The Weight of Cities: A Case Study of the Region of Waterloo

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The global population is growing at a fast rate, which is resulting in the growth of urban areas worldwide. With the additional 2.1 billion people living in cities by 2050, the urban population will reach 6.5 billion by this year. As a result of this growth and change in society's affluence, global material consumption will increase from 50 billion tonnes in 2015 to 90 billion tonnes in 2050. Construction materials are one of the major contributors to material consumption in cities. These materials are continuously used to build city stocks, such as buildings and infrastructure to provide services for the growing urban population. Accounting for the current and future material stocks helps policy makers to have an understanding of the quantity of materials that is embedded in cities and how much is required to provide for the future demand. This thesis investigates the quantity of construction materials in residential, non-residential building, road, and sidewalk stocks from 2003 to 2018 in the cities of Kitchener and Waterloo, located in the fastest growing urban area in Canada. The methodology used for this research is in two parts: a bottom-up retrospective approach to account for the quantity of materials from 2003 to 2018, and a mix of demand-driven and bottom-up approaches in the same group of stocks to project the required materials by 2041. The results of this study indicate that the quantity of construction materials in Kitchener and Waterloo has grown from 53Mt in 2003 to 65Mt in 2018, with 24Mt in Waterloo and 41Mt in Kitchener. Material use is estimated to be 160t/capita in Waterloo and a 171t/capita in Kitchener in the year 2018. Based on the growth of population in these cities it is estimated that by 2041 an additional 12Mt of materials will be added to Kitchener and Waterloo's building and road stocks. This research provides insight for decision makers at the city level to implement more sustainable resource and waste management strategies in the buildings and construction sector.

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List of Abbreviation

E-BAMB – Existing Buildings as Material Banks

FA – Floor Area

GDP – Gross Domestic Production

GFA – Gross Floor Area

GHG – Greenhouse Gas

GIS – Geographical Information Systems

HL – Hot Laid

KW – Kitchener Waterloo

MF – Material Footprint

MI – Material Intensity

MS – Material Stock

MSA – Material Stock Accounting

NAS – Net Addition to Stocks

PCC – Portland Cement Concrete

PQI - Pavement Quality Index

RAP – Reclaimed Asphalt Pavement

SDG – Sustainable Development Goal

SP – Super Pave

Chapter 1: Introduction

1.1 Background

The growing global population is turning into a universal concern. The World Population Prospects report states that by 2050 an additional 2.1 billion people will be added to the 7.7 billion global population reported in 2019 (United Nations, 2019). These predictions show that by 2050 around 6.5 billion people of the 9.8 billion global population will be residing in cities, whereas in 2015 where the population was recorded to be 7.3 billion, only 4 billion people lived in urban areas. The population prospects indicate a rise from the 55% urban population in 2015 to 66% in 2050.

As the urban population grows, material use in cities increases as well. Material use is associated with different environmental stresses such as waste production, greenhouse gas (GHG) emissions, air pollution, and water pollution (Schandl et al., 2016). Cities are responsible for more than 70% of the global GHG emissions, coming mainly from buildings, infrastructure, and transportation systems as the mains sources of emission (Davoudi and Sturzaker, 2017; United Nations, 2018). Cities also generate around 80% of the global GDP; to be more specific, among more than 4500 cities worldwide, only 600 of these cities are responsible for 60% of the global GDP (IRP, 2013).

Construction activities are inseparable from cities. Infrastructure is constantly being constructed and maintained in cities in order to provide for the growing urban population. Therefore, there is always an inevitable material use in cities in the construction sector. Around 60% of the infrastructures required to provide services, such as accommodation and transportation, for the population in 2050 in urban areas has not been built yet. Therefore, the number of construction activities in cities is predicted to increase (IRP, 2013). These infrastructures include dwelling units for the growing population, transit facilities, sewage and water systems to name a few.

Since cities are the biggest material consumers and produce the largest contribution to GDP, they indicate a great point of focus in order to decouple economic growth from resource use. Resource decoupling means decreasing the use of materials per unit of GDP (IRP, 2011). Indicators such as resource productivity, which is the total materials used in relation to the Gross Domestic Production (GDP) in urban areas, and Material Footprint (MF) are developed to assess resource decoupling in different nations. However, some of these indicators seem to not provide completely accurate information due to the method they are quantified which results in the loss of some information. Therefore, in some cases, it is falsely understood that decoupling is happening while the trade and domestic extraction data proves otherwise (Wiedmann et al., 2015). It is beneficial for municipalities to have a vision of the material flows and stocks of their cities for them to first understand their material consumption rate and then be able to implement feasible decoupling strategies, such as decreasing virgin material use by increasing the rate of recycling, improving maintenance processes, and reducing the production of construction waste (Pao and Chen, 2019).

Quantifying the flows and stocks of materials in urban areas has been of interest to scholars around the world. An example of work in the field of material flows and stock accounting is “The Weight of Nations” report conducted in 2000 (World Resource Institute, 2000). In this report, the input and output flows of a wide range of materials were quantified using indicators such as Total Material Required (TMR), Domestic Processed Output (DPO), and Total Domestic Output (TDO) for five nations: Austria, Germany, The Netherlands, Japan, and The United States. They were able to estimate the Net Addition to Stocks (NAS) by calculating the difference between inflows and outflows (World Resource Institute, 2000). Some of these indicators have proven to be inadequate for quantification of inflows and outflows at the country level since this report was published. A summary of a number of indicators used in this report and a short description for each indicator is provided in Table 1. A representation of the indicators and material flow methodology used in this report is presented in Figure 1.

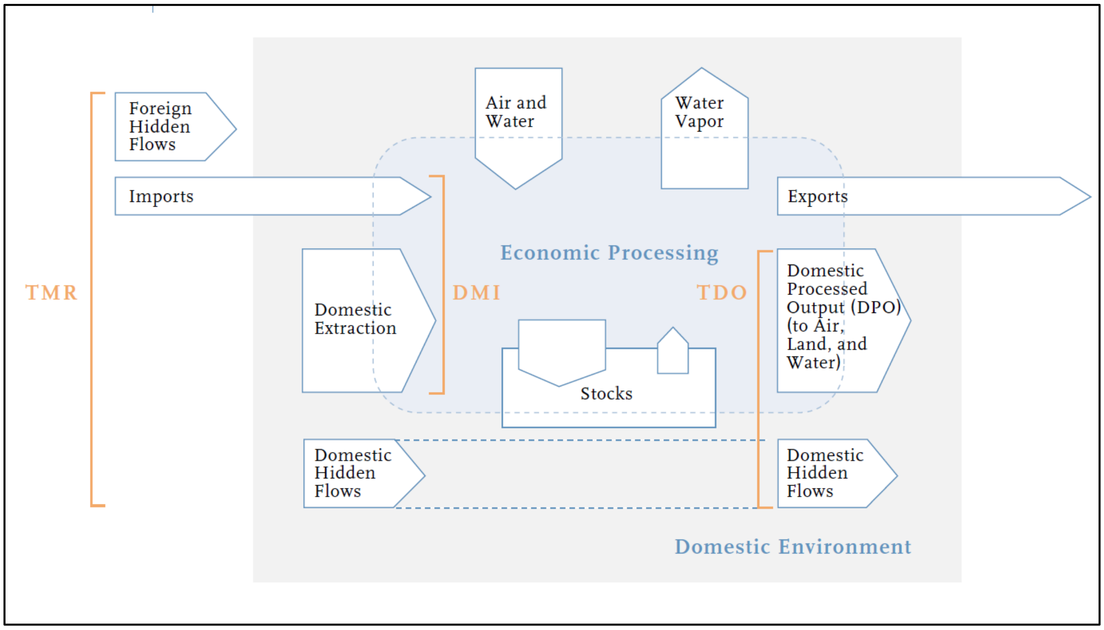

Figure 1. Schematic Representation of the Material Flows – TMR (Total Material Required), DMI (Direct Material Input), TDO (Total Domestic Output) (World Resource Institute, 2000)

Table 1. A Number of the Main Indicators Used in “The Weight of Nations” Report (World Resource Institute, 2000)

Indicator	**Explanation**
TMR (Total Material Requirement)	TMR is calculated from the sum of direct material input, domestic hidden flows, and foreign hidden flows. This indicator measures the total quantity of primary resources required for a production process.
DMI (Direct Material Input)	DMI is the total domestic extraction in addition to the quantity of imports. This indicator measures the input of materials from the environment or other countries in the domestic economy. This indicator also represents the material scale of the economy.
NAS (Net Addition to Stocks)	NAS equals the difference between direct material input and the sum of domestic processed output with the quantity of exports. This indicator presents the quantity of new material used in the system. It is usually calculated indirectly to balance the input and output flows.
TDO (Total Domestic Output)	TDO equals to the domestic processed output plus the domestic hidden flows. This indicator shows both the direct and indirect quantity of outputs caused by human activities to the domestic environment
DPO (Domestic Processed Output)	DPO is calculated from deducting the total of net addition to stocks and the quantity of exports from direct material input. This indicator represents the quantity of materials that are both extracted domestically and exported from other countries. These flows take place at all stages of the production-consumption chain

Following “The Weight of Nations” report (2000), in the field of quantifying material flows, Schandl et al. (2016) worked on measuring the global material flows of biomass, fossil fuels, metal ores, and non-metallic minerals over a 40-year time period by studying extraction and trade databases published by different countries (Schandl et al., 2016). The results of their study showed that the built environment accounts for the largest share of global material use. Non-metallic minerals, which are mostly used for construction purposes, have the fastest growth rate among groups of materials, including fossil fuels, biomass, and metal ores. (Schandl et al., 2016). More than 70% of the material flows in cities are either directly or indirectly related to the construction sector (Ferrão and Fernández, 2013). If the rate of material consumption in cities does not decrease, cities would face serious issues regarding the long-term availability of resources such as the recent shortage example of aggregates in Ontario, Canada (OSSGA, 2018).

In 2018, "The Weight of Cities" report was published with a special focus on quantifying material stocks in cities (IRP, 2018). A graph from this report containing the Domestic Material Consumption (DMC) from 2010 to 2050 in different global areas is presented in Figure 2. This figure shows the total materials that are consumed globally, including non-metallic minerals, such as materials used in the construction industry.

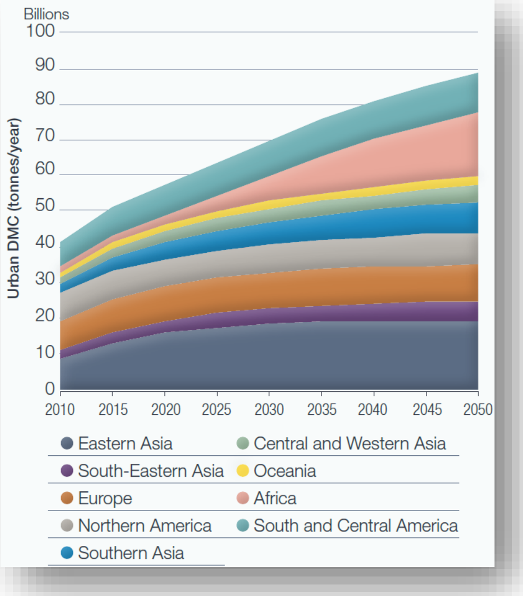

Figure 2. DMC from 2010 to 2050 by world regions (IRP, 2018)

Quantifying material stocks at different scales is a beneficial tool that helps planners, engineers, and other responsible decision-makers in municipalities or higher authorities to better assess the production of waste and resource productivity. By developing a database that includes an estimation of the location and quantity of different materials, cities will be able to have an understanding of their rate of material consumption and make the required intervention to be more productive. It is estimated that the global construction sector is responsible for around 25% of the overall GHG emissions (Huang et al., 2018). Considering the share of construction materials in global material use, their effect on GHG emissions throughout their life cycle, and the fact that more than half of global population resides in cities; accounting and mapping the construction materials in cities seem like a reasonable starting point to decrease material use and GHG emissions.

1.2 Thesis Structure

The first and current chapter of this thesis is an overall introduction and some background information followed by the geographical description, the boundary, and the scale of the study area. The research questions and objectives of the research are also defined in this first chapter. In the second chapter, a summary of the literature review conducted for this research is provided. The third chapter contains a description of the methodological approach of the thesis explained in three individual sections for buildings, roads and sidewalks, and projections for the future quantity of materials embedded in the defined system. The assumptions and limitations of the methods are also mentioned in this chapter. The results of the study, which is an estimation of the total quantity of construction materials in the buildings, roads and sidewalks in the studied system, in addition to the projection of the material stocks in the same stock categories is provided in Chapter 4. The GHG emissions associated with the construction material use in the studied group of materials are also calculated. The results of the sensitivity analysis performed on two of the main factors that affect the results of the study is also made available in Chapter 4. A discussion of the results is presented in the same chapter which includes an explanation of how the results can be used in industry and the policy implications associated with the results. Finally, in the final and fifth chapter of this thesis, recommendations for future work that can follow this study are mentioned as a suggestion for scholars who wish to pursue this research, and build upon its methodology and findings, and a conclusion is made available based on the obtained results.

This thesis contains two appendices. In appendix A, the original databases and maps are presented. Appendix B includes a sample of the new datasets that were developed in this research using the available data sources. Since the dataset is very large to include in print, it was difficult to present all the data. However, for clarity, a representative sample is included in the appendix.

1.3 System Description: The Region of Waterloo

The Region of Waterloo is located in the southern part of Ontario. Kitchener, Waterloo, and Cambridge are the three main cities of the Region of Waterloo alongside the townships of Wellesley, Woolwich, Wilmot, and North Dumfries. The total area of this region is around 1369km^2 (Statistics Canada, 2016). The total population of the region in 2018 was 601,220 people, which is a 1.20 % change compared to the Region's population in 2017 (Region of Waterloo, 2019c). The population growth in the Region of Waterloo is presented in Figure 3.

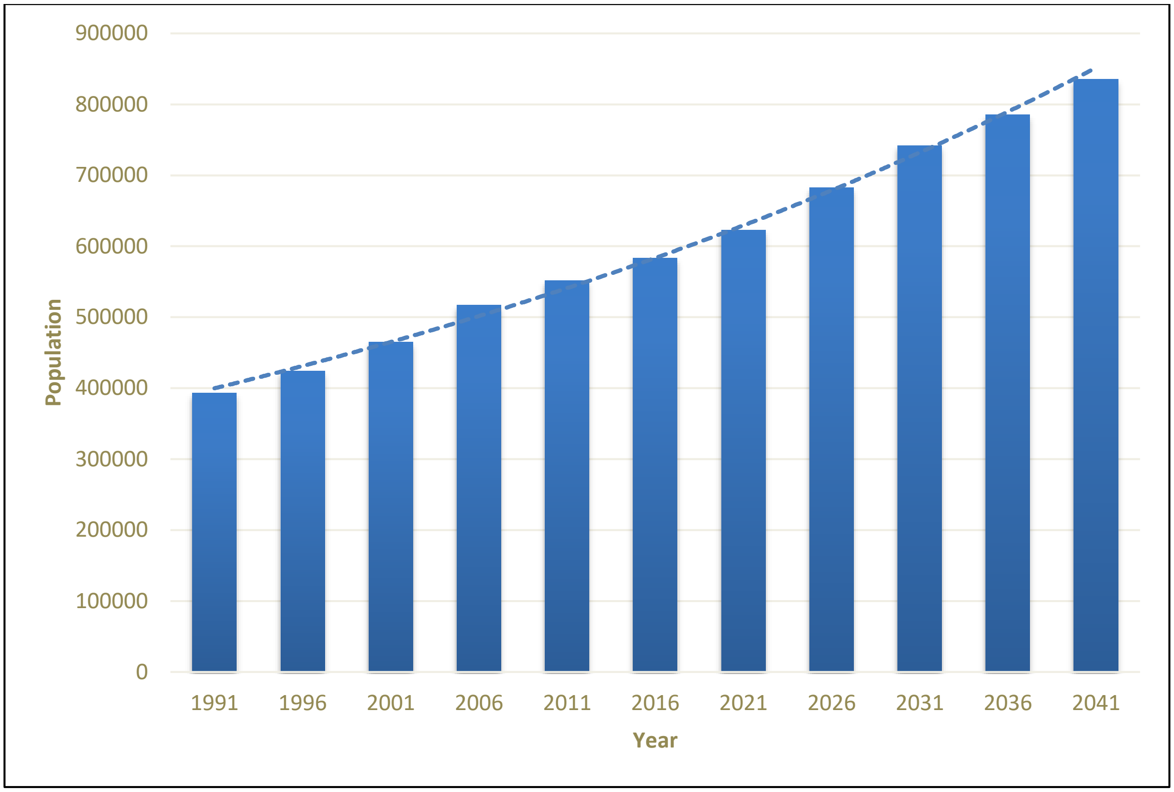

Figure 3. The Region of Waterloo's Population Growth 1991-2041 (Region of Waterloo, 2016b)

The Region of Waterloo is home to three main educational institutes, University of Waterloo, Wilfred Laurier University, and Conestoga College, where every year thousands of students move to this area for studying purposes. A significant number of these students find jobs in the region and decide to reside here, which is an important driver of population growth in this region. The Region of Waterloo is referred to as the next tech-hub and the Silicon Valley of Canada. University of Waterloo's innovation plans and the support they provide for student startups have affected the growth of tech companies in this area. Huge companies in the tech industry, such as Google, Blackberry, and OpenText, have located their headquarters in the

Region. To date, this region has the second highest startup density worldwide (Region of Waterloo, 2018c).

The Region of Waterloo has experienced a growth in GDP, rising from $25.80 billion in 2015 to $27.01 billion in only two years by 2017, which was reported to be higher than the average GDP in Ontario and Canada (Region of Waterloo, 2018c). The Region of Waterloo has been named as the second fastest growing urban area in Canada in 2018 with a growth rate of 5.5% per year, exceeding both national and provincial growth rates, and the fastest growing urban area in 2020 (Statistics Canada, 2019; Statistics Canada, 2020). With the increasing number of students moving to this area every year, studentification and gentrification are occurring at a faster rate in the region which leads to a higher urban metabolism in the cities (Chatterton, 2010). Also, the demand for student housing is increasing, resulting in massive apartment construction around the campus areas. A significant number of older single-family homes located on the streets close to university campuses are being replaced with mid-rise and high-rise apartments. The building permit activities in 2017 and 2018 in the Region of Waterloo indicate a transition towards more multiple dwelling construction rather than single family homes as they accommodate more people while covering a smaller land area (Region of Waterloo, 2018a; Region of Waterloo, 2019a). As multi-family homes are more material intensive, there will be increased demand for construction materials as well as more accumulation of material stocks in cities.

The Region of Waterloo's Climate Action Report published in 2013, invited all stakeholders to play their roles in order to reduce the region's GHG emissions. The five main areas of focus in this report are homes, agriculture and food, workplaces, transportation, and waste

(Region of Waterloo, 2013). Quantification of the construction materials in the Region and the GHG emissions associated with material use will provide insight for the decision makers in the region to better manage GHG emissions, specifically in the transportation and building sector.

In the Region of Waterloo, the two cities of Kitchener and Waterloo contain more than 60 % of the population and 65% of the buildings. Figures 4 and 5 show the distribution of population and buildings in the Region of Waterloo for each of its cities. Kitchener has an area of 136.9 km^2 and the population in 2018 was 255,070. The City of Waterloo's area is 64 km^2 and 139,490 people were recorded to be living in this city in 2018 (Statistics Canada, 2016; Region of Waterloo, 2019b). The cities of Kitchener and Waterloo together, commonly referred to as KW, play a big role in the growth of the Region of Waterloo, and was therefore, chosen as the geographical boundary of this study. Although the City of Cambridge has 23% of the population and buildings in the Region of Waterloo, accurate data regarding the characteristics and location of these buildings are not available. Therefore, this city is excluded from the scope of this research. This is mainly because of the lack of data in this city and inconsistency of the available data with Waterloo and Kitchener. Also, the cities of Waterloo and Kitchener are very much geographically connected and can be even be assumed as one larger city.

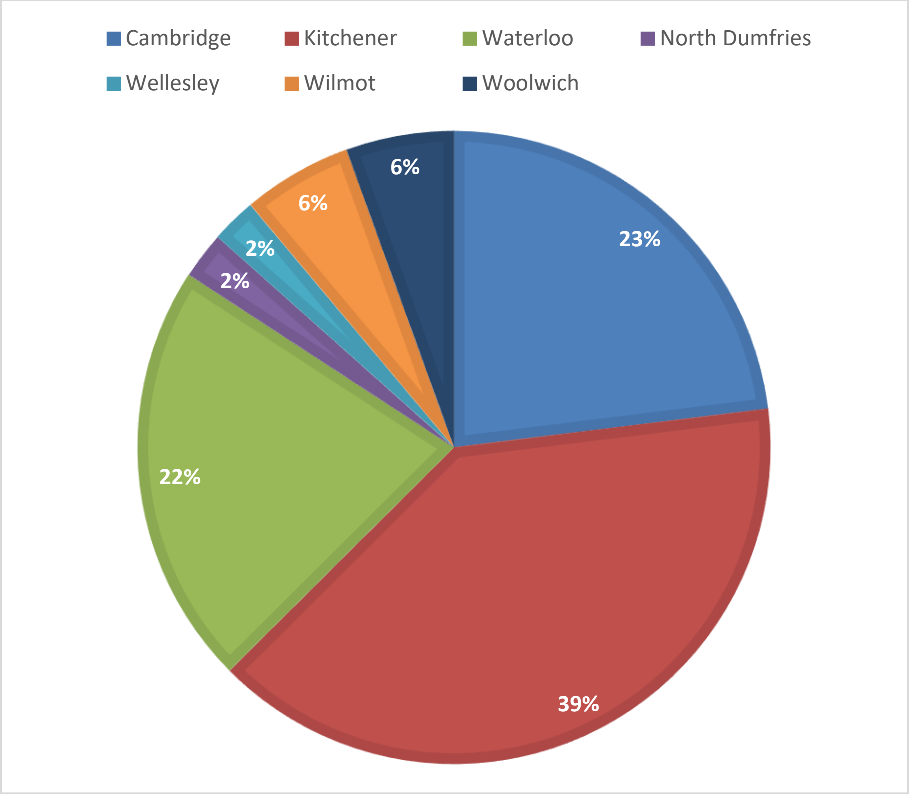

Figure 4. Building Distribution in the Region of Waterloo (Region of Waterloo, 2019a)

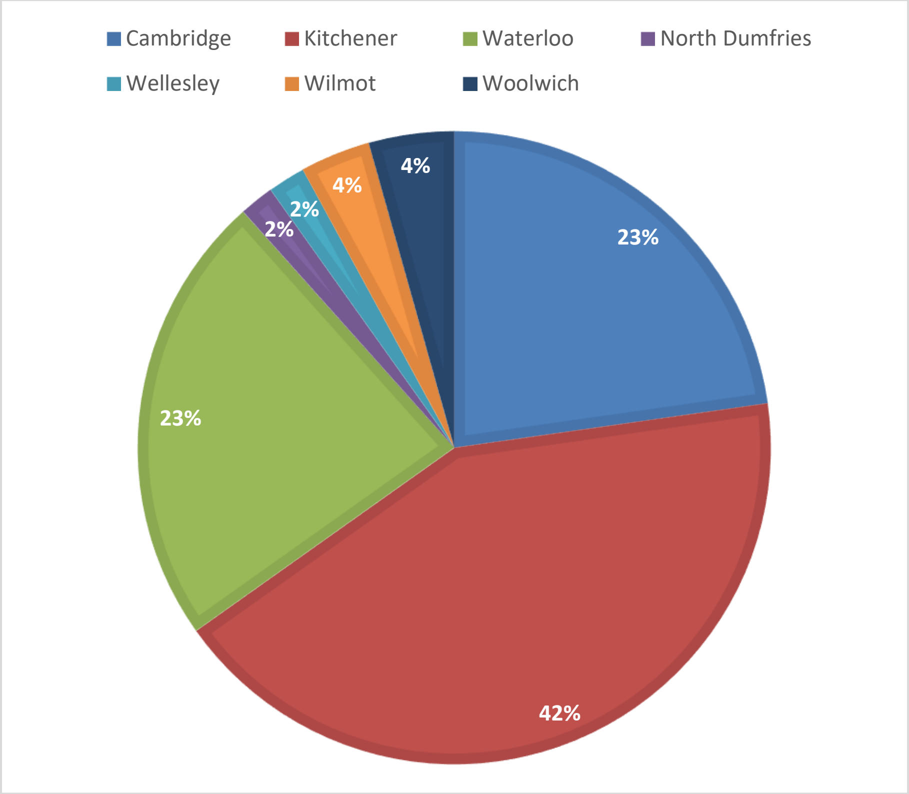

Figure 5. Population Distribution in the Region of Waterloo Cities (Region of Waterloo, 2019c)

For the purpose of this research, materials in building and roads are quantified as an indicator of the total weight of the city. Although it has been used in this term by several researchers, there is no clear definition of what the weight of a city means (World Resource Institute, 2000; Shi et al., 2012; Tanikawa et al., 2015; Huang et al., 2018) . It is mostly used as a metaphor to show the quantity of materials in a defined boundary. In this context, it is assumed as the physical weight of every single material that is located in the geographical boundary of the system such as, buildings, infrastructure, food, and even furniture. However, calculating this number is a huge and challenging exercise that is very data intensive. Construction materials are dense materials that are used in vast volumes in cities. Buildings and roads have proven to be two of the most material intensive stocks among the built environment stocks according to similar studies in quantification of material stocks in cities (Augiseau and Barles, 2017; Lanau et al., 2019). Therefore, due to the higher quantity of construction materials in cities, specifically in buildings and infrastructure, the quantity of construction materials in these two types of stocks are considered as a proxy of the city's weight.

1.4 Research Questions and Objectives

Even though growth in the Region of Waterloo is a great sign of economic development in the area and most of these developments will likely have a positive impact on the wellbeing of the Region's residents, environmental pressures associated with this growth should also be considered. As the area grows and more job opportunities are available, demand for housing and services will increase. This will result in more construction activities in order to build residential buildings to provide accommodation and non-residential buildings and city infrastructures to deliver other services. As a result of this growth in the construction sector, the construction material use will significantly increase. The Region of Waterloo should take action in order to prevent facing environmental issues such as increase in GHG emissions. The aim of this research is to take the first steps in this aspect and start quantifying the construction materials that have already been consumed and estimate the quantity that may be required for future developments. Therefore, two main research questions were posed for this research:

1) What is the total quantity of construction materials in the building and road stocks of the cities of Kitchener and Waterloo in a defined time period and how much GHG emissions are associated with these materials?
2) What quantity of construction material stocks will be added to Kitchener and Waterloo’s buildings, roads, and sidewalks by a certain year in the future, and how will these additional materials affect the cites’ GHG emissions?

By addressing these two research questions the following objectives will be accomplished:

1) Quantifying and mapping the aggregated distribution of construction materials used in the two main cities of the Region of Waterloo to gain insight regarding the construction material use in the area;
2) Providing information for policymakers to develop resource management strategies and investigate the potential of “urban mining” of construction materials, which is a strategy that is implemented to supply the required materials for developments from materials that are already in-use in cities rather than using virgin materials and depleting natural resources; and
3) Developing a geospatial material composition dataset for existing buildings and roads in Kitchener and Waterloo for practical use in municipalities. This database will include an estimation of the quantity and the location of the studied construction materials.

Chapter 2: Literature Review

2.1 Cities as Systems

Cities can be studied as systems that have spatial and temporal boundaries. The spatial boundary is defined according to the geographical conditions of the city and the temporal boundary is defined based on the purpose and scale of the research, which could be a reference year or a longer time period (Pauliuk, 2018). Flows, stocks, and processes are three main elements that define a system. Input flows enter the system, a fraction of the flows stay within the system, which are then called stocks, and output flows exit the system. Any transformation that happens within the system is called a process (Brunner and Rechberger, 2004). Residential and non-residential buildings, transportation infrastructure, and other city infrastructure such as pipelines are some of the most material intensive stocks in cities (Augiseau and Barles, 2017).

Studying the relationship between the inflows, stocks, and outflows in urban areas has led to the notion of "urban metabolism", which was inspired by the metabolism of the human body (Brunner and Rechberger, 2004). It is defined as the "The sum total of the technical and socioeconomic processes that occur in cities, resulting in growth, production of energy, and elimination of waste." (Kennedy et al., 2007, p.44).

The first urban metabolism study was conducted in a hypothetical city in the US with one million residents (Wolman, 1965). There are a significant number of metabolism studies in different parts of the world over several time periods. The overall conclusion is that the metabolism in cities has increased due to growth in populations, change in consumption patterns, and technological improvements (Kennedy et al., 2007). Decision-makers at the city level require an understanding of the metabolism of their cities in order to transfer them into more sustainable cities, and thereby creating more circular (rather than linear) flows through cities.

2.2 Material Stock Accounting

Stocks in the urban system are the components that provide services and satisfy the needs of the residents of that urban area. These needs include accommodation, nourishment, cleaning, and transportation (Brunner and Rechberger, 2004). Categorizing stocks based on their services provided helps policymakers better identify the material intensive services and sectors that require more attention towards dematerializing (Haberl, Wiedenhofer, Erb, Görg, and Krausmann, 2017). Therefore, opportunities for decoupling economic growth from material consumptions can be identified (Wiedmann et al., 2015). Understanding urban material stocks are important since they have long lifespans (Wiedenhofer et al., 2015). The stocks require materials not only in their construction phase but also in their use and maintenance phases. (Pauliuk and Mu, 2014; Krausmann et al., 2017). Around half of the total materials that are extracted annually are used to build new stocks or to maintain current in-use ones (Krausmann et al., 2017).

In urban systems, construction materials make up a large part of the stocks. Examples of construction materials in cities are concrete, wood, bricks, aggregate, and steel, which are the most widely used materials in the construction sector. Material Stock Accounting (MSA) helps quantify the construction materials in urban areas at different scales and provides insight into the quantity of materials embedded in cities, and by visualizing and mapping the distribution of materials in cities, material hotspots would be identified (Tanikawa, Fishman, Okauka, and Sugimoto, 2015).

When this information is available, the next step is adopting this information in order to develop resource and waste management strategies at the city level (Schiller, 2007). For instance, resources that present risk of supply disruption can be identified and alternative materials can be taken into consideration and adjustments can be made to regulations to prevent resource depletion (Kennedy et al., 2007; Heeren and Hellweg, 2018).

MSA is also helpful in taking advantage of urban mining to decrease virgin material use and increase reuse or recycling of construction materials (Brunner, 2011). Urban mining is referred to as "reuse of anthropogenic materials from urban areas" (Brunner, 2011, p.339). Urban stocks produce waste flows when they reach the end of their lifespan (Tanikawa et al., 2015). Information regarding the quantity of in-use materials in the urban stocks will enable cities to better understand the availability of construction materials and locate future waste flows to implement urban mining strategies (Koutamanis, Reijn, and Bueren, 2018). Meaning that they would be aware of the available quantity of materials in the city that could supply new developments rather than using virgin materials to do so. An example study of urban mining from the built environment is the work of Lederer et al. (2016) regarding Vienna's subway network in investigating the quantity of materials available for reusing and recycling (Lederer et al., 2016). However, it is difficult to directly use MSA results for urban mining purposes. Rose and Stegemann (2018) suggest recording the material use of buildings using as-built drawings to contribute to E-BAMB (existing building as material banks) since these drawings are more comprehensive and accurate than the ones developed at the earlier stages of the project and indicate a better representation of the total material use of buildings. They argue that existing research is not much help to actual urban mining practices in the industry since most of the results show the total used materials and there is not much disaggregated information available regarding the use of each type of material (Rose and Stegemann, 2018). MSA results can be helpful in urban mining if the quantity, location, distribution, and quality of each type of material is available individually. Implementing novel design practices in the built environment, such as designing for deconstruction and disassembly are helpful in the pathway of applying urban mining strategies in the construction sector (Bradley, Shell, and Homsey, 2006). Successfully implementing these ideas require considering the whole life cycle in designing and constructing buildings and infrastructure, which will then enable engineers to reuse or recycle the construction materials when the structure is ready for demolition towards its end of life.

Using information about in-use stocks and consumption patterns in defined time periods, predictions of future material use can be made (Fishman et al., 2014; Fishman, Schandl, and Tanikawa, 2016). This information helps take effective steps towards achieving a circular economy at the city level where construction waste flows are treated as valuable input materials for future construction projects in the city (Stephan and Athanassiadis, 2017).

2.3 Material Stock Accounting Methods

Material stock accounting research involves five main steps (Augiseau and Barles, 2017). First, the researcher clarifies the purpose of the study. The next step is identifying the temporal and spatial scale and the boundary of the research. Based on the previous two steps, a suitable methodology is chosen and according to the method, the required data is collected. Material stock accounting is a data-intensive research where collecting localized data adds value to the research, though, collecting this data can be challenging under certain circumstances. Therefore, each methodology is associated with a set of assumptions. The available data is a driver of the choice of methods. The final step is analyzing the data and presenting the results in a meaningful manner for use by policy makers.

The four main methodologies to conduct MSA studies are bottom-up, top-down, remote sensing and demand-driven approaches (Tanikawa et al., 2015). Bottom-up and top-down approaches are the two main methods commonly used to quantify the built environment stocks (Göswein et al., 2019). MSA methods can be either static, where the results indicate the quantity of material stocks in a reference year, or dynamic, where a longer time period is taken into consideration. Additionally, the time span of the research can be either retrospective and provides insights regarding the past material consumption patterns or prospective in which a projection of the future material use is made (Augiseau and Barles, 2017). It may also be a combination of both retrospective and prospective approaches. On the other hand, the dynamic aspect of MSA can be shown in the spatial scale of the study and material composition of various stocks built in different time periods, where these differences are considered in the analysis (Göswein et al., 2019). In some cases, researchers use a mix of the four approaches both due to data gaps and also to validate the results by comparing the outcomes of different methods (Tanikawa et al., 2015; Augiseau and Barles, 2017).

2.3.1 Bottom-up Approach

In a bottom-up approach, stocks are classified based on their features. These classes can be further categorized into smaller groups according to similar characteristics. For instance, Gontia et al. (2017) have categorized the residential building stocks in Sweden on several levels, where these stock categories are based on the type of the building, construction period, and structure type (Gontia et al., 2017). The number of categories and detail in each group depends on the availability of data and the scope of the study. For each group, a Material Intensity (MI) factor is defined, which is in units of mass per area, volume, length or any other unit, depending on the type of stock, which can convert the physical attribute of the stock into units of weight (Tanikawa et al., 2015). By adding up the sum of materials used in each group, the total materials consumed in the defined system are calculated. In recent years, bottom-up approaches have been the most popular MSA methodologies used by scholars (Lanau et al., 2019).

Bottom-up approaches normally provide information about the current materials in use at a certain time, or a "snapshot" of materials (Tanikawa et al., 2015; Augiseau and Barles, 2017). However, by putting a series of snapshots together in a longer time period, the change in material use can be shown (Tanikawa et al., 2015). A significant number of studies in the field of material stock accounting have chosen a bottom-up method in their research (Ortlepp et al., 2016; Österbring et al., 2017; Mesta et al., 2018; Göswein et al., 2018; Nguyen et al., 2018; Miatto et al., 2019; Arora et al., 2019). Use of Geographical Information Systems (GIS) data is extremely helpful in demonstrating the results of bottom-up MSA and producing accurate visualizations of results (Mesta, Kahhat, and Santa-Cruz, 2018).

2.3.2 Top-down Approach

Top-down approaches is one of the common methods in urban metabolism studies (Kennedy, Cuddihy, and Engel-yan, 2007; Göswein et al., 2019). It is also the second most popular method in MSA studies (World Resource Institute, 2000; Fishman et al., 2014; Guo et al., 2014; Tanikawa et al., 2015). From a stock accounting perspective, a top-down approach estimates the net addition to stocks by studying the material inflows and outflows (Tanikawa et al., 2015). This methodology is based on the law of conservation of mass. An example of a study of material stocks using a top-down approach is by Fishman et al. (2014), where they measured the material stocks of the United States and Japan over a 75-year period (Fishman et al., 2014). Accessing data for top-down approaches is possible through macroeconomic data in input-output tables published by governments (Fishman et al., 2014; Guo et al., 2014). The availability of this type of data gives an advantage to this method compared to other methods. However, since the results obtained using this method normally show the overall material use in the defined system it is difficult to identify the quantity of material stocks associated with each sector individually.

2.3.3 Remote Sensing and Demand-driven Approach

The idea of demand-driven approaches is the same as bottom-up and top-down approaches, however, this method is based on socioeconomic indicators, where the total material required to build the stocks is measured according to the service that each specific stock provides (Haberl et al., 2017; Tanikawa et al., 2015). In remote sensing, the material stock accounting is based on the information received by satellites that locate human activities and their densities (Tanikawa et al., 2015). This method is sometimes used when the required data for a bottom-up or top-down approach is difficult to access in an area (Göswein et al., 2019). Since, remote sensing approaches consume less time and require less labor compared to data-intensive bottom-up and top-down approaches, they are gaining more attention among researchers (Liang et al., 2016). Another advantage of remote sensing is that it enables the researchers to study a wider variety of stock types on a larger spatial scale. Normally, in case of inadequate data, remote sensing approaches are utilized that locate stocks using satellites (Rauch, 2009; Hsu, Elvidge, and Matsuno, 2013; Liang et al., 2016)

2.4 Case Studies of MSA

"The Weight of Nations" report is a seminal study in the field of material stocks and flows. The net addition to stocks of five countries was quantified over a period of 22 years (World Resource Institute, 2000). Regardless of some data limitations in that study, the results gave a great insight into the quantity of in-use material stocks at the time. Ever since, there has been a growing interest in research about material flows and stocks of urban areas. Augiseau and Barles (2017) conducted a review of 31 case studies on both material flow and stock assessment studies up until 2017, where they have specifically studied the ones that account for construction materials. Among them, 15 studies focused solely on the quantity of in-use stocks and estimating this quantity for a certain time in the future (Augiseau and Barles, 2017). A more recent review of material stock accounting research was conducted by Lanau et al. (2019), where 249 publications were included in this review. Of them, 128 studies considered construction materials in their analysis, and 90 out of 249 articles were published only in the last five years, which indicates how research regarding quantifying the material stocks has grown over a short time. Around 60% of these research publications used bottom-up approaches in their analysis, 30% had a top-down methodology, and the remaining 10% used a combination of these methods, including remote sensing, and demand-driven methodologies (Lanau et al., 2019).

Japan, Austria, Australia, Peru, Italy, USA, and Singapore are examples among many countries in which a detailed material stock accounting has been done, either at the national or city level (Tanikawa et al., 2015; Wiedenhofer et al., 2015; Stephan and Athanassiadis, 2017; Augiseau and Barles, 2017; Mesta et al., 2018;Miatto et al., 2019; Arora et al., 2019; Lanau et al., 2019). At the national level, China is one of the countries that is well studied in the context of urban weight. Since the 1980s, the demand for expansion of buildings and infrastructure has grown due to rapid economic growth in China (Shi et al., 2012). There are around ten studies focusing only on the building stock of different urban areas in China. Huang et al. (2018) studied China's buildings on a national level in order to estimate the environmental impact of the use of construction materials (Huang et al., 2018). These studies indicate that although limited signs of decoupling are observed, however considering the economic growth, China needs to target the built environment for more efficient use of materials to reduce environmental impacts (Huang, Han, and Chen, 2016; Huang et al., 2018; Li et al., 2019; Guo et al., 2019). Figure 6 extracted from the work of Lanau et al. (2019) which shows the number of MSA case studies that included construction materials in different countries.

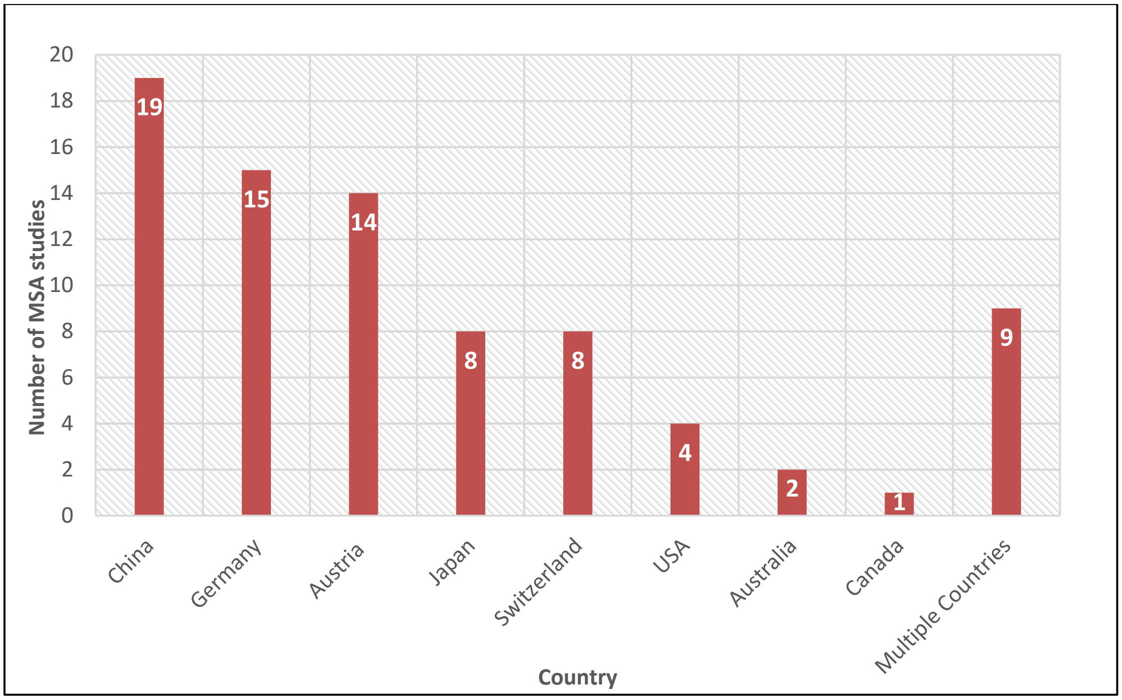

Figure 6. Number of Material Stock Accounting (MSA) Studies that included Construction Materials in Different Countries (adapted from Lanau et al., 2019)

Three examples of material distribution maps developed from MSA studies are presented in Figures 7 to 9. Figure 7 is a map of a country-level MSA study in Japan that illustrates the distribution of construction materials quantified in buildings, roads, railways, underground pipelines, airports, dams, and seaports (Tanikawa et al., 2015). Figure 8 and Figure 9 are city-level MSA studies. Figure 8 is an example map that shows the distribution of one of the material types studied in buildings in Melbourne (Stephan and Athanassiadis, 2017). Figure 9, which is from a more recent study conducted in 2018, presents the distribution of concrete in residential buildings in Chiclayo city in Peru (Mesta et al., 2018).

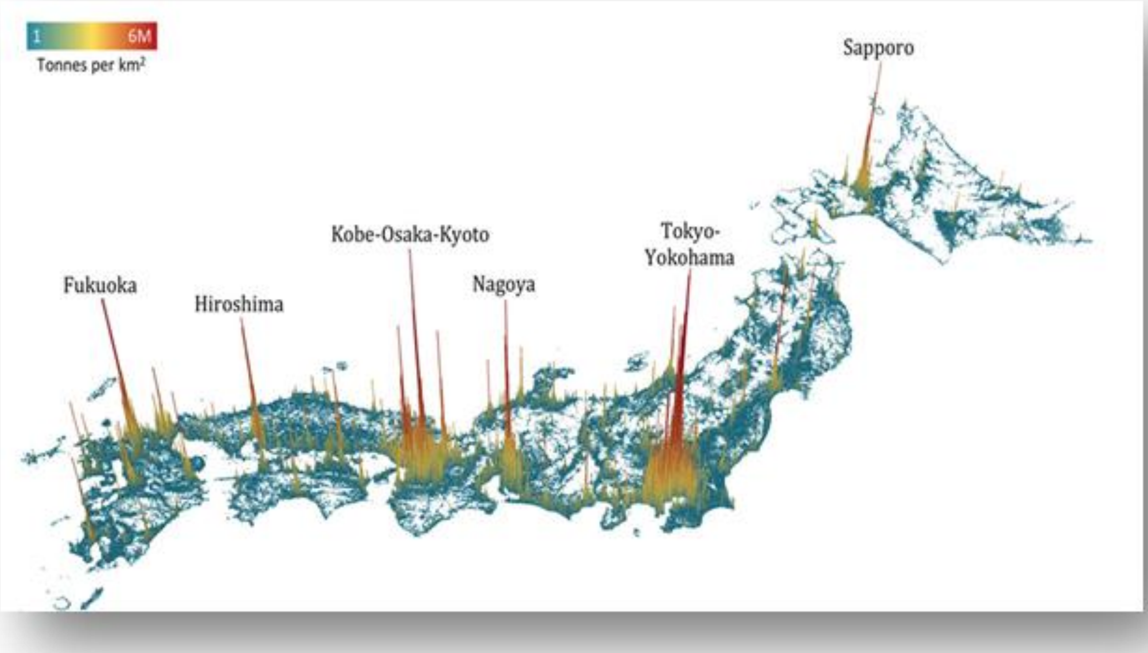

Figure 7. Construction Material Distribution in Japan in 2010 (Tanikawa et al., 2015)

Figure 8. Distribution of Concrete Used in Building Stocks in Melbourne in 2017 (Stephan and Athanassiadis, 2017)

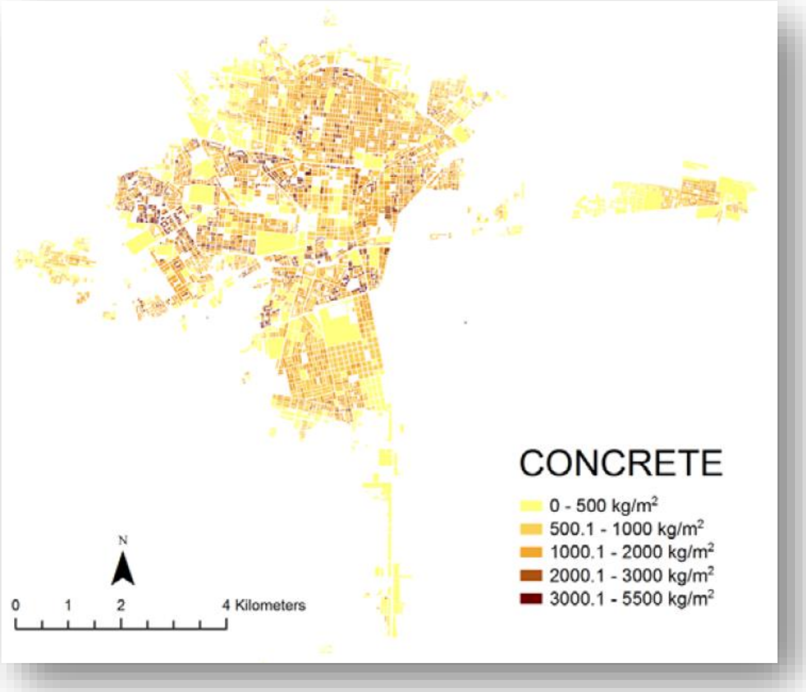

Figure 9. Distribution of Concrete in Residential Buildings in Chiclayo City in 2007 (Mesta et al., 2018)

Most researchers focus solely on residential building stocks as they compose the largest part of the total building stocks in cities; however, non-residential buildings, such as commercial, industrial and institutional buildings, are valuable sources of potential urban mining since they contain large quantities of materials that are concentrated in a smaller area (Ortlepp et al., 2016; Augiseau and Barles, 2017; Lanau et al., 2019). Infrastructure also plays a dominant role in the material stocks of cities. City infrastructure such as roadways and railways not only consume large quantities of materials in their construction phase, but the need for regular maintenance is another source of material consumption in cities (Schiller, 2007). Therefore, including infrastructure in the defined system helps produce more detailed results regarding the weight of a city. Guo et al. (2014)

conducted a material stock accounting study on the whole urban road system in Beijing, including all road classifications and ancillary facilities, in a bottom-up approach by field investigation and using remote sensing imagery (Guo et al., 2014). Miatto et al. (2017) were able to quantify the road stocks of USA in a novel bottom-up approach specifically developed for road systems. They also estimated the inflows and outflows of materials according to the required materials for maintenance of the existing roads and constructing new roads based on their expansion plans (Miatto et al., 2017). As a first in a developing country, materials contained in road networks of Vietnam were studied recently (Nguyen et al., 2018). Railway systems are also included in some material stock accounting research since they are rich in both mineral and non-mineral materials (Tanikawa et al., 2015; Lederer et al., 2016; Wang et al., 2015). However, results indicate that they only represent a small part of the total built environment compared to other stocks (Tanikawa et al., 2015).

In 2018, Canada has experienced a 1.4% growth rate, which is the greatest population growth over the past 20 years, and is the highest rate of growth among all G7 countries (Statistics Canada, 2018). As the population grows, material consumption, specifically the consumption of construction materials, will increase as a result of providing services such as accommodation and transportation for the residents. Sahely, Dudding, and Kennedy (2003) conducted a study in the Greater Toronto Area (GTA) which accounted for the input and output flows of energy, water, materials and waste in a top-down approach. The results show that the overall inputs are larger than the outputs, which indicate a net addition to stocks (Sahely, Dudding, and Kennedy, 2003). A neighborhood level urban metabolism study was also done in Toronto, which does not specifically look at the material stocks in the city but provides an overview of the flows (Codoban and Kennedy, 2008). The closest study to material stock accounting in a Canadian city quantifies the stocks of bricks in single-detached residential buildings in Toronto to investigate the potential for reusing and recycling bricks (Ergun and Gorgolewski, 2015). Considering the growth in Canada, it is important to start investigating the material stocks in Canadian cities by covering a wider range of built environment stocks and construction materials.

Considering the lack of MSA studies in Canada, this research aims to account for the construction materials in the cities of Kitchener and Waterloo, the two main cities of the Region of Waterloo located in southern Ontario in Canada. The research adds to the body of knowledge of the weight of cities and can be considered a contribution to MSA in a Canadian city. The scale of this research includes buildings' stocks, both residential and non-residential, roadways and sidewalks. By providing a visualization of the distribution of construction materials in Kitchener and Waterloo and a projection of future demand, cities would be able to gain a better understanding of the future material stock accumulations and implement more sustainable approaches to take advantage of the available construction materials in cities.

Chapter 3: Methodology

3.1 Urban System Description

The Region of Waterloo is the fastest growing urban area in Canada (Statistics Canada, 2020). The Region of Waterloo consists of the cities of Cambridge, Waterloo, and Kitchener and the townships of North Dumfries, Wellesley, Wilmot, and Woolwich. The population in 2018 was 601,220 and is predicted to grow to around 835,00 by 2041. This area is turning into the tech-hub of Canada with the increasing number of start-ups and well-known tech companies located in Kitchener and Waterloo (Region of Waterloo, 2018c). Indeed, the Region of Waterloo has been referred to as the next Silicon Valley and has the second largest startup density in the world (LITT, 2018). Growth indicates great opportunities for cities; however, it should be managed in a way where environmental pressure on the city is considered alongside economic growth and developments.

This study is focused on the cities of Kitchener and Waterloo. Both residential and non-residential buildings including commercial, industrial, and institutional in addition to the roadways and sidewalks are included in this material stock accounting study. The timeline for this research is from 2003-2018. A projection of the quantity of materials required to build future building and roadway stocks by year 2041 is also estimated. Since 2041 is census year in Canada, most future development reports and projections in the Region are based on this year (Region of Waterloo, 2016b; Region of Waterloo, 2018b). Therefore, the same year is chosen for this research. A map of the Region of Waterloo is presented in Figure 10.

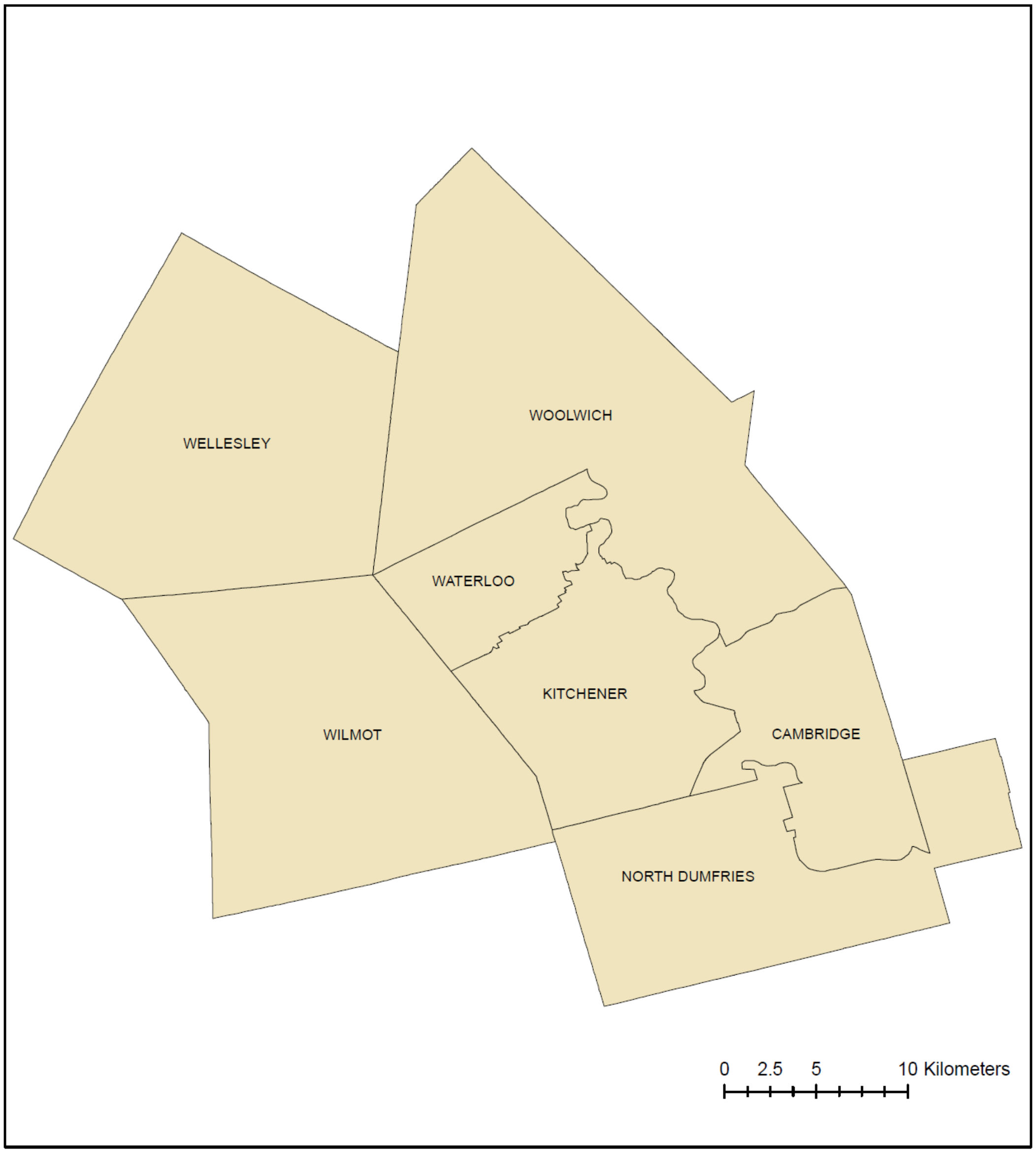

Figure 10. The Map of the Region of Waterloo (Region of Waterloo, 2020)

3.2 Bottom-up Method to Quantify Material Stocks

The main method used for this research is a bottom-up retrospective approach based on the methodology developed by Tanikawa et al. (2009) to quantify urban material stocks (Tanikawa and Hashimoto, 2009). However, in some cases due to data gaps, top-down and demand driven approaches are used. The methodology is divided into two parts: buildings, and roads and sidewalks. For all groups of material stocks, the weight of concrete, wood, bricks, steel, aggregates, gypsum, and asphalt are analyzed since these materials are the most common materials used in construction and are the most commonly studied materials among the material stock accounting research focused on construction materials (Lanau et al., 2019). The following sections present the methodological steps to quantify each material stock group, and the method used to estimate the required materials to build new building, road and sidewalk stocks by 2041 is described.

3.2.1 Buildings

To quantify the material stock of buildings, the buildings are categorized into four main groups: residential, commercial, institutional, and industrial based on their functional use. The residential group is further categorized into three groups of single/semi-detached homes, townhouses, and multi-family homes. Then, the single and semi-detached homes are again classified based on their year of construction. Ergun and Gorgolewski (2015) developed five main construction types for single and semi-detached residential homes in Toronto based on their year of construction (Ergun and Gorgolewski, 2015). These five types of buildings are century homes for the buildings which were built before 1930, wartime homes for the buildings built from 1931 to 1960, baby boomer homes for the buildings constructed in 1961 to 1975, Ontario building code homes which were built from 1976 to 2000, after the first publication of the provincial building code, and modern homes which are built from 2001 to present time (Ergun and Gorgolewski, 2015). The same construction types are assumed to be applicable to the single and semi-detached buildings in the Region of Waterloo since the construction norms are very similar in both Toronto and the Region of Waterloo due to geographical proximity, similar construction companies operating in both areas, and the use of Ontario's Building Code as the main building regulation for both cities. All the townhouses are considered as one group since it is not possible to further categorize based on the available data.

In the multi-family homes category, they are divided into two groups according to the number of stories based on a similar approach that was considered in other studies to categorize multi-family homes (Heeren and Fishman, 2019). Multi-family homes with 1 to 4 stories are considered as one group and the ones with 5 stories or more are considered as another group due to the difference in the building structure as the number of stories increase.

The buildings in Kitchener are categorized using the GIS data available in the Region of Waterloo's open database (Region of Waterloo, 2019b). This set of data includes 105,744 polygons representing the buildings in the city, and contains the use, number of stories, year of construction, and building footprint for each building. The building footprint is the area that the building structure covers on land without considering the number of stories. Sheds make up 34,690 of these polygon data that are excluded from this research. Sheds are small structures that cover a small surface and are normally pre-built or can be easily built with small material quantities. Therefore, the quantity of materials used to build the sheds in Kitchener are insignificant compared to other structures in the city.

The building data from the City of Waterloo includes 37,064 polygons and only contains building footprints (Region of Waterloo, 2019b). In order to fill this data gap, GIS data of the

Waterloo districts, zoning by-laws, and building permits are joined into one spatial dataset using the "spatial join" command in ArcMap (Region of Waterloo, 2019b; Esri, 2019). By this means, all the information allocated to a certain spatial area in all the joined maps will be saved in one single dataset that contains all the required information. However, this results in the loss of some information since even a small error in the spatial position of an attribute will result in the software assuming that there is no shared location for these attributes and will automatically delete them from the dataset. It is assumed that buildings located in the same district and same zone have similar characteristics of use, type of structure, and number of stories (City of Waterloo, 2018). Districts are referred to the neighbourhoods in the city, whereas zones are areas that have similar land use and construction regulations. Districts are defined by the cities planning communities to facilitate assessing the implementation of planning policies in each city such as distribution densities, stage of growth, and land subdivision These districts have no legal status under the Planning Act of Ontario (City of Waterloo, 2012). These assumptions are mostly checked with the help of Google Street View (Google, n.d.). The building permit issued for a specific location also helped in filling the missing building information (Region of Waterloo, 2019b). The year of construction from 2003 to 2018 is added based on the year of the new built permits that were issued for the new building constructions. The only missing information that cannot be added is the year of construction for the buildings that are built before 2003 in Waterloo for all buildings.

3.2.1.1 Material Intensities for Buildings

After classifying the building stocks, the next step is defining MI indicators for each group. The defined MIs are in units of kg/m^2. The MIs are calculated separately for each type of material and the overall MIs of the buildings are calculated based on the sum for each material. Building MIs are gathered through consulting with professionals in building construction, contacting local companies, and literature review. The summary of the building categories and MIs in addition to the reference for the MIs are shown in Table 2. Civil engineering professors in the fields of structural engineering and construction management at the University of Waterloo helped develop an overview of the building groups in the Region of Waterloo (Zurell, personal communication, July 30, 2019). Estimator manager at Activa Company, one of the major construction companies in Canada and the Region of Waterloo, kindly provided data regarding the construction materials of recent single detached homes and townhouses (Torrezao, personal communication, December 2, 2019). This data helped develop MIs for groups 1.5 and 2.1 in presented in Table 2.

The MIs of the rest of the single detached homes are calculated according to a study conducted in Toronto (Ergun and Gorgolewski, 2015). This study calculated the average volume of different materials in each type of residential buildings in Toronto and due to the similarities in construction norms and operating companies in both areas, the same MI are assumed for single detached residential buildings in KW. MIs for groups 1.1 to 1.4 are calculated according to this study. The MI database developed by Heeren and Fishman (2019) helped navigate through the available MI data in literature from around the world (Heeren and Fishman, 2019). Groups 3.1 and 3.2 are extracted from the MI database in Sweden since it was the closest to the scale of this research and contained the required information for the materials studied in this research (Gontia et al., 2017).

The MIs of non-residential buildings are calculated according to the MSA study conducted in the United States (Reyna and Chester, 2015). The main source of the classification and material components of the non-residential buildings in this study is RSMeans, which is a North American construction database applicable in North America (RSMeans, 2009). RSMeans contains information about the cost of materials, required labor for different construction tasks, and average construction material estimates for general building types. The same source is used for this research since applying the location factors available in RSMeans to the material cost and composition of buildings enables using this resource for material calculations in buildings in Canadian cities as well (RSMeans, 2009).

For each category, the MI are calculated in the unit of kg per m^2 of Gross Floor Area (GFA), which is the sum of all floor areas in the building. Therefore, in some cases, a unit conversation coefficient is used. For instance, in cases where the materials were reported by volume, volume was converted to mass by using the density of materials.

Table 2. Building Material Intensity Developed for Kitchener and Waterloo Using the Available Resources

			Material Intensity (kg/m^2)								
Use	**Level 1 Categories**	**Level 2 Categories**	**Concrete**	**Wood**	**Brick**	**Gypsum**	**Aggregates**	**Asphalt**	**Steel**	**Total**	**Reference**
Residential	Single/ Semi Detached	**Group 1.1 (Built before 1930)**	-	105	637	-	9	4	-	755	(Ergun and Gorgolewski, 2015).
		Group 1.2 (Built 1930 - 1960)	323	120	145	140	199	9	-	936	
		Group 1.3 (Built 1961 - 1975)	388	86	141	97	171	5	-	888	
		Group 1.4 (Built 1976 - 1999)	547	84.81	186	111	184	11	-	1124	
		Group 1.5 (Built 2000 - 2018)	650	124	73	53	716	-	-	1616	(Torrezao, 2019)
	Townhouse	**Group 2.1**	574	129	104	57	717	-	-	1581	
	Multiple	**Group 3.1 (1-4 stories)**	165	163	263	-	162	-	56	810	(Gontia et al., 2017)
		Group 3.2 (5+ stories)	288	35	61	11	5	4	61	465.12	
Non-Residential	Commercial	**Commercials**	426	1	-	-	66	20	74	588	(RSMeans, 2009)
		Office	321	5	60	4	47	14	49	500	
	Industrial	**Light Industrial**	533	-	-	-	66	20	111	732	
	Institutional	**Educational Facility**	464	-	50	-	66	20	102	702	
		Place of Worship	399	14	109	-	66	20	95	703	
		Hospital	692	-	7	8	22	20	131	880	
		Office	321	5	60	4	47	14	49	501	

3.2.1.2 Estimating Building Material Stocks

The GIS file is imported into Microsoft Excel to perform the calculations. The data is sorted according to the defined categories, and the MIs are added to the spreadsheet each category. By multiplying MI by Floor Area (FA) of the buildings, the total material in each building followed by the total materials embedded in all the building stocks is calculated according to Equation 1. FA was calculated by multiplying the building's footprint, which was calculated in the database using ArcGIS, by the number of stories for each building (Esri, 2019).

$$MS_{Buildings,y} = \sum_{i=1}^{m} \sum_{j=1}^{n} MI_i . FA_j \qquad \text{(Equation 1)}$$

Where,

m is the total number of building categories,

n is the total number of buildings in each category,

i represents each building category,

j represents each building in each category,

y represents the year when the material stocks are calculated,

MI is the Material Intensity Factor in units of kg per square meter,

FA is the building Floor Area in units of square meters, and

MS is the total materials used in the building stocks in units of kg.

In the final step, according to the year of construction of the buildings from 2003 to 2018, the quantity of materials used annually by different categories of buildings in each city is estimated.

For better interpretation of the results, GIS maps showing the distribution and intensity of materials are developed to present a visualization of the results.

3.2.2 Roads and Sidewalks

A similar bottom-up methodology as the buildings is used to account for material stocks in the roads and sidewalks categories. First, all the existing roads and sidewalks are classified into six groups of local roads, minor collectors, major collectors, arterials, highways, and concrete sidewalks. These categorizations are done according to the province and city's available road design guidelines (Ministry of Transportation, 2013; City of Kitchener, 2015). Average MIs are calculated for each road category to estimate the total amount of materials in KW's road network.

3.2.2.1 Material Intensities for Roads

Road classification and MI development are conducted after detailed consultation with researchers at the University of Waterloo who specialized in pavement design (Baaj, personal communication, October 10, 2019). The pavement structures for different road types are extracted from regional and local pavement design manuals and relevant literature (Holt et al., 2011; Ministry of Transportation, 2013; City of Kitchener, 2015). Mostly, cities publish specific pavement manuals based on their conditions. However, no document was found that contained this information for the city of Waterloo. Therefore, information from Kitchener is applied to the City of Waterloo. Also, in case of missing information and data gaps, the City of Toronto's pavement design manual is used (Toronto Transportation Services, 2019). A summary of the road classes and MIs are given in Table 3.

Table 3. Road and Sidewalk Classes, Thickness, MIs and Width in Kitchener and Waterloo

	Thickness (m)	MI (kg/m^2)	Average Width (m)
Type 1 (Local Roads)	0.650	1542	9.0
Type 2 (Minor Collectors)	0.715	1698	10.4
Type 3 (Major Collectors)	0.750	1782	14.0
Type 4 (Arterials)	0.820	1950	16.0
Type 5 (Highways)	0.810	1921	11.0
Type 6 (Concrete Sidewalks)	0.190	740	1.5

3.2.2.2 Road Sections

Road pavement structures are made up of four main layers of sub-base course, base course, binder course, and surface course from bottom to top. The thicknesses and materials of these layers affect the strength and quality of the pavement. The two bottom layers are made of aggregates while the upper two are made of asphalt. In this study, it is assumed that for all pavement categories, except for highways and concrete sidewalks, the sub-base layer is granular B, the base layer is granular A, and the binder and surface layers are Hot Laid asphalt type 4 (HL4) and Hot Laid asphalt type 3 (HL3), respectively (City of Kitchener, 2015; City of Kitchener, 2017). The difference between granular A and granular B is in their material size. In granular B, all materials must pass sieve size 150mm and in granular A, sieve size 16.5mm (Ministry of Transportation, 2013).

The difference between HL3 and HL4 is in their design mix and the percentage of bitumen and aggregates used in the material. HL3 is a dense-graded surface course mix used for roads with intermediate volumes and HL4 is a dense-graded mix used as a surface mostly for roads with lower traffic volume (City of Kitchener, 2017).

In highways, due to the higher traffic load the asphalt used is a Super Pave (SP) mix. SP19.0 and SP12.5 are used for the binder and surface layers of highways in KW, respectively. In SP19.0, 90 to 100 percent of aggregates must pass sieve size 19mm and in SP12.5 they must pass sieve size 12.5mm. SP19.0 is a suitable asphalt mix in binders used for almost all traffic loads and is a replacement for HL4. SP12.5 is used as a surface course, normally for lower volume traffic loads (Ministry of Transportation, 2013).

For the concrete sidewalks, a two-layered pavement structure is assumed; one layer of base made of granular A and one layer of surface made of Portland Cement Concrete (PCC). This is a typical structure of rigid pavements that is very common in constructing local sidewalks (Ministry of Transportation, 2013; City of Kitchener, 2015). In case of asphaltic sidewalks, which are used much less than concrete sidewalks in this area, a similar MI as local roads is assumed.

The road sections are presented in Figures 11 to 16 for all the road classes used in this research. Also, Tables 4 to 9 show the density, thickness, and weight of each layer in the pavement sections.

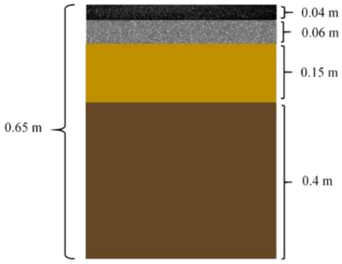

Figure 11. Type 1 Section
(Local Roads)

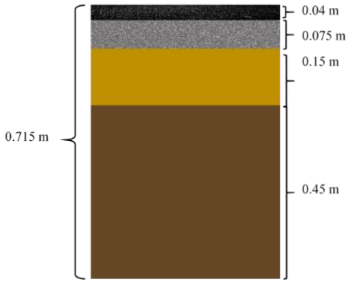

Figure 12. Type 2 Section
(Minor Collectors)

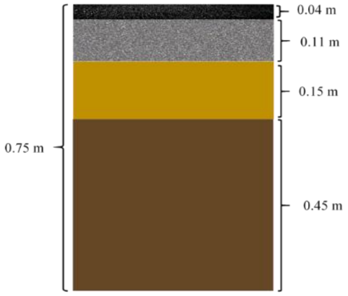

Figure 13. Type 3 Section
(Major Collectors)

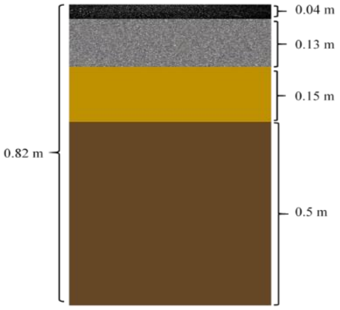

Figure 14. Type 4 Section
(Arterials)

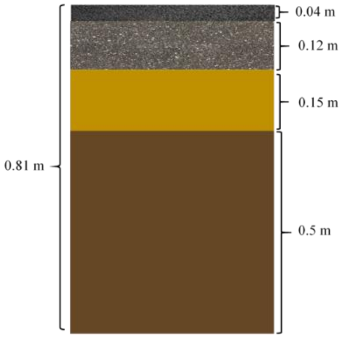

Figure 15. Type 5 Section
(Highways)

Figure 16. Type 6 Section
(Concrete Sidewalks)

Legend

■ HL3
■ HL4
■ Granular A
■ Granular B
■ SP 12.5
■ SP 19.0
■ Concrete Pavement

Table 4. Pavement Components of Type 1 Roads (Local Roads)

	Density (kg/m^3)	**Thickness** (m)	**Weight** (kg/m^2)
HL 3	2350	0.04	94
HL 4	2390	0.06	143.4
Granular A	2300	0.15	345
Granular B	2400	0.4	960
Total		**0.65**	**1542.4**

Table 5. Pavement Components of Type 2 Roads (Minor Collectors)

	Density (kg/m^3)	**Thickness** (m)	**Weight** (kg/m^2)
HL 3	2350	0.04	94
HL 4	2390	0.075	179.25
Granular A	2300	0.15	345
Granular B	2400	0.45	1080
Total		**0.715**	**1698.25**

Table 6. Pavement Components of Type 3 Roads (Major Collectors)

	Density (kg/m^3)	**Thickness** (m)	**Weight** (kg/m^2)
HL 3	2350	0.04	94
HL 4	2390	0.11	262.9
Granular A	2300	0.15	345
Granular B	2400	0.45	1080
Total		**0.75**	**1781.9**

Table 7. Pavement Components of Type 4 Roads (Arterial)

	Density (kg/m^3)	**Thickness** (m)	**Weight** (kg/m^2)
HL 3	2350	0.04	94
HL 4	2390	0.13	310.7
Granular A	2300	0.15	345
Granular B	2400	0.5	1200
Total		**0.82**	**1949.7**

Table 8. Pavement Components of Type 5 Roads (Highways)

	Density (kg/m^3)	**Thickness** (m)	**Weight** (kg/m^2)
SP 12.5	2350	0.04	94
SP 19.0	2350	0.12	282
Granular A	2300	0.15	345
Granular B	2400	0.5	1200
Total		**0.81**	**1921**

Table 9. Pavement Components of Type 6 Roads (Concrete Sidewalks)

	Density (kg/m^3)	**Thickness** (m)	**Weight** (kg/m^2)
PCC	2325	0.17	395.25
Granular A	2300	0.15	345
Total		**0.32**	**740.25**

3.2.2.3 Estimating Road and Sidewalk Material Stocks

GIS datasets including the road and sidewalks in the cities of Kitchener and Waterloo in the year 2018 are available in the Region of Waterloo's open database website (Region of Waterloo, 2019b). Kitchener GIS data for roads is much more complete than that of Waterloo's. Kitchener's road dataset contains 5367 lines with detailed information regarding the location of roads, road types, length, and pavement width, while the Waterloo road GIS data, which includes 3420 lines, only contains road lengths and location of roads. The type of roads is added to the dataset one by one using a pdf map from the city that identified the road types in the city (City of Waterloo, 2012). Also, the data gap in the City of Waterloo's road widths was filled using the average width.

After importing the GIS file into the spreadsheet and sorting the roads, MIs are added for each group. Using the length and width of the roads and the MIs that were generated, the weight of materials in roads and sidewalks can be calculated according to Equation 2.

$$MS_{Roads,y} = \sum_{i=1}^{m} \sum_{j=1}^{n} MI_i . W_j . L_j \qquad \text{(Equation 2)}$$

Where,

m is the total number of road categories,

n is the total number of roads in each category,

i represents each road category,

j represents each road in each category,

y represents the year when the material stocks are calculated,

W is the width of the road in units of meters,

L is the length of the road in units of meters,

MI is the Material Intensity Factor in units of kg per square meter, and

MS is the total materials used in the road and sidewalk stocks in units of kg.

Following the previous steps provides a snapshot of the quantity of materials located in the roadway networks in 2018. No accurate information is available regarding the historical road networks before 2003 in Kitchener and Waterloo. For this earlier period, the only available data is archived GIS road maps from 1992 in Kitchener and 1955 in Waterloo (Region of Waterloo, 2019b). According to this available data, the same approach is applied to the data to quantify the quantity of material stocks in roads in 1992 in Kitchener and 1955 in Waterloo. Assuming a consistent growth rate in the road materials based on the available information, a linear interpolation is used to calculate the quantity of material stocks in roads from 2003 to 2018 in both cities.

3.2.2.4 Material Use for Road and Sidewalk Maintenance

Roads and sidewalks require continuous maintenance to provide the essential level of service. The maintenance processes vary depending on the conditions of the road from minor road repairs to full reconstruction of roads. To calculate the quantity of materials used for maintenance, information about road closures over the past 15 years are collected from the municipalities (Region of Waterloo, 2019b). The closures due to road resurfacing and road reconstruction are selected, and the material consumption for these maintenance procedures are calculated. For the City of Waterloo, the data has missing information from 2003 to 2014. The quantity of materials used for maintenance in this time period is estimated according to the correlation between material use for maintenance purposes in Kitchener and Waterloo in the years where data existed for both cities (2014 to 2018). It is assumed that since the cities have similar overall characteristics a correlation exists among the road maintenance activities in both areas. In the maintenance process, the old pavement is removed, and the new pavement is constructed on the roads. The old pavement is partly recycled and partly landfilled. There is no exact information regarding the percentage of recycled pavement. There is data to suggest a 75% recycling rate recorded in USA (Rajendran and Gambatese, 2007). Some of this quantity is used in construction material production industries, such as concrete. Due to the similarities in pavement design practices between USA and Canada, a similar number is assumed for this study.

The use of Reclaimed Asphalt Pavement (RAP), which is recycled pavement, is only allowed in the binder layer or the second asphaltic layer from the top (City of Kitchener, 2017). Therefore, the remaining material is supplied from virgin materials. The City of Kitchener permits the use of 20% RAP in the second layer. The same rule is applied to the City of Waterloo. Therefore, the total quantity of virgin material required to maintain the existing roads, and the quantity of old pavement that will be transferred to landfills as waste, is calculated in the defined period.

3.2.3 Material Stock Projection by 2041

The year 2041 is chosen as a reference year for projecting the quantity of materials required to build up new stocks in the city to satisfy the needs of the growing population, where 2041 is an upcoming census year in Canada and most of the forecasts in the Region of Waterloo's reports are made for this year. Therefore, a 23-year horizon is chosen for projecting material requirements for Kitchener and Waterloo. The projection is made individually for residential buildings, non-residential buildings, roads, and sidewalks.

To measure the quantity of materials in residential building stocks, a mix of demand-driven and bottom-up approach is used. First, the number of dwellings required by 2041 was calculated. The region's population is estimated to be 835,000 people in 2041 (Region of Waterloo, 2016b). The region has made an estimation of the population distribution in the cities located in the Region of Waterloo by 2041. It is projected that in 2041, nearly 323,356 people will be living in Kitchener and 172,235 in Waterloo (Regional Municipality of Waterloo, 2017). Census information from 2011 and 2016 indicates that in this region, there are around 2.65 people living per dwelling (Region of Waterloo, 2016a). Considering the same number of people per dwelling for 2041 results in an additional 55840 dwellings required by 2041 in Kitchener and Waterloo compared to the latest census information stating 141,590 dwellings existed in these two cities in 2016. According to the 2017 and 2018 building permit activity in the Region, 47% of the newly built dwelling units are apartments, 33% are single and semi-detached houses, and 10% are townhouses (Region of Waterloo, 2018a; Region of Waterloo, 2019a). The same distribution is applied to the required dwellings in 2041. Based on the available data from 2003 to 2018, assumptions were made for average footprint, average number of stories, and average number of units. Using these numbers, the quantity of materials that will be added to the residential building tocks in the future is estimated following the same bottom-up approach.

For the non-residential buildings, the building permit activity shows that there is no sign of a specific trend in the rate of non-residential construction in the region (Region of Waterloo, 2019a). It is very difficult to make a future projection for this type of stock. Building permit activity reports in the Region of Waterloo show that normally when there are multiple non-residential construction projects implemented in a year, the following year experiences lower non-residential construction due to the saturation of projects in the previous year. Therefore, it could be assumed that, while looking at longer time periods, there is almost similar non-residential construction activity on average. Therefore, the quantity of materials required to build new non-residential stocks is projected according to the previous construction patterns in a business-as-usual scenario assuming an annual similar non-residential building activity.

In the case of roads and sidewalks, the materials required to build new roads are quantified according to the region's road expansion plans for 2041 (Regional Municipality of Waterloo Transportation and Environmental Services Department, 2019). For the quantity of materials that will be put into road maintenance, the municipalities' future asset management plans are used as a proxy of material consumption for different maintenance purposes since these scenarios are developed according to the Pavement Quality Index (PQI) of roads. According to the city's standards, a road will require maintenance upon reaching a certain threshold for PQI after it has been in operation for a while (City of Kitchener, 2012; City of Waterloo, 2015). Higher budgets associated with maintenance in a year indicate higher material use in that year.

3.3 Greenhouse Gas Emissions Associated with the Construction Material Use in KW

To calculate the GHG emission of construction material use in KW, the GHG emission factors in the unit of kgCO_2eq per kg of materials are extracted from the Inventory of Carbon and Energy (ICE) database (Crawford, Stephan, and Prideaux ,2019). This database includes building material carbon emissions that are gathered from different sources. Based on the descriptions available for each material in this database, the corresponding factor is used for the materials in this study. For the roads more localized factors are used from a carbon footprint study performed on Ontario's pavements by "Ontario Hot Mix Producers Association" (OHMPA, 2010). The factors applied to calculate the GHG emissions from material use in buildings, roads, and sidewalks in KW are presented in Table 10.

Table 10. Carbon Emission Factors Used for Construction Materials in KW

Material Name	**Carbon Emission Factor ($kgCO_2eq$/kg material)**	**Reference**
Concrete	0.119	(Crawford et al., 2019)
Wood	0.493	
Brick	0.210	
Gypsum	0.780	
Aggregates	0.007	
Asphalt used in Buildings	0.054	
Steel	1.550	
Asphalt used in Roads	0.010	(OHMPA, 2010)
Aggregate - Granular A	0.008	
Aggregate - Granular B	0.005	
PCC	0.107	

By multiplying these emission factors by the mass of materials the GHG emissions associated with the material stocks in KW are calculated according to Equation 3.

$$CO_2eq = \sum_{i=1}^{n}(Carbon\ Emission\ Factor)_i . M_i \qquad \text{(Equation 3)}$$

Where,

n is type of materials which here is equal to 11,

i represents each material type,

"Carbon Emission Factor" is used from Table 10 for each material in units of $kgCO_2eq$ per kg of material, and

M is the mass of material in units of kg.

3.4 Assumptions and Limitations

The bottom-up accounting method is extremely data-intensive. Where there is lack of required data, a series of assumptions are made to conduct the research and fill gaps in the dataset. In this study, the main issue is with the buildings' GIS data provided by the municipalities that have gaps. Not all information about the buildings is complete and in order to fill these data gaps, the previously mentioned approaches were used which affects the results of total material use. This is particularly true in the City of Waterloo, where the GIS data was very incomplete. In the case of MI factors, the assumption is that the same MI applies to all the buildings in one category. However, not all buildings have the same material composition. MIs are only the average material quantities that the construction companies have used. It should also be noted that MIs vary depending on the year of construction due to the change in construction norms, building codes, and general knowledge advancements that lead to changes in construction. However, due to lack of data, categorization based on the year of construction is only available for single/semi-detached residential buildings in the dataset developed for this study. Therefore, a sensitivity analysis is performed on some of the main assumptions made in this study to assess the impacts of these assumptions on the results, which is discussed in the following section.

3.5 Sensitivity Analysis

A sensitivity analysis is conducted on the results of the total quantity of calculated construction materials. The number of building stories in Waterloo and the MI coefficients are the two factors that are chosen for this sensitivity analysis. In this sensitivity analysis, Building MIs for each type of material are deviated by ±20% and the effect is calculated on the total material stocks of buildings.

Road MIs are calculated according to the municipalities' guidelines and in consultation with expert engineers in the field of pavement design. The accuracy of road MIs are rather higher than of buildings. Road pavement structures are normally standardized and follow similar regulations. However, a sensitivity analysis is conducted on the road MIs to assess the effect of a ±20% deviation of mean road MIs on the total road material stocks in KW

In the case of the buildings in Kitchener, the GIS dataset provided in the municipality's open data contains information regarding the number of stories for each building. Therefore, no sensitivity analysis was conducted on the results of material stocks in Kitchener's buildings from the perspective of building stories. However, as previously explained, Waterloo building data was very limited. Hence, multiple assumptions were made to fill the data gaps. One of the main assumptions in this section was the number of building stories in buildings located in Waterloo. These numbers were estimated based on Zoning by-laws, district information, and Google Street View. Therefore, a sensitivity analysis is beneficial; specifically, considering the role of the number of stories as the main factor in calculating GFA and the total material stocks in buildings. To conduct this sensitivity analysis, the average number of stories for different building categories are deviated by ±1 story. The effect of this change is calculated on the quantity of building material stocks in Waterloo.

Chapter 4: Results and Discussion

4.1 Material Stocks in KW's Buildings, Roads and Sidewalks

The results of this study indicate that in the year 2018, 22.550 Mt of materials were embedded in the building sector of Kitchener and 13.691 Mt in Waterloo. Among all the building types, residential buildings contain the most material (more than 80% of the total material consumption in both cities). The quantity of each material is presented in Table 11. Among the studied materials, concrete is the most used construction material (45% in Kitchener and 42% in Waterloo) followed by aggregates (26% in Kitchener and 23% in Waterloo). Also, around 75% of the total construction materials in the residential buildings in Waterloo are embedded in single or semi-detached homes. The same number is approximately 73% in Kitchener.

Table 11. Quantity of Each Construction Material in KW's Buildings in 2003, 2018, and 2041

Year **Material (Mt)**	**2003**	**2018**	**2041**
Concrete	12.383	15.933	20.301
Wood	2.208	2.851	3.948
Brick	4.377	4.861	5.976
Gypsum	1.688	1.947	2.270
Aggregates	5.748	9.151	13.444
Asphalt	0.281	0.300	0.308
Steel	1.074	1.198	1.436

The use of construction materials in the building sector has grown steadily at a rather consistent rate of growth from 2003 to 2018 in the cities of Kitchener and Waterloo. Figure 17 shows the growth of building material stocks from 2003 to 2041 for each individual material in both cities. This figure indicates that the growth rate of material consumption is almost consistent from 2003 to 2018 in KW with an annual 1.7% rate of growth. Among the studied material, aggregate consumption has a slightly bigger rate of growth and concrete composes the largest share of material consumption in KW. Based on the assumptions made to conduct this research, the material consumption growth till 2041 follows an almost similar pattern of consumption to the previous years.

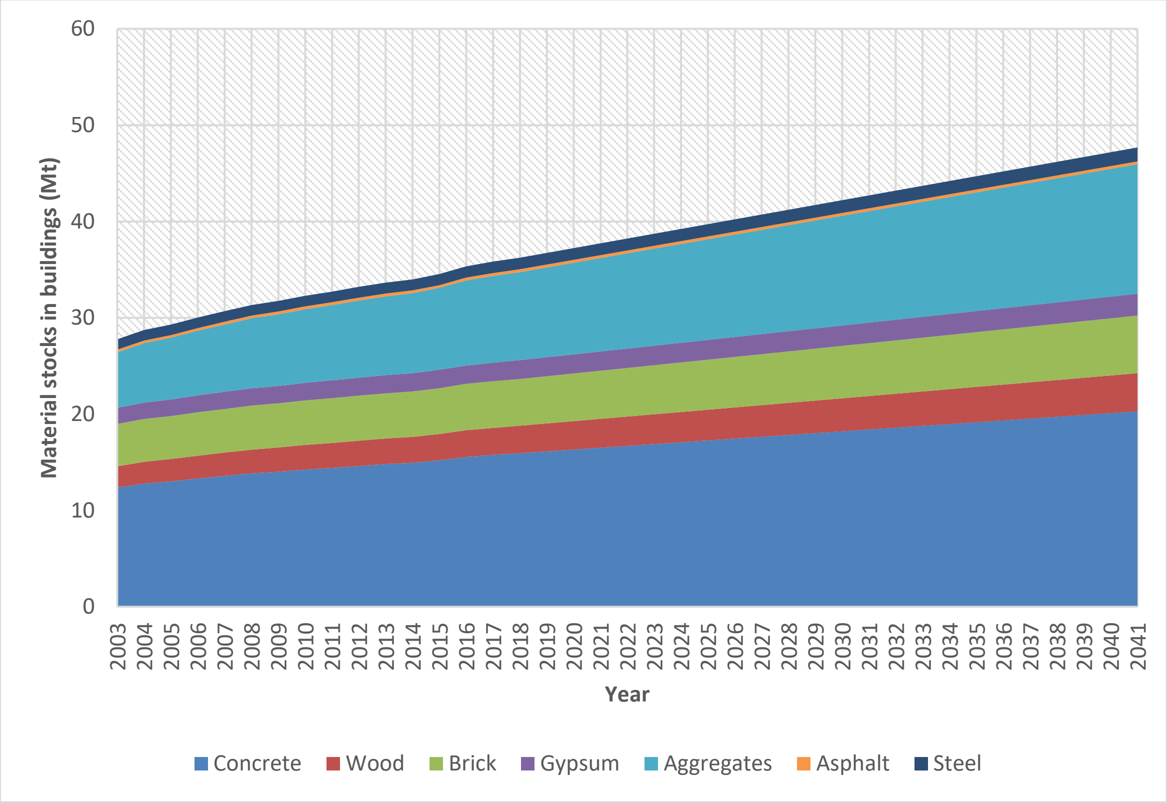

Figure 17. Building Material Stocks in Kitchener and Waterloo 2003-2018 and projected to 2041

Figures 18 and 19 illustrate the distribution of material use in the building sector in each district of KW for the year 2018. Waterloo has 26 districts and Kitchener has 54. Downtown Kitchener is one of the most material intensive areas in KW. This area is shown in the dark red color. University of Waterloo's campus is not identified as a district in Waterloo. However, to show the intensity of materials in this area, it was manually added to the dataset and the building intensity is calculated. In Waterloo, the most intensive areas are University of Waterloo’s campus and the main residential neighborhoods shown in dark green, and after that is uptown Waterloo located in the southern part of the city. The two white spots in Waterloo’s material distribution maps indicates no building activities. These are conservation areas where construction is nor permitted. Overall, in both cities, the neighborhoods with larger population densities and the downtown cores have higher material intensity due to the location of several buildings with little spaces between buildings in these areas. It is understood from the maps that the darker areas have higher potential for urban mining due to both the existence of materials and the higher chance of construction in these areas.

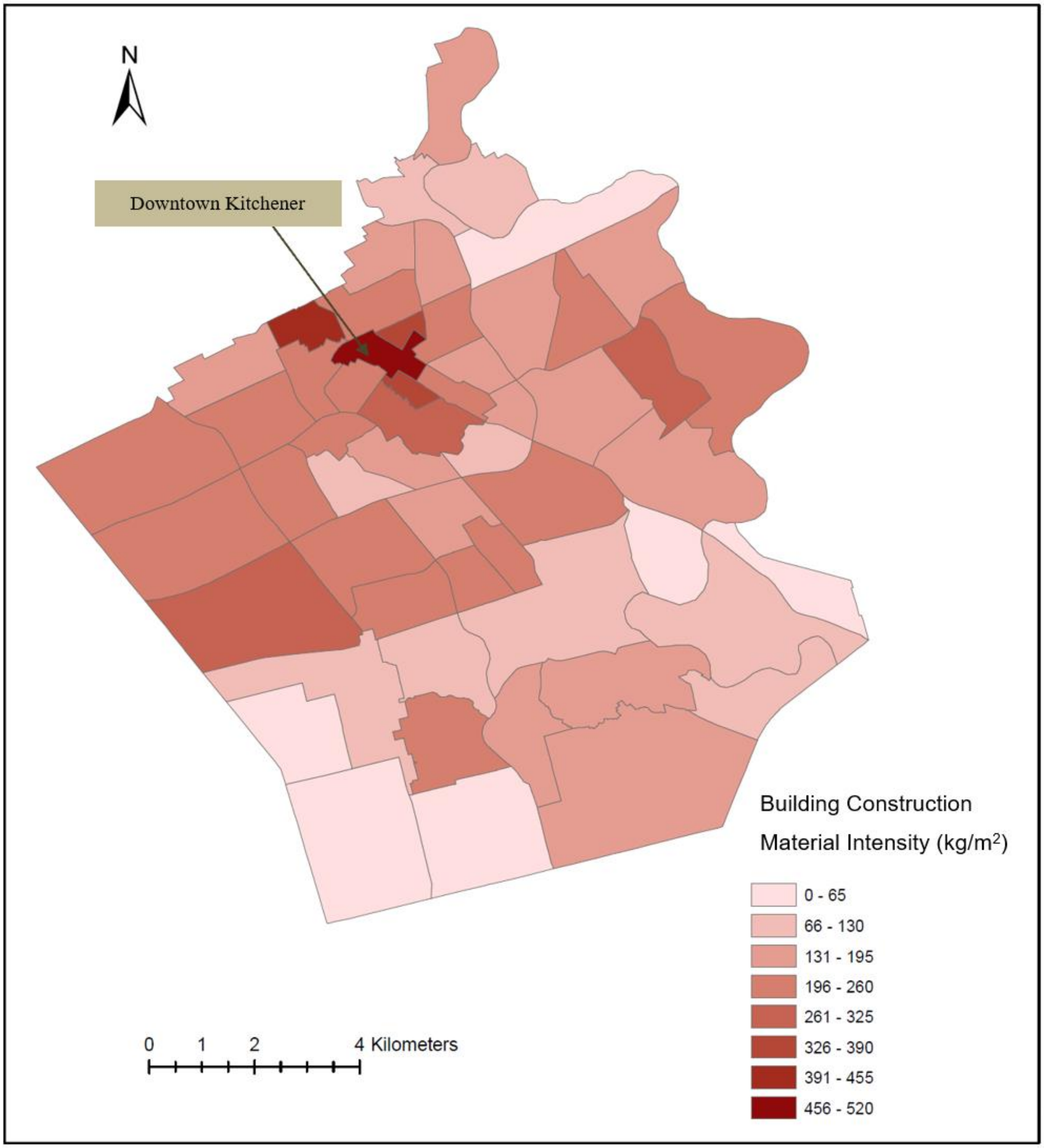

Figure 18. Distribution of Building Material Intensities in Kitchener in 2018

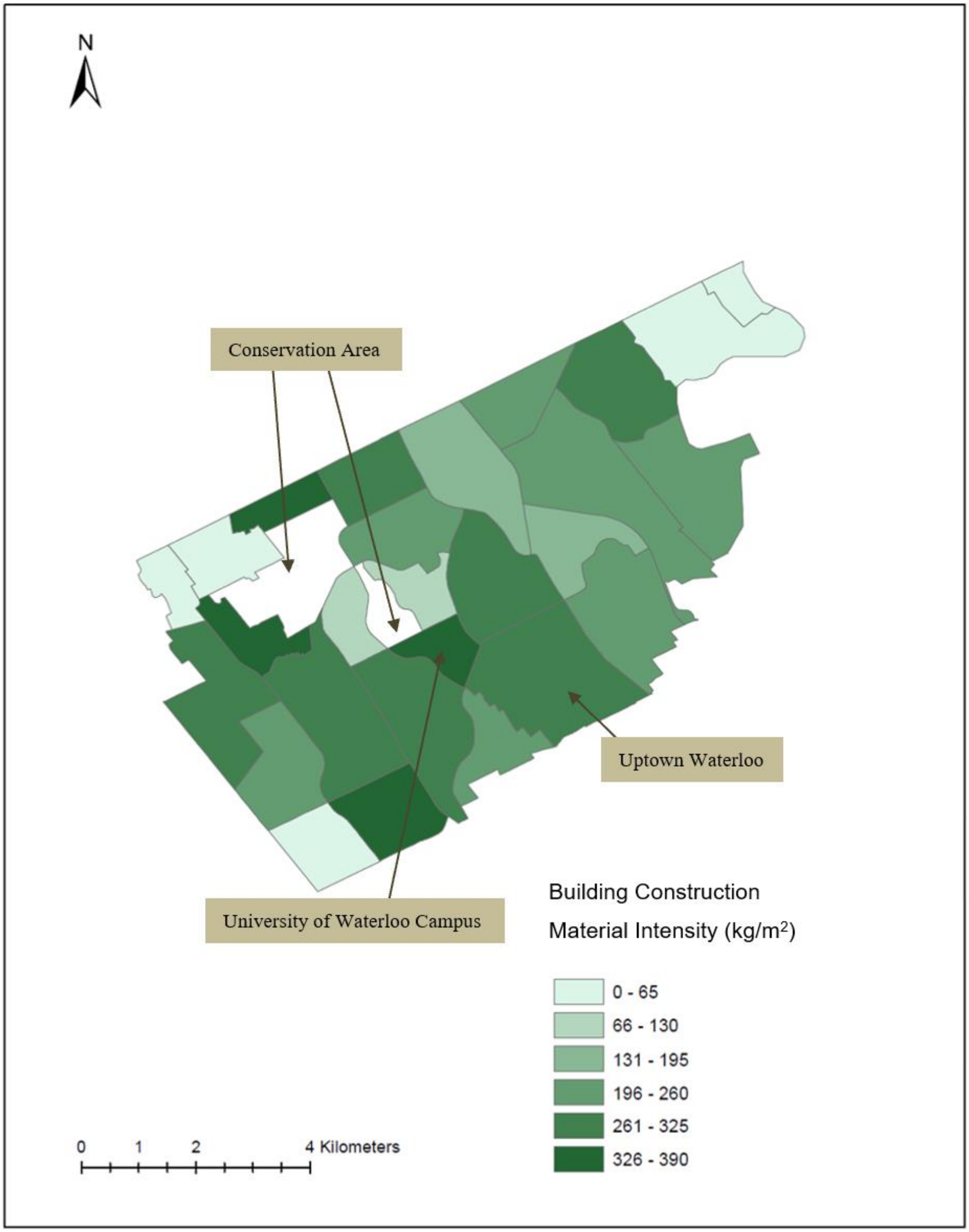

Figure 19. Distribution of Building Material Intensities in Waterloo in 2018

In 2018, the roads and sidewalks of Kitchener contained 16.813Mt and 1.508Mt of materials, respectively. For the same year, in Waterloo 9.574Mt of materials was calculated in roads and 0.603 Mt of materials in the sidewalk stocks. The quantity of materials used in roads stocks in 2018 are shown in Table 12 individually. The quantity of aggregates is around five times the quantity of asphalt used in the road networks. This is due to the larger mass of aggregate used in the base and sub-base layers of pavements.

Table 12. Quantity of Construction Materials in Roads and Sidewalks of KW in 2018

Materials (Mt) **City**	**Concrete**	**Aggregates**	**Asphalt**
Waterloo	0.322	8.194	1.661
Kitchener	0.711	14.663	2.946
Total	1.033	22.857	4.607

Figure 20 shows the distribution of materials in the roadway network of Kitchener and Waterloo. The downtown areas of both cities, which are located on the above and below of Kitchener and Waterloo boundaries, have a higher density of roads. However, these roads are mostly local roads with smaller MIs. Farther from the downtown areas, the number of roads decreases while the material composition of each road increases. This is due to the physical shape of the city where major roads are designed to be farther from the core of the city in order to reduce motor transportation and promote walking and cycling in downtown areas.

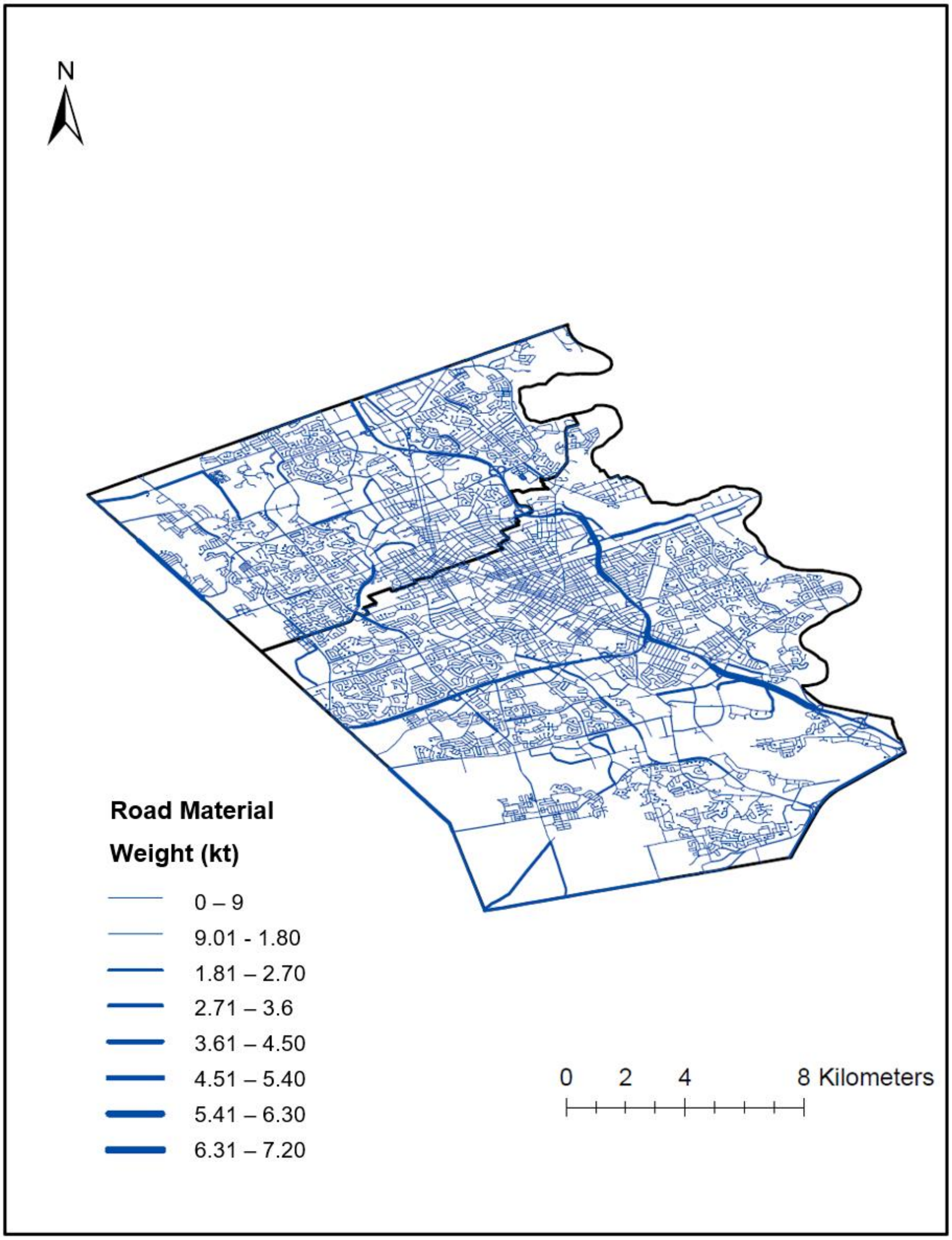

Figure 20. Distribution of Materials in Roads of Kitchener and Waterloo Showed by Road Thickness

Regional transportation master plan’s in both 2010 and 2018 was aimed to implement strategies to shift towards public transportation and encourage people to use more sustainable modes of transportation such as biking and public transportation (Region of Waterloo, 2018b). Therefore, the quantity of materials in roads is almost stable in the past 15 years. Only 2.180 Mt of materials were used to build new roads in Kitchener from 2003 to 2018 and 1.183 Mt in Waterloo. However, the existing roads still need scheduled maintenance, which results in continued material use. Almost 5.181Mt was consumed from 2003 to 2018 for road maintenance in Kitchener and 2.059 Mt in Waterloo. Only 0.268 Mt of this quantity is provided from recycled materials and the rest is supplied from virgin materials. The material use from 2003 to 2041 in road stocks is shown in Figure 21. The material consumption in this graph is represented cumulatively.

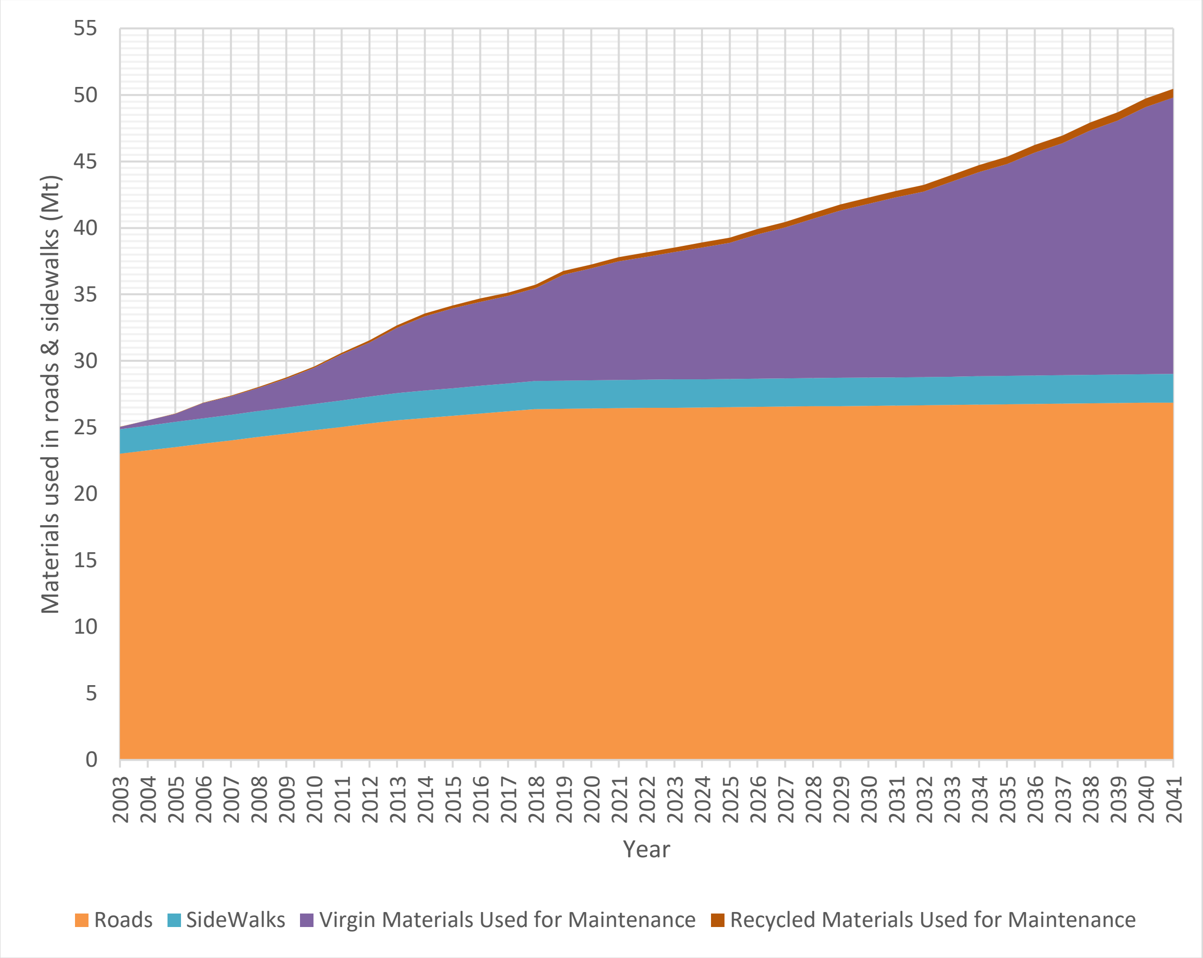

Figure 21. Cumulative Materials Consumption in Roads and Sidewalks in Kitchener and Waterloo from 2003 to 2041

In road maintenance processes, layers of the old pavement structure are removed to replace them with new materials. This could be either a resurfacing maintenance, where only the top layers are reconstructed, or if the pavement is in extremely bad condition a full pavement reconstruction is performed on all the layers. Removing old pavement produces waste which has a high potential for recycling. Around 25% of this quantity ends up in landfills, whereas the rest gets recycled. Only a small percentage of the 75% recycled pavement is permitted to be used in pavement structures due to its lack of strength. However, the remaining materials can be recycled into aggregate and concrete production. It is estimated that in KW around 1.810Mt of pavement waste ended up in landfills from 2003 to 2018 while 5.430 Mt was recycled. From this recycled quantity only 268kt was used in the two cities pavement maintenance. Figure 22 shows the distribution of pavement waste production in the KW area from 2003 to 2041. The quantity of waste production is different in every year and does not normally follow a pattern. This is mostly due to weather conditions in each year that affects the quality of pavements and the necessity to reconstruct the roads.

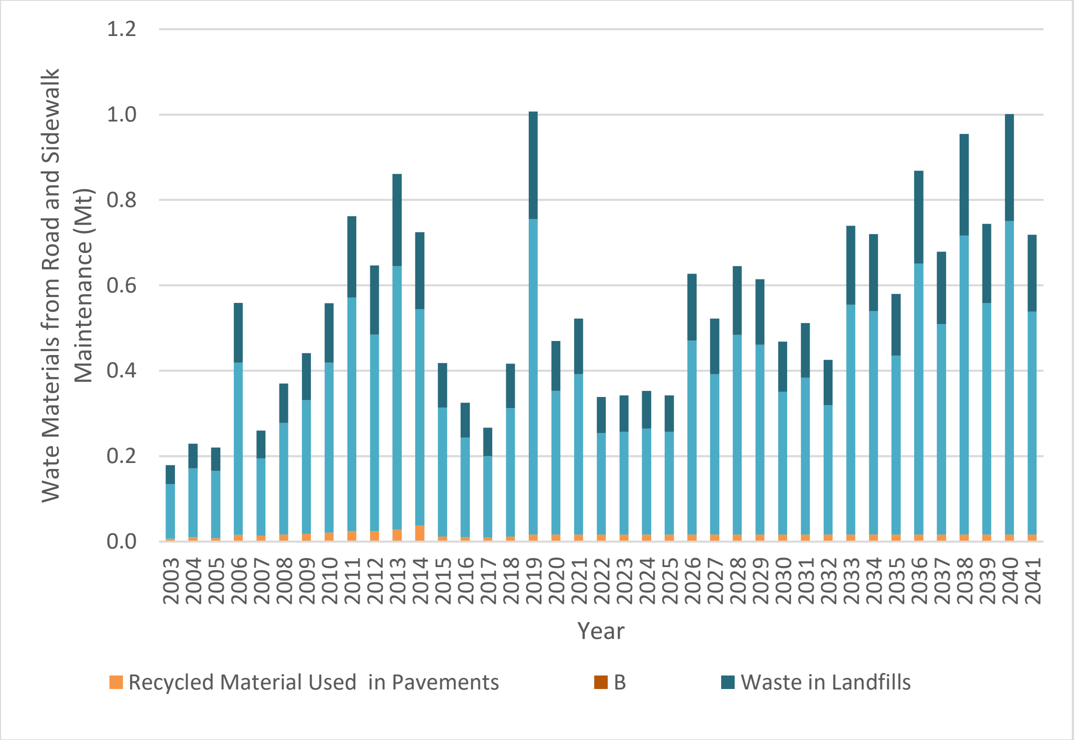

Figure 22. Waste Produced from Road Maintenance in Kitchener and Waterloo from 2003 to 2041

By applying the methodology to project the quantity of material stocks in the year 2041, it is estimated that as a result of the growth in building construction there will be 10.135 Mt of construction materials in the building stocks of Kitchener and 8.363 Mt in Waterloo. It should be noted that this quantity is calculated according to GIS building data on new built permits issued (Region of Waterloo, 2019b). In this projection, due to lack of sufficient data regarding the construction year of buildings in both cities, it is assumed that the previously built stocks as of 2018 are still existent in the system and have not reached the end of their lifespan. However, the projections will be more accurate if the information is gathered regarding the demolition and deconstruction activities in the urban system for the previously built buildings.

Studying the region's future road expansion plans indicates that by the year 2041, there will be 18.668 Mt of materials in the road stocks and 10.354 Mt of materials in the sidewalk stocks of Kitchener and Waterloo. Also, around 14.198 Mt of virgin materials will be used for maintenance purposes such as reconstruction and rehabilitation in both cities from 2003 to 2041. Only 20% of these materials are used in Waterloo and the remaining 80% is used for roads in Kitchener. This is mainly due to the existence of more roads in Kitchener with the need of maintenance according to the cities reports and asset management plans (City of Kitchener, 2012; City of Waterloo, 2015).

4.2 Greenhouse Gas Emissions from Construction Material Use in KW

The total GHG emissions resulting from the construction material use in KW in buildings, and road networks in 2018 are estimated to be 7.783 MtCO_2eq and 0.747 MtCO_2eq, respectively. This number will increase to 9.730 MtCO_2eq and 1.179 MtCO_2eq by 2041. More than 90% of this

GHG emission is related to the buildings. The disaggregated results showing the emissions for each type of material in buildings, roads and sidewalks are presented in Table 13 and Table 14. Since concrete has the highest use in KW it also has the highest total GHG emission. Steel is very carbon intensive. Therefore, despite its low use percentage in KW (only 3% of the total construction material use in buildings), it is responsible for around 22% of the GHG emissions.

Table 13. GHG Emission of Building Materials in 2018 and 2041

	GHG emissions ($MtCO_2eq$)							
Year	**Concrete**	**Wood**	**Brick**	**Gypsum**	**Aggregates**	**Asphalt**	**Steel**	**Total**
2018	1.896	1.405	1.021	1.518	0.068	0.016	1.857	7.783
2041	2.416	1.946	1.255	1.771	0.100	0.017	2.225	9.730

Table 14 GHG Emission of Road and Sidewalk Materials in 2018 and 2041

	GHG emissions ($MtCO_2eq$)				
Year	**Road Asphalt**	**Aggregate - Granular A**	**Aggregate - Granular B**	**PCC**	**Total**
2018	0.063	0.058	0.516	0.111	0.747
2041	0.079	0.065	0.923	0.113	1.179

Considering the year 2018, the total material stocks contained in the residential and non-residential buildings, roadways, and sidewalk stocks in the KW area are 64.738 Mt of construction materials, and the GHG emissions associated with this material use is 8.530 $MtCO_2eq$. Notwithstanding the limitations of this study, an estimation of the quantity of material stocks contained in the building, road and sidewalk infrastructure, and the GHG emissions for construction material use in KW is provided.

4.3 Sensitivity Analysis Results

4.3.1 Building Material Intensities

The results of the sensitivity analysis conducted on building MIs indicate that material stock of concrete in buildings is most affected by changing the MI followed by aggregates. Table 15 presents a summary of the results of the sensitivity analysis on building MIs.

Table 15. Sensitivity Analysis Results Summary regarding Building MIs

Material	**Mean MI (kg/m^2)**	**MI with -20% deviation from mean MI (kg/m^2)**	**MI with +20% deviation from Mean MI (kg/m^2)**	**Quantity of material in KW (kt)**	**Quantity of material in KW with -20% deviation from mean MI (kt)**	**Quantity of material in KW with +20% deviation from mean MI (kt)**	**% Change in MS with %20 deviation of mean MI**
Concrete	436	349	523	15933	12746	19120	8.79
Wood	102	82	123	2851	2281	3421	1.57
Brick	186	149	224	4861	3889	5833	2.68
Gypsum	86	69	103	1947	1557	2336	1.07
Aggregates	306	245	368	9151	7321	10982	5.05
Asphalt	9	7	10	300	240	360	0.17
Steel	79	63	94	1198	959	1438	0.66

4.3.2 Road Material Intensities

In the case of road MIs, the results of this sensitivity analysis show that in the roads, material stock of aggregate is most affected by changing the MI. Therefore, the calculation of the aggregate MIs should be done very precisely to produce accurate results. The results of this sensitivity analysis are presented in Table 16.

Table 16. Sensitivity Analysis Results Summary regarding Road and Sidewalk MIs

Material	**Mean MI (kg/m^2)**	**MI with -20% deviation from mean MI (kg/m^2)**	**MI with +20% deviation from Mean MI (kg/m^2)**	**Quantity of material in KW Roads and Sidewalks (kt)**	**Quantity of material in KW roads and sidewalks with -20% deviation from mean MI (kt)**	**Quantity of material in KW roads and sidewalks with+20% deviation from mean MI (kt)**	**% Change in road and sidewalk MS with %20 deviation of mean MI**
Aggregates	271	217	325	22857	18286	27429	16.65%
Asphalt	1366	1093	1639	4607	3686	5528	3.35%
PCC	395	316	474	1033	826	1240	0.75%

4.3.3 Building Stories in Waterloo

Another sensitivity analysis was also performed on the number of building stories in the city of Waterloo due the limited data and assumptions that were made to add the story numbers to the dataset in the City of Waterloo. The results of the sensitivity analysis show that the total quantity of building material stocks is most sensitive to the number of stories of single/semi-detached homes. This is mainly because single-family homes make up most of the buildings in KW. The next most effective story number of the building groups is the townhouses. However, the MSA results of are significantly less sensitive to the number of stories in townhouses compared to the number of stories in single/semi-detached homes. The sensitivity analysis results are available in Table 17.

Table 17. Sensitivity Analysis Results Summary regarding Building Stories in Waterloo

Building Type	Average stories	Average Stories with -20% deviation	Average Stories with +20% deviation	Quantity of MS in Waterloo (kt)	Quantity of Building MS in Waterloo with -20% deviation from average number of stories (kt)	Quantity of Building MS in Waterloo with+20% deviation from average number of stories (kt)	% Change in Waterloo Building MS with %20 deviation of average stories
Single/Semi	1.74	1.39	2.09	8386	6709	10064	12.25
Townhouse	2.00	1.60	2.40	1509	1207	1811	2.20
Multiple	4.25	3.40	5.10	1287	1030	1544	1.88
Commercial (Office)	2.31	1.85	2.77	132	106	159	0.19
Commercial (Other)	1.53	1.22	1.84	424	339	509	0.62
Industrial	1.50	1.20	1.80	1338	1071	1606	1.96
Institutional	2.83	2.26	3.40	614	492	737	0.90

4.4 Discussion

4.4.1 Comparative Analysis of the Results

On a per capita basis, Waterloo has a slightly greater construction material consumption compared to Kitchener with 171 t/cap material consumption in Waterloo and 160 t/cap in Kitchener. However, this difference is minor, and it can be due to the data gaps in Waterloo's databases.

Comparing the results of this MSA study with other case studies around the world, these two North American cities seem to have a similar range of construction material stocks per capita compared to the other case studies. For instance, in Vienna, a 210 t/cap of material consumption was calculated in 2013 for building stocks (Kleemann et al., 2016), which is around 20% higher than the material consumption in Kitchener and Waterloo. In Japan, the per capita material consumption is around 110 t/cap (Tanikawa et al., 2015), which is slightly lower than of Kitchener and Waterloo in both buildings and roads. Padua, a mid-size city in Italy, had a 209 t/cap construction material consumption in 2007 considering all buildings (Miatto et al., 2019). Also in 2007, Chiclayo city in Peru was estimated to have 47 t/cap construction material consumption in the residential building sector (Mesta et al., 2018), which is significantly lower than in the KW area due to the differences in construction practices in these two urban areas and their physical shape.

The range of per capita material consumption is different in each urban area and it is related to multiple reasons. Construction norms and regulations, climate, topography, common engineering practices, and available construction materials in the area are some of the factors that affect the material use rate in cities (Fishman et al., 2014). It is difficult to compare the results of different cities since each study has included different types of stocks and construction materials in their analysis. An accurate comparison is only possible if the conditions are similar in the compared areas. A summary of the comparative analysis with some recent studies is provided in Table 18.

Table 18. Comparison of Material Stocks of KW with other Urban Areas

Urban System	Year	Type of Stocks	Total Weight of Materials (Mt)	Per capita Material Use (t/cap)	Source
Kitchener and Waterloo	2018	Buildings - Roads	64.739	164	This Research
Grenada	2014	Buildings	11.9	112	(Symmes et al., 2019)
Padua	2007	Buildings	44	209	(Miatto et al., 2019)
Taipei City	2014	Buildings	186	68	(Cheng et al., 2018)
Chiclayo City	2007	Residential Buildings	24.4	47	(Mesta et al., 2018)
Vienna	2013	Buildings	380	210	(Kleeman et al., 2016)

In the road and sidewalk infrastructure stocks, the difference between the quantity in Kitchener and Waterloo is mostly because of the size of the cities and the number of roads. Therefore, by excluding the effect of size and calculating the quantity of road material stocks per area in Kitchener and Waterloo, the results are almost similar with Waterloo having a slightly overall bigger material intensity. In Kitchener, the material intensity of road and sidewalk material stocks is around 0.132 t/m^2 and in Waterloo 0.159 t/m^2.

The per capita material consumption in road and sidewalks of KW is 72 t/cap. Comparing the MSA results in the road and sidewalk stocks is difficult since most city level MSA studies have not included roads in their analysis. However, at the country level, the study conducted by Miatto et al. (2017) shows the material stocks in roads in USA in 2015 was estimated to be 15.1 billion tonnes which translates into a per capita consumption rate of 41 t/cap (Miatto et al., 2017). A similar study conducted in the road networks of Vietnam indicates 30 t/cap consumption rate in 2012 (Nguyen and Fishman, 2018). Since Vietnam is a developing country it is predicted that the consumption rate will increase as more construction activities take place in the country, whereas in USA it was mentioned that the quantity of materials in road stocks have been almost consistent in the past decade and therefore, the consumption rate is decreasing (Miatto et al., 2017;Nguyen and Fishman, 2018).

The interesting point about the road infrastructure is that up until 2018, a quantity equal to more than 25% of the total material in the existing roads is used only for maintenance and by 2041 material use for maintenance will reach a quantity almost equal to the total mass of road stocks in KW in 2041. However, forecasting maintenance material use is challenging; as the population grows and the traffic load on roads increases, the service life of the pavement decreases due to higher pressure (Tighe, Ken, and Haas, 2007). At the same time, technological advancements enable engineers to design longer lasting and higher quality pavement mixes and structure. Therefore, there are many factors that affect the maintenance schedule of roads. However, a rough estimation is a useful starting point for future projections of material consumptions.

Old pavements have high recycling potential; however, according to municipal regulations, only a small percentage of recycled pavement is permitted to be used in pavement construction. Improving RAP quality and designing longer-lasting pavements can help reduce material use for maintenance purposes. In Ontario, perpetual pavements are designed and constructed in three trial areas. Perpetual pavements are flexible pavement structures designed in three layers using a deep-strength asphaltic mix (Ministry of Transportation, 2013). These pavements have longer service lives, around 50 years, and require less rehabilitation and maintenance compared to conventional pavements (Ponniah et al., 2009).

Looking at the projections, materials in the roads and sidewalks' stocks in 2041 do not indicate a significant growth of material consumption from 2018. This is because of the Region's transportation plan for the future that focuses on the expansion of public transportation and providing the infrastructure for more sustainable modes of transportation (Region of Waterloo, 2018b). Therefore, there will not be much road expansion projects by 2041. Even comparing the number and distribution of the roads in the City of Kitchener available from the 1992 with 2018, it is evident that there is not much difference between the two years, which are roughly two decades apart. Figure 23 shows the visual comparison of the roads from 1992 to 2018 that was developed using Waterloo Region's Open database for historical roads in Kitchener (Region of Waterloo, 2019b).

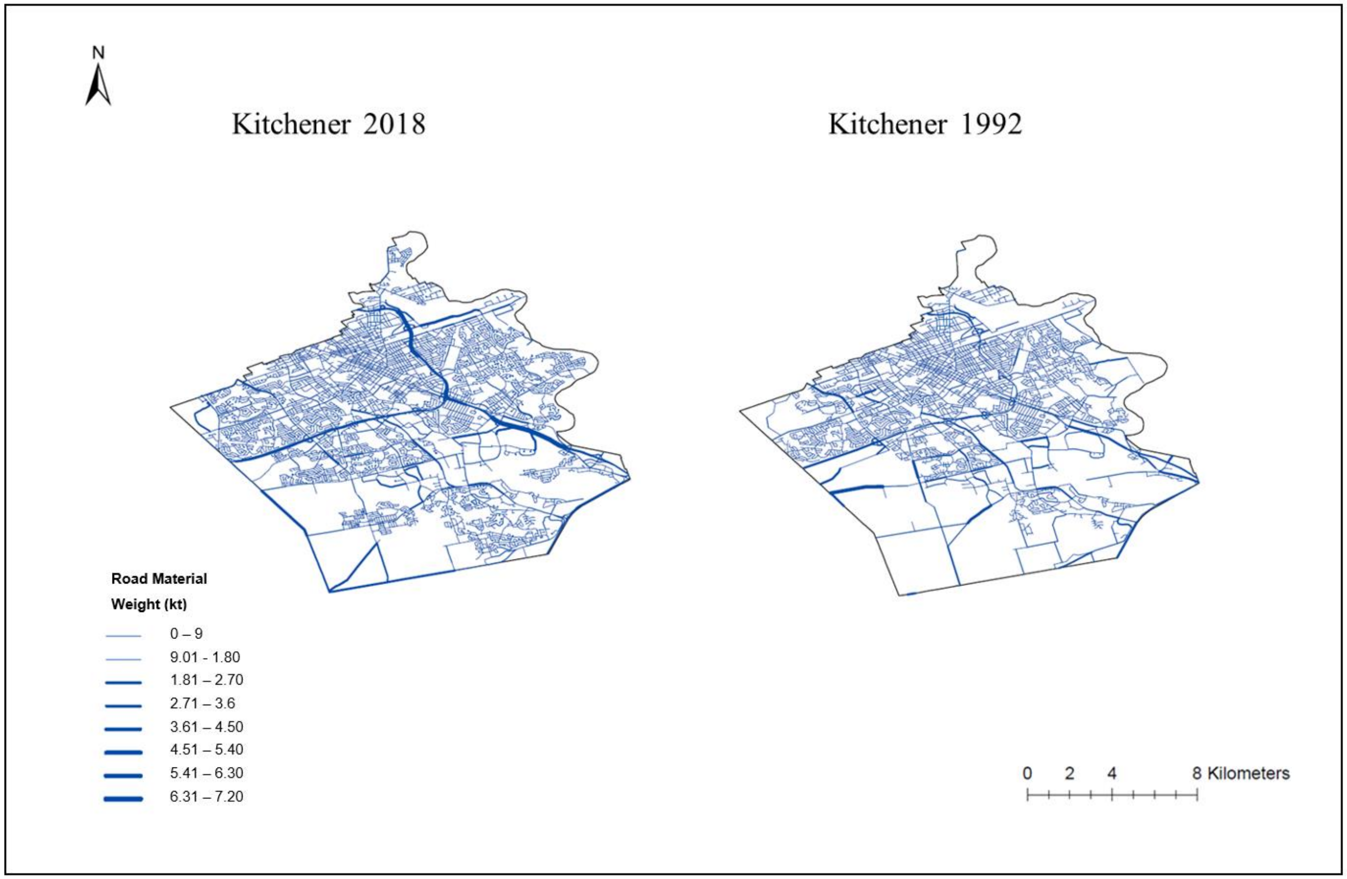

Figure 23. Comparison of the Kitchener’s Road Network Material Distribution in 1992 and 2019

The quantity of construction materials in building, roads, and sidewalk stocks has grown 23% in the KW area in a 15-year time period from 2003 to 2018. Based on the projections, by 2041, there will be a 24% growth in material stocks in 23 years, from 2018. These results show that the growth rate of material stocks will slightly decrease, which is mainly because of reduction in road expansion plans in the road sector and a shift towards more multi-family homes building construction that has a less overall per capita material use compared to single-family homes.

4.4.2 Policy Implications

There is a variety of theoretical work conducted in the field of urban flows and stocks and studies relevant to urban metabolism at different scales, from the scale of small neighborhoods to larger scales, such as multiple countries. However, the gap between theoretical work and feasible applications is yet to be filled (Kennedy et al., 2011). By interpreting the results of theoretical studies in ways that are useful and understandable, effective changes can be implemented in cities. In order to manage the material use, we need to measure what we have already consumed. Being aware of the construction materials embedded in cities will help municipalities better identify the resources at risk and develop more sustainable resource management plan.

In this research, using the available GIS data from the region, a more comprehensive data set is developed that consists of the building, road, and sidewalk stocks' material compositions for the studied materials for each stock alongside other existing characteristics such as footprint, use, number of stories, and year of construction for buildings, in addition to length, width and type for roads. This dataset can be expanded as new stocks are built in the cities and can be used as a valuable source for applying urban mining strategies to construction materials. This can be done by comparing the required materials for building or maintaining future stocks with the current available materials. By investing in the reusing and recycling potentials of the in-use material stocks, cities will be able to rely on these materials for developments and decrease the use of virgin materials. The available datasets will help locate the future material flows and bring insights regarding the quantity of these potential material flows (Tanikawa et al., 2015). Therefore, the future material waste flows can be treated as useful input material flows which will help municipalities take effective steps towards achieving circular economy, which is a more sustainable approach than linear economy (Korhonen, Honkasalo, and Seppälä, 2017). Material loops can be partially closed in construction activities by increasing the use of recycled materials and preventing the entrance of new virgin material flows in construction activities.

MSA results also help indicate the material hotspots in cities and shed light on the required intervention points in construction material consumption patterns in urban areas. Building awareness of the material use conditions by measuring the amount of in-use materials helps in waste and resource management in the construction sector. The next step is to seek consumption reduction strategies to decrease the use of virgin materials. Less virgin material use means less need for natural resources and landfill space. Construction and demolition waste normally end up in landfills and take up a lot of landfill space (Wu et al., 2014). Providing suitable landfill sites in urban areas has always been a challenge due to the toxicity that these landfills produce affecting the population living in the city (Vrijheid, 2000). Therefore, by reducing or even preventing construction materials from ending up in landfills, the pressure on landfill sites in urban areas will decrease.

Among the construction materials studied in this research, aggregates have a special position. The Ontario Stone, Sand, and Gravel Association (OSSGA) have estimated that each year around 164 Mt of aggregate is being consumed in Ontario (OSSGA, 2018). Supplying aggregates to meet the increasing demand of this material will be challenging in the coming years (Ministry of Natural Resources and Forestry, 2016). At the same time, this research shows that in 2018, 32 Mt of aggregates were embedded in KW. Although these materials are currently in-use, considering their recycling potential can help in planning for future aggregate demands.

Canadian cities spend over $10 Billion annually on pavement maintenance (Hajek, Hein, and Olidis, 2004). This translates into millions of tonnes of pavement materials getting used to rebuild pavement structures and simultaneously millions of tonnes of pavement waste production. Municipalities do not permit the use of more than a certain percentage of RAP, which is a type of recycled asphalt, in pavement construction. Therefore, even if all the waste from pavement deconstruction is recycled there is no practical use for it in pavement sections. Improving RAP quality that has the essential strength to be used more widely should be assessed by pavement engineers. The technical details for enhancing RAP quality do not fit into the scope of this research. Here, it is only mentioned as a policy recommendation derived from the results of this study. Professionals in the field of road and pavement design can further investigate the production of recycled pavement layers that can substitute virgin materials in pavement construction.

The GHG emissions associated with the material use for both constructing new stocks or maintaining the current ones increases with the use of virgin materials. Decreasing virgin material use by implementing effective resources and waste management strategies will directly impact the

GHG emissions and help cities contribute to mitigating GHG emissions and achieve their GHG reduction targets. Buildings account for 40 percent of the global GHG emissions (UNEP, 2017). Construction material use in buildings is responsible for a fraction of these emissions which can be better controlled with the help of MSA results by reducing virgin material use and bringing awareness regarding the recycling and reusing potential of existing materials.

4.4.3 Limitations of this study

This study carried out a data-intensive exercise in material stock accounting for the Kitchener-Waterloo area to place the weight of the two cities among the results of other published weights of cities globally. However, the methodology and results include some limitations.

The main limitation of this study is the lack of localized data for all groups of stocks to develop the MIs. Some of the contacted construction companies had no motivation in sharing their information. In some cases, secondary data was used which results in less accurate results for KW. Also, municipalities have different data gathering systems which makes it difficult to apply a unified methodology to all the cities and finding consistent datasets. This issue was evident in this research where there were problems in finding similar data in two cities that were located in the same region and had very similar general policies and governed by the same political jurisdiction.

Another limitation to this study is the scale of the work. This study covered seven construction material types. However, there are much more materials that are used in the built environment, specifically in the construction of buildings. The stock types that were included in this research were also limited to buildings, roads, and sidewalks. As more stock types and materials are included in the analysis a more accurate estimation of the weight would be possible.

Regarding the temporal scale, because of lack of data for all stock groups, the material use was only studied from 2003to 2018. However, if more historic data was available, the consumption pattern would be better understood in longer time period.

In this research it was attempted to present the results as disaggregated as possible. However, the data only allowed to go as far as it was shown. A critique that is mentioned for MSA research is how the aggregated results do not actually have significant use in reducing virgin construction material use in the industry. However, when the results are presented in a more disaggregated and refined manner, where the quantity of each material used for every different building type is more clearly determined, the engineers would be able to better assess the availability of construction materials for their purposes.

Chapter 5: Conclusions

This thesis investigated the construction materials in all types of building, roadway, and sidewalk stocks located in Kitchener and Waterloo in a retrospective bottom-up approach from 2003 to 2018. The results of the study show that Kitchener and Waterloo have a total of 65 Mt of materials with 24 Mt in Waterloo and 41 Mt in Kitchener. The difference between the quantity of construction materials in the two cities is mostly due to the larger population that lives in Kitchener and the bigger area that the city of Kitchener covers. The per capita construction material use is 171t/cap in Kitchener and 160 t/cap in Waterloo, which is rather similar in both cities. Also, the construction material intensity is 0.299 t/m^2 in Kitchener and 0.375 t/m^2 in Waterloo. The results also indicated that around 77 Mt of materials will be accumulated in KW's building and road stocks by 2041.

The roads and sidewalks of the KW area account for 44% of the total materials quantified in this research. Aside from the materials that are currently embedded in the roads and sidewalks, around 1.2 t/cap of construction materials are used annually for different road maintenance activities such as, resurfacing or full pavement reconstruction in this area. Even though 75% of the old pavement waste has the potential to be recycled, only 5% of the quantity of materials required for maintenance was used in 2003 to 2018 from recycled materials. This is due to the city regulations that only allow a limited quantity of RAP in pavement structures.

In this research it was estimated that the construction materials in buildings, roads, and sidewalks have produced 8.5 MtCO$_2$eq of GHGs in 2018. This number will grow to around 11 MtCO$_2$eq by 2041. Considering the emission factors of different construction materials, cities can shift from using GHG intensive materials such as steel to more sustainable alternatives in the construction sector.

The future paths that can stem from this research can be both at the macro and micro levels. A useful potential work is to apply the methodology to other built environment stocks such as railways, pipelines, and other infrastructure. Specifically, with the growth of new Light Rail Transit (LRT) system in the Region of Waterloo and the plans to implement the second phase of the LRT soon, information regarding the construction material use for this infrastructure can be valuable to make a comparison of this aspect with other transportation infrastructure such as roads. Also, the spatial scale of the work can be expanded to include areas in the Region, and beyond that, to include more cities in Ontario. By this means, a more comprehensive data set can be developed that would enable policymakers to compare the material consumption of different cities and make the required interventions. However, as the scale of the research expands, collecting the required data gets more challenging.

Another potential approach as a follow-up to this work is to scale down and focus on detailed analysis of building stock material composition and their qualities after demolition for recycling and reuse purposes. This will help produce more disaggregated results to implement urban mining strategies more accurately.

A problem with used construction materials in different built environment stocks is that the quality decreases significantly as time passes to the point where they will not have the required strength to support the structural design of the stock. Therefore, even though the material exists, and the quantity and availability are clear, it is difficult to state how much of this material can be reused or recycled. According to some discussions with expert engineers and researchers in the field, developing a methodology to help assess the quality of materials on demolition sites can be extremely helpful in preventing construction materials from ending up in landfills. So, putting together the results of MSA research with a methodology that evaluates the material performance and strength will help the construction sector be more sustainable.

Finally, a useful approach that could be added to this work is to get into a deeper investigation of future demand of different construction materials' categories. Therefore, by knowing the required quantity for the future and the quantity of available materials in the city, an estimation can be provided on how much of the in-use materials can be used in supporting the future generation's construction material demand.

A suggestion for municipalities is to continuously keep track of the construction materials that are being used in the construction sector. This can be done easily by adding on to the current developed database, especially the building material data. Canadian municipalities typically keep track of the building permits that are issued in the city. Experience from this research shows that permit data is collected spatially and stored in a geospatial format. Therefore, the locations of the buildings are clear. A section can be added to this dataset, which will be filled out by the builders' estimation of utilized construction materials when the project is completed. All projects go through a material estimation process before starting the construction phase in order to estimate the required budget. So, calculating this number will not necessarily constitute additional work. However, by saving the material composition information of buildings, projecting demolition waste will be possible. Using this information and assessing the quality of available materials after demolition, the recycling and reuse potential of the materials canl be determined. Therefore, instead of using virgin construction materials to construct new buildings, a portion of these required materials can be provided from used materials. This is a method that cities can use to apply urban mining strategies in the construction sector.

Considering the high contribution of national GDP by cities, the economy of urban areas will keep growing. So far, material consumption proved to be an inseparable part of economic development. It is hoped that the results of this study can effectively demonstrate the need to change consumption patterns and the necessity to move towards sustainable development strategies.

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Appendix A: Used Data Sources and Maps

Developing the building material intensity maps presented in Figure 18 and Figure 19 was done using the datasets presented in Table 19 and Table 20. These datasets present the districts in Kitchener and Waterloo, and are available in the Region of Waterloo Open Database (Region of Waterloo, 2019b)

Table 19. City of Waterloo Districts (Region of Waterloo, 2019b)

DISTRICT NAME	AREA (m^2)
Central	4394591
Westmount	1439181
Beechwood	3206577
Columbia Hills	2907469
Conservation Meadows	910450
Beaver Creek Meadows	1561202
Country Squire	651110
Lakeshore North	1738294
Clair Hills	2264527
Northland	1602623
Erbsville	908625
Conestoga	2965580
Lincoln	4657958
West Hill	1604820
Westvale	1919152
Columbia	2826533
Willowdale	3166907
Dearborn	1724741
Lexington	3117549
Beechwood West	3629253
UW Northwest Campus	1090282
Eastbridge	2742210
Lakeshore	1997654
Rural East	3030034
Laurelwood	1252926
UW Research and Technology Park	1056397

Table 20. City of Kitchener Districts (Region of Waterloo, 2019b)

DISTRICT NAME	AREA (m^2)
VICTORIA HILLS	2219459
ST. MARYS	824139
COUNTRY HILLS WEST	1848377
HURON SOUTH	2540667
IDLEWOOD	1962900
TRILLIUM INDUSTRIAL PARK	6138271
COUNTRY HILLS EAST	1014467
COUNTRY HILLS	1037216
ROSEMOUNT	2631935
HERITAGE PARK	1912306
EASTWOOD	713625
SOUTHDALE	1313001
BRIGADOON	2292148
MEINZINGER PARK-LAKESIDE	1262539
VANIER	3506218
HIDDEN VALLEY	2187717
STANLEY PARK	3269095
ALPINE	1748961
PIONEER TOWER WEST	5420386
GRAND RIVER NORTH	2772273
CENTREVILLE CHICOPEE	4408965
GRAND RIVER SOUTH	4799233
CENTRAL FREDERICK	1097373
AUDITORIUM	951580
CIVIC CENTRE	328484
SOUTH PLAINS	5965143
VICTORIA NORTH	3320188
FOREST HEIGHTS	4954347
BRIDGEPORT WEST	1434869
HIGHLAND WEST	5189594
WESTMOUNT	1916466
FAIRFIELD	1247805
BRIDGEPORT NORTH	2299939
BRIDGEPORT EAST	2338426
DUNDEE	4607582
PIONEER TOWER EAST	1896237
CEDAR HILL	370317
KING EAST	635621

ROCKWAY	1133137
MILL COURTLAND WOODSIDE PARK	1712310
VICTORIA PARK	744329
CITY COMMERCIAL CORE	924124
DOON SOUTH	8805389
PIONEER PARK	3605492
LOWER DOON	2268205
FOREST HILL	1865136
LAURENTIAN HILLS	2980564
LAURENTIAN WEST	5598818
CHERRY HILL	1116921
KW HOSPITAL	858815
MT. HOPE HURON PARK	1485705
ROSENBERG	4302973
TRUSSLER	2701533
HURON PARK	2588476
NORTHWARD	1227954

The map of the districts in the City of Waterloo is presented in Figure 24.

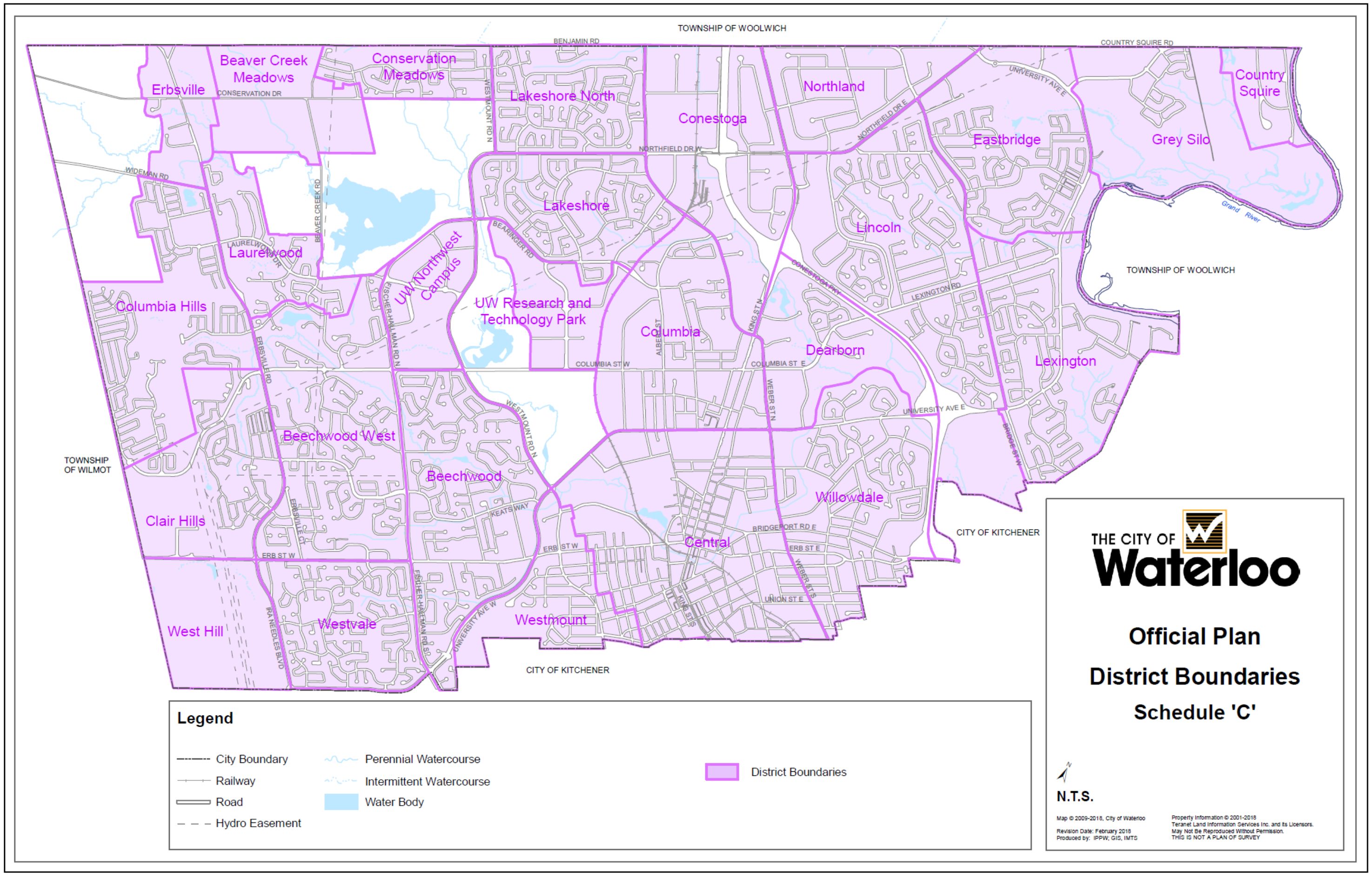

Figure 24. Map of the City of Waterloo’s Districts (City of Waterloo, 2012)

Figure 25 shows the map of the zones in the City of Waterloo. The GIS format of this map was used to develop Waterloo's Buildings Construction Material Dataset

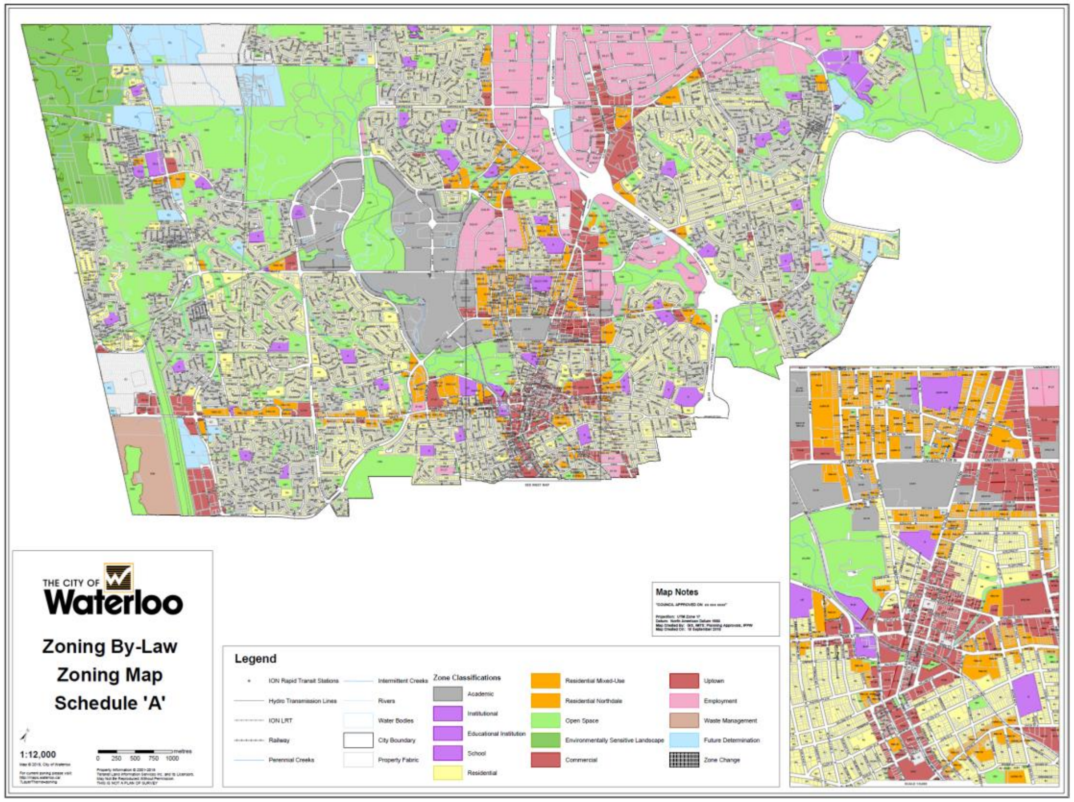

Figure 25. Zones in the City of Waterloo (City of Waterloo, 2018)

Figure 26 shows the road type in the city of Waterloo. To fill the gap in the City of Waterloo's "Roads" data, the road types were added manually using the roads names.

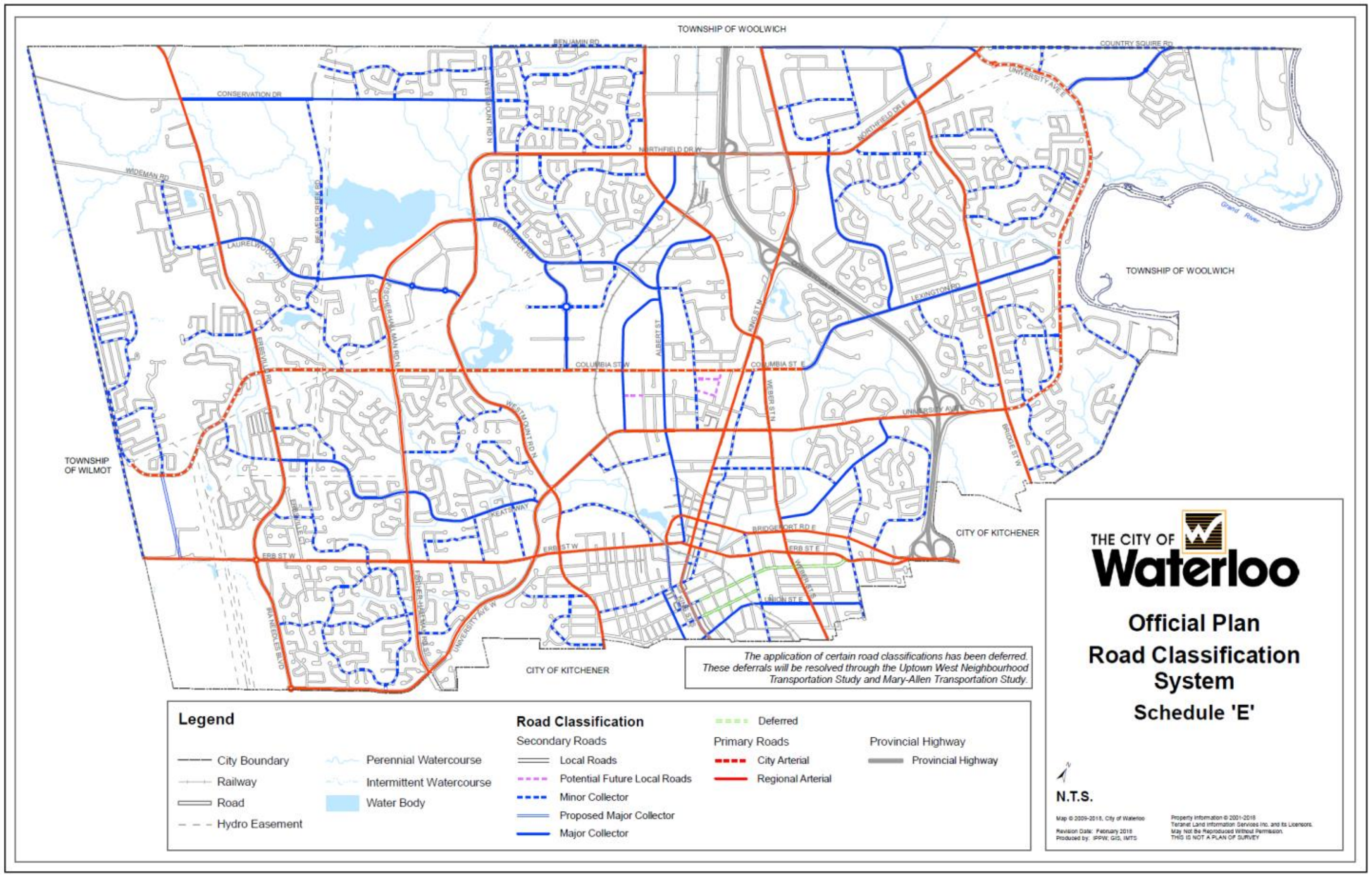

Figure 26. Road Classifications in Waterloo (City of Waterloo, 2012)

Appendix B: Developed Datasets

Various databases are used in this research. These databases are all extracted from the Region of Waterloo's open database (Region of Waterloo, 2019b). These databases are in the format of GIS files that can be exported into Excel files for calculations. The main databases used for buildings are: Kitchener Building Outlines, which helped develop Kitchener Buildings Construction Material dataset, and Waterloo Building Footprints, Waterloo District Plans, Waterloo Zoning Plans, and Waterloo Building Permits, which are used to develop Waterloo Buildings Construction Material dataset. For the roads and sidewalks, the following databases are used: Kitchener Roads and Sidewalks, Waterloo Roads and Sidewalks, Kitchener Road Closures, Waterloo Historic Road Closures. These databases consist of large amounts of data therefore, a sample of the developed datasets are provided in the following tables.

Table 21. Kitchener Buildings Construction Material Dataset (1/3)

Column Tag	OBJECTID	CATEGORY	SUBCATEGORY	STORIES	LOCATION	YEAR_BUILT	Shape_Area (m2)	GFA (m2)
Description	Available in the database	Available in database - Includes: Residential, Commercial, Industrial, Institutional	Available in database - Includes: Single/Semi, Townhouse, Multiple, Commercial, Office, Educational, Hospital	Available in the dataset - In case of missing data used google street view	Available in the dataset - In case of missing data used google maps	Available in the database	Calculated with ArcMap	Calculated by multiplying "Shape_Area" in "STORIES"
Reference	Kitchener “Building Outlines” GIS Data	Kitchener “Building Outlines” GIS Data	Kitchener “Building Outlines” GIS Data	Kitchener GIS Building Outlines Data - Google Street View	Kitchener GIS Building Outlines Data - Google Maps	Kitchener GIS Building Outlines Data	Calculated	Calculated
Samples	997129	RESIDENTIAL	TOWNHOUSE	2	139 KRAFT AVE	1962	64	33
	997130	RESIDENTIAL	SINGLE/SEMI/DUPLEX	1	139 HUBER ST	2013	115	52
	997971	RESIDENTIAL	MULTIPLE	4	155 ST LEGER ST	2016	1492	5967
	997683	COMMERCIAL	COMMERCIAL	1	4 CHARLES ST E	2010	2894	2894

Table 22. Kitchener Buildings Construction Material Dataset (2/3)

Column Tag	Concrete (kg/m^2)	Wood (kg/m^2)	Brick (kg/m^2)	Gypsum (kg/m^2)	Aggregates (kg/m^2)	Asphalt (kg/m^2)	Steel (kg/m^2)	Total (kg/m^2)
Description	MIs extracted from table 2 for each building category							
Reference	Calculated from Mentioned Sources in Section 3.2.1.1							
Samples	574	129	104	57	717	-	-	1581
	650	124	73	53	716	-	-	1616
	165	163	263	-	162	-	56	810
	426	2	-	-	66	20	74	589

Table 23. Kitchener Buildings Construction Material Dataset (3/3)

Column Tag	W_Conc (kg)	W_Wood (kg)	W_Brick (kg)	W_Gyps (kg)	W_Agg (kg)	W_Asph (kg)	W_st (kg)	W_tot (kg)
Description	Calculated by multiplying MIs in GFA for each Material							Sum of all the material quantities
Reference	Calculated							Calculated
Samples	73071	16482	13222	7304	91262	-	-	201342
	74506	14255	8392	6110	82076	-	-	185340
	986474	972552	1569210	-	966586	-	336117	4830939
	1233801	5383	-	-	191938	58416	214886	1704424

Table 24. Waterloo Buildings Construction Material Dataset (1/3)

Column Tag	OBJECTID	AREA (m^2)	ZONE	DISTNAME	ADDRESS	PERMIT	ISSUEDATE
Description	Available in database	Calculated with ArcMap	Available in database after "Spatial Join" - Indicates the Zone of the building	Available in database after "Spatial Join" - Indicate the district of the buildings	Available in database after "Spatial Join" - In case of missing data used google maps	Available in database after "Spatial Join" - A short description of the building permits	Available in database after "Spatial Join" - Date of permit issue data used for construction year
Reference	City of Waterloo "Building Footprints" GIS Data	Calculated	City of Waterloo Building Footprints GIS Data	City of Waterloo "District Plans" GIS Data	City of Waterloo "Building Permits" GIS Data – Google Maps	City of Waterloo "Building Permits" GIS Data	City of Waterloo "Building Permits" GIS Data
Samples	21432	75	FR	Clair Hills	669 ZERMATT DR	Residential Building	2001
	19086	435	MD3	Beechwood	115 REIBER CRT	Residential Building (multi)	2001
	24159	3016	(H)NC4-	Columbia	140 UNIVERSITY AVE W	Non-Residential	2000
	29677	183	(H)NC6-25	Columbia	9 HICKORY ST W	Residential Garage/Carport	2002

Table 25. Waterloo Buildings Construction Material Dataset (2/3)

Column Tag	**Category**	**Subcategory**	**Stories**	**GFA (m^2)**	**Concrete (kg/m^2)**	**Wood (kg/m^2)**	**Brick (kg/m^2)**	**Gypsum (kg/m^2)**	**Aggregates (kg/m^2)**	**Asphalt (kg/m^2)**	**Steel (kg/m^2)**	**Total (kg/m^2)**
Description	Assumed based on "ZONE_LABEL", "DISTNAME", "PERMITDESC" and Google Street View			Calculated by multiplying "AREA" in "Stories"	MIs extracted from table 2 for each building category							
Reference	Assumptions			Calculated	Calculated from Mentioned Sources in Section 3.2.1.1							
Samples	Residential	Single detached	2	150	650	124	73	53	716	-	-	1616
	Residential	Townhouse	2	870	574	129	104	57	717	-	-	1581
	commercial	store	1.5	4524	426	2	0	0	66	20	74	589
	Residential	Apartment	3	550	165	163	263	0	162	-	56	810

Table 26. Waterloo Buildings Construction Material Dataset (3/3)

Column Tag	**W_Conc (kg)**	**W_Wood (kg)**	**W_Brick (kg)**	**W_Gyps (kg)**	**W_Agg (kg)**	**W_Asph (kg)**	**W_st (kg)**	**W_tot (kg)**
Description	Calculated by multiplying MIs in GFA for each Material							Sum of all the material quantities
Reference	Calculated							Calculated
Samples	97376	18631	10968	7986	107270	-	-	242232
	499252	112613	90337	49904	623540	-	-	1375647
	1928531	8414	-	-	300015	91309	335884	2664153
	91014	89730	144779	-	89179	-	31011	445713

Table 27. Kitchener Road and Sidewalk Material Dataset (1/2)

Column Tag	**OBJECTID**	**STREET**	**FROM_STREET**	**TO_STREET**	**CATEGORY**	**PAVEMENT_WIDTH**	**Length (m)**
Description	Available in database	Available in database	Available in database – Starting point of road	Available in database - Ending point of road	Available in database	Available in database – Shows the width of Pavements	Calculated with ArcMap
Reference	Kitchener "Roads" GIS Data	Kitchener "Roads" GIS Data	Kitchener "Roads" GIS Data	Kitchener "Roads" GIS Data	Kitchener "Roads" GIS Data	Kitchener "Roads" GIS Data	Calculated
Samples	52802	FAIRWAY RD N	NORTH HILL PL	OLD CHICOPEE TRAIL	ARTERIAL	15	171.5477
	52803	BLACK WALNUT DR	CARLYLE DR	BIEHN DR	MINOR COLLECTOR	10	153.4332
	52804	BECHTEL DR	PIONEER DR	DOON VILLAGE RD	MINOR COLLECTOR	10	320.1055
	52805	ANVIL ST	WHIPPLETREE PL	FARMINGTON PL	LOCAL	9	101.9949

Table 28. Kitchener Road and Sidewalk Material Dataset (2/2)

Column Tag	**HL3 (Kg/m^2)**	**HL4 (Kg/m^2)**	**Granular A (Kg/m^2)**	**Granular B (Kg/m^2)**	**MI (Kg/m^2)**	**W_HL3 (kg)**	**W_HL4 (kg)**	**W_GranA (kg)**	**W_GranB (kg)**	**W_tot (kg)**
Description	MIs extracted from tables 4 to 9 for each road category					Calculated by multiplying MIs in "PAVEMENT_WIDTH" and "Length" for each Material				Sum of all the material quantities
Reference	Calculated from Mentioned Sources in Section 3.2.2.1					Calculated				Calculated
Samples	94	310.7	345	1200	1948	241882	799498	887759	3087859	5016999
	94	179.25	345	1080	1698	144227	275029	529344	1657079	2605679
	94	179.25	345	1080	1698	300899	573789	1104364	3457139	5436191
	94	143.4	345	960	1542	86287	131634	316694	881236.2	1415853

Table 29. Waterloo Road and Sidewalk Material Dataset (1/2)

Column Tag	OBJECTID	STREET_NM	FROM_STR	TO_STR	LENGTH (m)	Type
Description	Available in database	Available in database	Available in database - Starting point of road	Available in database - Ending point of road	Calculated with ArcMap	Added Manually from PDF Map (Figure 26)
Reference	Waterloo "Roads" GIS Data	Waterloo "Roads" GIS Data	Waterloo "Roads" GIS Data	Waterloo "Roads" GIS Data	Calculated	(City of Waterloo, 2012)
Samples	30496	ALLEN ST E	KING ST S	DODDS LANE	54	Local Roads
	28867	AINSWORTH CRT	WINCHESTER DR	AINSWORTH CRT	80	Local Roads
	30482	ALBERT ST	SEAGRAM DR	UNIVERSITY AVE W	237	Major Collector
	29533	ALEXANDRA AVE	EMPIRE ST	MELBOURNE CRES	254	Minor Collector

Table 30. Waterloo Road and Sidewalk Material Dataset (2/2)

Column Tag	**HL3 (Kg/m)**	**HL4 (Kg/m)**	**Granular A (Kg/m)**	**Granular B (Kg/m)**	**MI (Kg/m)**	**W_HL3 (kg)**	**W_HL4 (kg)**	**W_GranA (kg)**	**W_GranB (kg)**	**W_tot (kg)**
Description	MIs extracted from tables 4 to 9 for each road category					Calculated by multiplying MIs in "LENGTH" for each Material				Sum of all the material quantities
Reference	Calculated from Mentioned Sources in Section 3.2.2.1					Calculated				Calculated
Samples	846	1291	3105	8640	13882	45371	69215	166521	463361	744467
	846	1291	3105	8640	13882	67542	103037	247893	689788	1108260
	1316	3681	4830	15120	24947	311712	871799	1144050	3581375	5908937
	978	1864	3588	11232	17662	248627	474110	912513	2856563	4491813

Table 31. Kitchener and Waterloo Road Maintenance Dataset (1/3)

Column Tag	OBJECTID	STREET_NAME	STREET_FROM	STREET_TO	DATE_FROM	DATE_TO	REASON
Description	Available in database	Available in database	Available in database - Starting point of road	Available in database - Ending point of road	Available in database - Identifies the time of maintenance		Available in database - Includes: Road Reconstruction, Road Resurfacing
Reference	Kitchener "Road Closures" GIS Data / Waterloo “Road Closure Data”	Kitchener "Road Closures" GIS Data / Waterloo “Road Closure Data”	Kitchener "Road Closures" GIS Data / Waterloo “Road Closure Data”	Kitchener "Road Closures" GIS Data / Waterloo “Road Closure Data”	Kitchener "Road Closures" GIS Data / Waterloo “Road Closure Data”		Kitchener "Road Closures" GIS Data / Waterloo “Road Closure Data”
Samples	7693	ADELAIDE ST	BELMONT AVE W	LAWRENCE AVE	2019-06-05T04:00:00.000Z	2019-09-30T04:00:00.000Z	Road Reconstruction
	7782	APPALACHIAN CRES	KINGSWOOD DR	KINGSWOOD DR	2019-06-03T04:00:00.000Z	2019-06-28T04:00:00.000Z	Road Resurfacing

Table 32. Kitchener and Waterloo Road Maintenance Dataset (2/3)

Column Tag	Shape_Length	PAVEMENT_WIDTH	CLASS
Description	Calculated with ArcMap	Available in database after "spatial join" with "Roads data"	Available in database after "spatial join" with "Roads data"
Reference	Calculated	Kitchener "Roads " GIS Data / Waterloo “Roads” Data	Kitchener "Roads " GIS Data / Waterloo “Roads” Data
Samples	274	9	Local Street
	638	9	Local Street

Table 33. Kitchener and Waterloo Road Maintenance Dataset (3/3)

Column Tag	HL3 (kg/m^2)	HL4 (kg/m^2)	Granular A (kg/m^2)	Granular B (kg/m^2)	MI (kg/m^2)	W_HL3 (kg)	W_HL4 (kg)	W_GranA (kg)	W_GranB (kg)	W_tot (kg)
Description	MIs extracted from tables 4 to 9 for each building category					Calculated by multiplying MIs in “PAVEMENT_WIDTH” and “Length” for each Material				
Reference	Calculated from Mentioned Sources in Section 3.2.2.1					Calculated				
Samples	94	143	345	960	1542	232078	354042	851775	2370158	3808053
	94	143	-	-	237	539658	823266	-	-	1362925