborhoods, so the generated boundaries lose their original sharp shape.

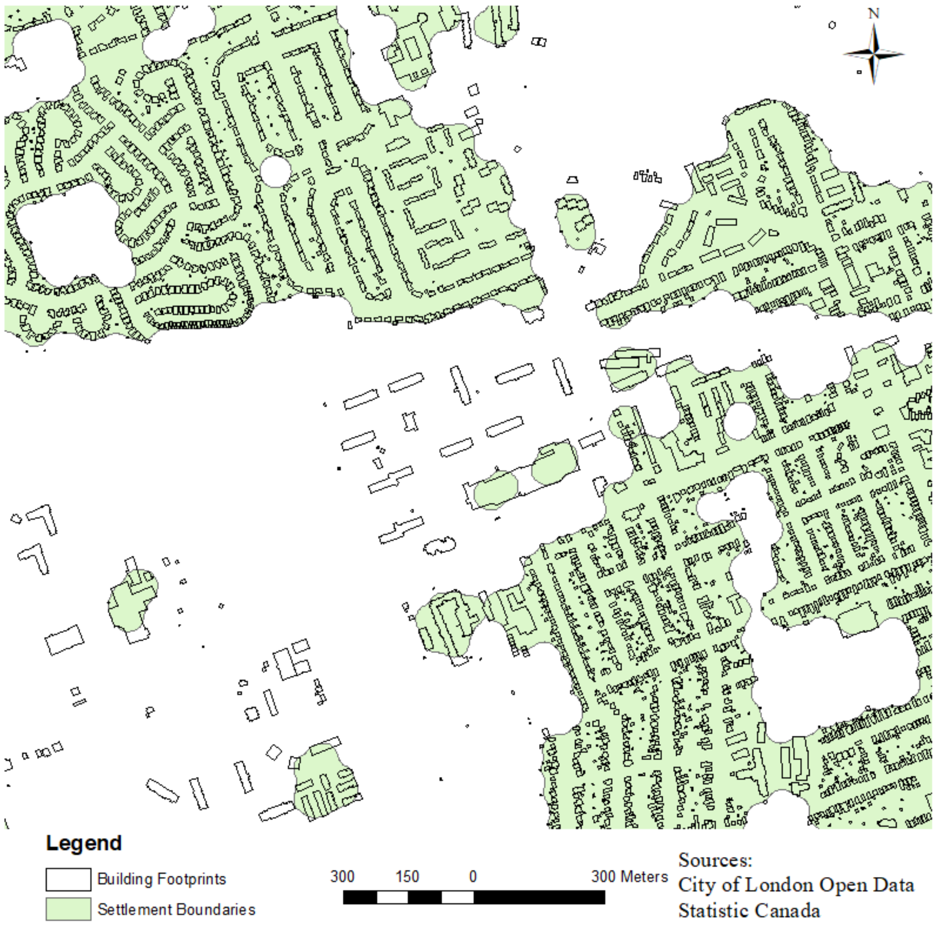

Figure 19: An Example of Distortion in a Neighborhood in City of London

The spatial pattern of settlement boundaries in Markham and London are similar, but they are different from the spatial pattern of settlement boundaries in Waterloo Region. In Markham and London, most of the building clusters are in urban area and little are outside urban area. However, in Waterloo Region, some building clusters are not located in the urban zone, and two major building clusters are outside the urban area, which are Town of Elmira and Town of New Hamburg. Therefore, the spatial pattern of a single city is different from a regional municipality.

The spatial pattern of boundaries using morphological measures is different from other delineation methods. On the one hand, the shape of the morphological boundaries is more fragmented than other methods, which is because the area does not include roads and urban trees. On the other hand, the areas are smaller because the boundaries snap to the outline of building footprints and do not include other area outside the building clusters.

3.5 *Accuracy Assessment*

The three error matrices below (Figures 27 and 28) show the results of our accuracy analysis. In each matrix, TN represents the accuracy of the road density method, LC represents the accuracy of the land use method, and MM represents the accuracy of the morphological measures method. Green cells represent the accuracy of individual methods, blue cells represent the accuracy of combined pairs of methods, and the orange cell represents the accuracy of all three combined methods. The additional dark orange cell below each table represents the accuracy of the most accurate combination of methods when merged with the Population and Employment Density result.

Waterloo	TN	LC	MM	
TN	65.80%			
LC	70.93%	60.15%		
MM	68.85%	67.23%	42.68%	
				72.24%
				70.58%
Markham	**TN**	**LC**	**MM**	
TN	79.11%			
LC	79.99%	65.67%		
MM	79.58%	73.02%	47.47%	
				80.09%
				80.11%
London	**TN**	**LC**	**MM**	
TN	71.81%			
LC	74.57%	70.76%		
MM	72.86%	72.35%	49.40%	
				74.80%
				74.30%

Figure 27: Error Matrix comparing results of each region to a 2010 land-use classification by Agriculture and Agri-Food Canada

Waterloo	TN	LC	MM	
TN	73.31%			
LC	77.84%	65.06%		
MM	75.77%	71.85%	45.74%	
				78.39%
				76.14%
Markham	**TN**	**LC**	**MM**	
TN	90.01%			
LC	90.91%	64.17%		
MM	90.35%	72.71%	46.08%	
				90.85%
				90.93%
London	**TN**	**LC**	**MM**	
TN	79.70%			
LC	82.44%	73.03%		
MM	80.68%	74.72%	50.20%	
				82.55%
				82.70%

Figure 28: Error Matrix comparing results of each region to manually digitized boundary

Overall accuracy was generally highest in Markham and lowest in Waterloo Region. We believe accuracy was highest in Markham region due to us only requiring the delineation of its outer border. The south and west borders of Markham are connected to the City of Toronto and the rest of York Region which consists of mainly built-up areas. Our results outline this inner border with almost perfect accuracy, so the only source of error comes from the urban-rural fringe of Markham, which is only on its north and east edges. In contrast, when delineating the boundary for the City of London, we must ensure accuracy of the border completely around the urban center. Waterloo is least accurate because of its complex urban form. The region is made up of three large urban areas (Waterloo, Kitchener, and Cambridge) which have expanded into one another and have poorly defined physical borders and boundaries. Additionally, the region contains many smaller settlements which must also be properly delineated. Errors occur when selecting parameters for the larger urban areas which are not ideally suited for delineation of the forms of the smaller towns.

Generally, the accuracy of the generated boundary was highest when using a combination of multiple methods. In all but one of the error matrices, the combination of all three primary methods used provided the highest accuracy result. In no case was a single method more accurate than all the pairs of methods. There are several possible explanations to this. Merging the polygons produced by each method tends to fill holes and gaps that exist in the individual polygons, which generally produces a more accurate result. Certain methods are unable to capture features within their boundaries. For example, a cluster of buildings on the side of a single road is detected by the morphological measures approach and the land use approach, but not by the road network method. This discrepancy is removed when the road networks polygon is merged with either of the other polygons.

There seems to be no clear evidence that accuracy is increased when including population and employment density (PED) in the accuracy assessment. Regardless of the region and whether there was an increase or decrease in accuracy, the difference was marginal, usually by only a fraction of one percent. When observing the result polygons before and after the addition of the PED result, most of the original polygon had already covered most of the census subdivisions in the city boundary. We expect this to happen because the combination of morphological measures, road networks, and land use results already approximate the urban settlement boundary to a degree of accuracy that is significantly higher than the boundary determined based on existing subdivisions. Results based on PED are severely limited based on the form of the statistical division which is almost always larger and less discrete than the more natural boundaries generated by the other three methods.

4.0 Discussion

4.1 *Limitations*

The shape of the generated boundaries and the size of generated boundaries are different from each other because they are acquired from different sources. For the boundary generated with population and employment density, its outline matches the outline of dissemination area, which is manually delineated by humans, so the boundary may be subjective. The boundary will never be more precise than the predetermined dissemination areas. Though it provides a good idea of settlements but will always lack in accuracy. The generated urban boundary is optimal to reflect the aggregation of population and employment. For the boundary generated from morphological measures, it is originated from building footprints data, so the generated boundary is effective for representing settlement area, but it ignores roads, urban trees and some developed lands. The boundary derived from road density is generated from road polyline data. Therefore, it is effective for representing the distribution and density of roads in urban area. For the boundary generated from land use method, the data is originated from satellite imagery. The area represents impervious surface effectively. In summary, every generated boundary has its own representation, and the four methods delineate the urban boundary in different perspectives.

The temporal resolution may have had an effect overall on the outcome of the land-use classification as well as on the overall accuracy of this research. There have been structural differences between 2018 and 2011, more recent imagery would have been preferred. Unfortunately, the last available date for data on the USGS Glovis website for our study areas was from Summer of 2011. There was also some difficulty with cost constraints as it was difficult for us to find quality satellite imagery that was freely available. There was also a potential for the use of high resolution data however that would have been costly for us to obtain.

In terms of comparing each of the methods to a land-cover classification, there are some potential issues that arise when using this metric for assessing the accuracy of delineated settlement boundaries. The binary classification assumes that urban areas contain only impervious features (roads and buildings). However, this is inaccurate because urban areas are often diverse and may contain waterbodies, street trees or other natural features. The land use comparison method contains some innate inaccuracy because land use does not correspond exactly to the boundary of settlement areas.

There is a degree of human bias when considering the comparisons of our results to the manually digitized boundary. The quality of the imagery could have influenced the comparison boundary that was manually digitized since it is was difficult to visual the characteristics of individual features at certain scales as the Landsat imagery that was utilized was relatively coarse as opposed to other multispectral data such as SPOT imagery which has a 10 metre resolution (Palko et al., 1995). Since the digitization is made manually, the accuracy of the comparison cannot be better than human results. Unfortunately, this data was unavailable for our chosen study areas and could have changed the overall outcomes of our research to some degree. Some features may be ambiguous or fall into multiple categories and it is up to the discretion of the individual performing the digitization to determine what to include and exclude, which may result in some human error.

4.2 *Broader Implications*

Using additional, more detailed data sets can allow much more accurate results to be obtained with implications that are much truer to real-world scenarios. Much of the project is limited by the accessibility of data and could be improved upon by employing more advanced data collecting methods. For the road network method, data detailing how much traffic is present on any given road could greatly increase the accuracy of our result by assigning different weights to different types of roads. This method was originally planned to use combinations of different transportation networks and assigning weights to each one based on the population that each node in a network is able to service. Including human dynamics, involving recording how many people pass through or visit a certain area can be another useful metric when exploring this method further (Humeres & Samaniego, 2017).

The delineation methods used in the study can be effectively applied to other cities in Ontario and other regions outside Ontario. The four delineation methods do not require scarce data or high computing power. The operations can be conducted in personal PCs, and all the required data is assessable online or in a local library. On the other hand, the delineation methods can be adjusted so that the methods can be applied to other states or regions. The input parameters of the methods are pre-determined and can be adjusted. For example, the distance threshold used in the morphological method is set to 35 m, which is suitable for all the three study areas, but the distance threshold may not suitable for delineating the boundaries of other cities in Ontario or cities outside Ontario. However, the same procedures to determine distance threshold can be replicated in other areas. Therefore, the delineation method can be applied in other regions effectively.

5.0 Conclusion

To delineate the urban boundary of Waterloo Region, the City of London and the City of Markham, four methods for delineation are implemented. Population and employment density, morphological measures, road network and land use type are used as factors for delineation. Using the four methods, four boundaries are generated. The four boundaries are compared with each other both in area and spatial pattern, and they are either used individually or merged in different combinations for comparison. The settlement area extracted from Land Use 2010 Agriculture and Agri-Food Canada and a manually digitized boundary are used as boundaries of validation. The classification accuracy is calculated to assess the match level between the produced boundaries and the validation boundaries. The result indicates that the generated boundaries varies in area and spatial pattern, and the classification accuracy tends to increase as the boundaries are merged.

In the accuracy assessment session, the boundaries are merged for comparison, which may be rough and ineffective. As the generated boundaries have different representations, future researches on effective integration of different boundaries are needed. Moreover, the boundary validation is limited to comparing with existing land use data and manually digitized boundary. Future studies can be focus on how to validate the efficacy of the generated boundaries. Finally, the urban boundary of a city is changing so that the data for delineation may be out-of-date. Future studies may integrate existing data with urban growth prediction to generate up-to-date urban boundaries.

Appendix B - Maps and Additional Figures

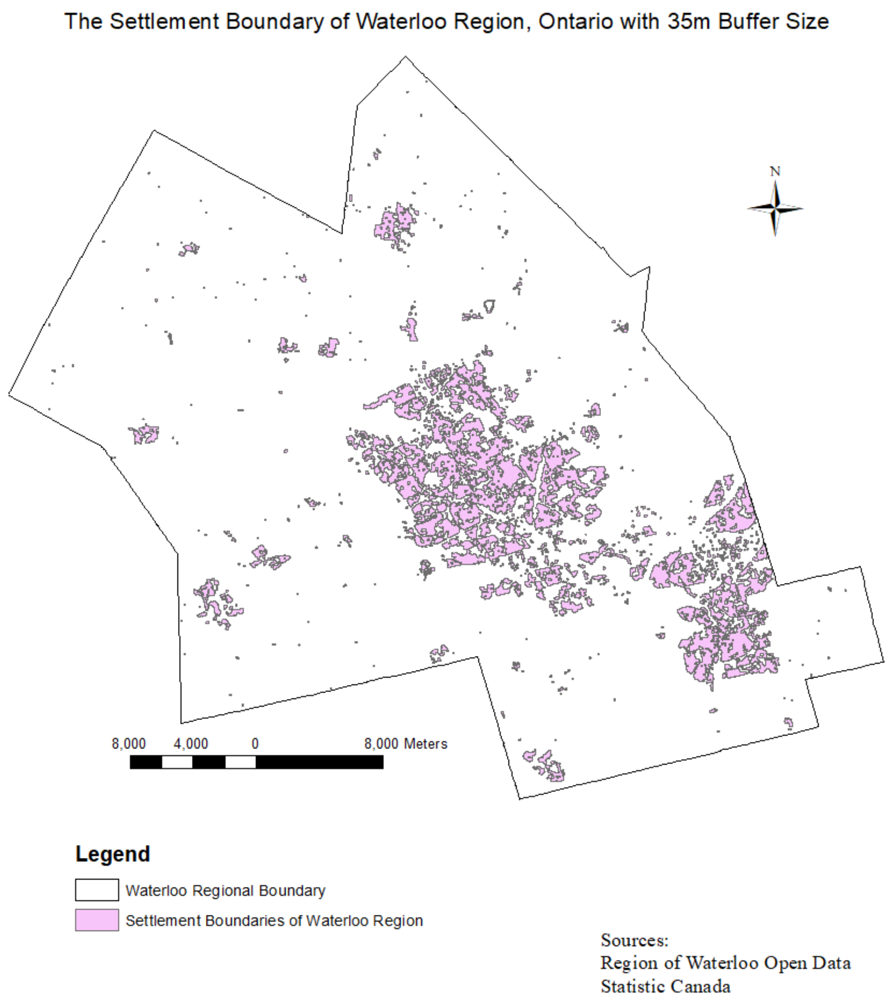

Figure 29: The Settlement Boundary of Waterloo Region, Ontario with 35m Buffer Size

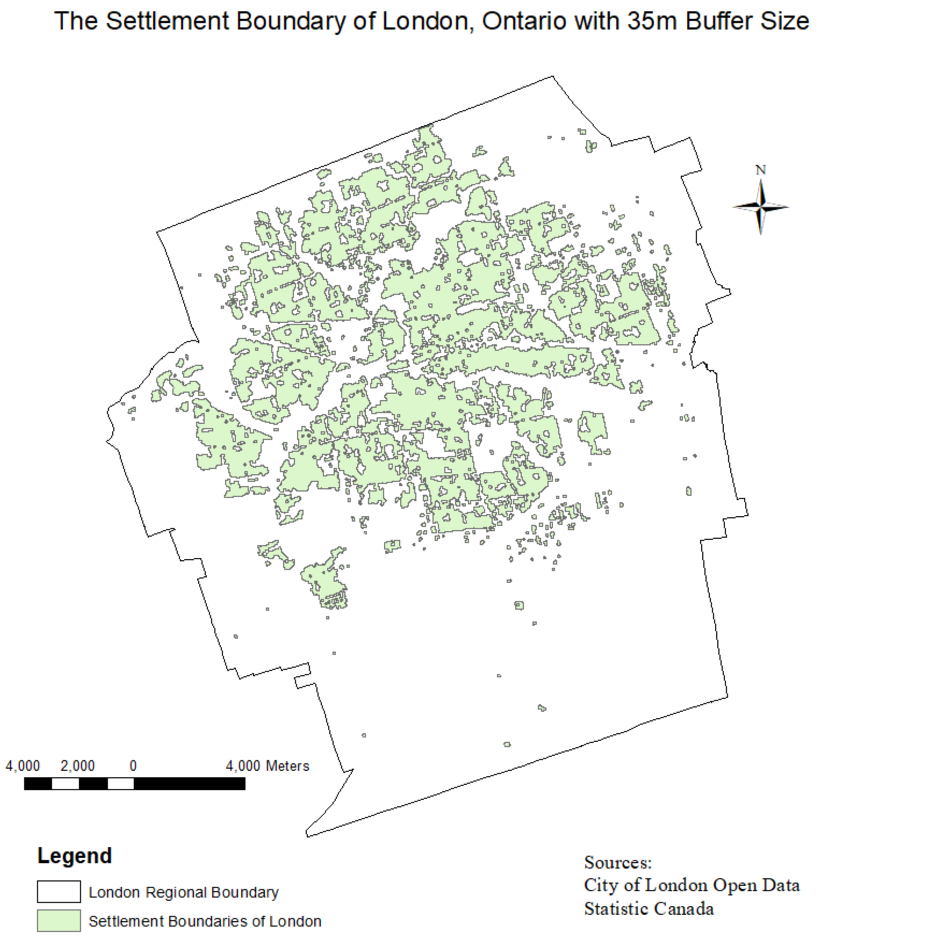

Figure 30: The Settlement Boundary of London, Ontario with 35m Buffer Size

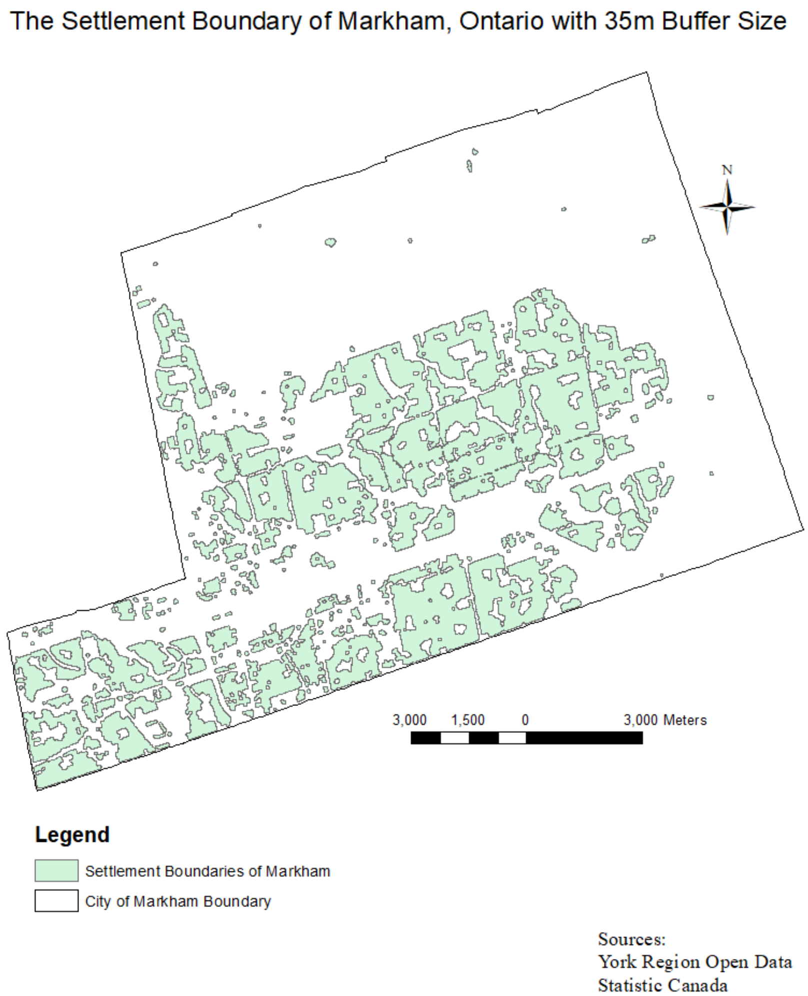

Figure 31: The Settlement Boundary of Markham, Ontario with 35m Buffer Size

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