WATER INFRASTRUCTURE RENEWAL POLICIES TO ENABLE EQUITABLE AND SUSTAINABLE PROSPERITY

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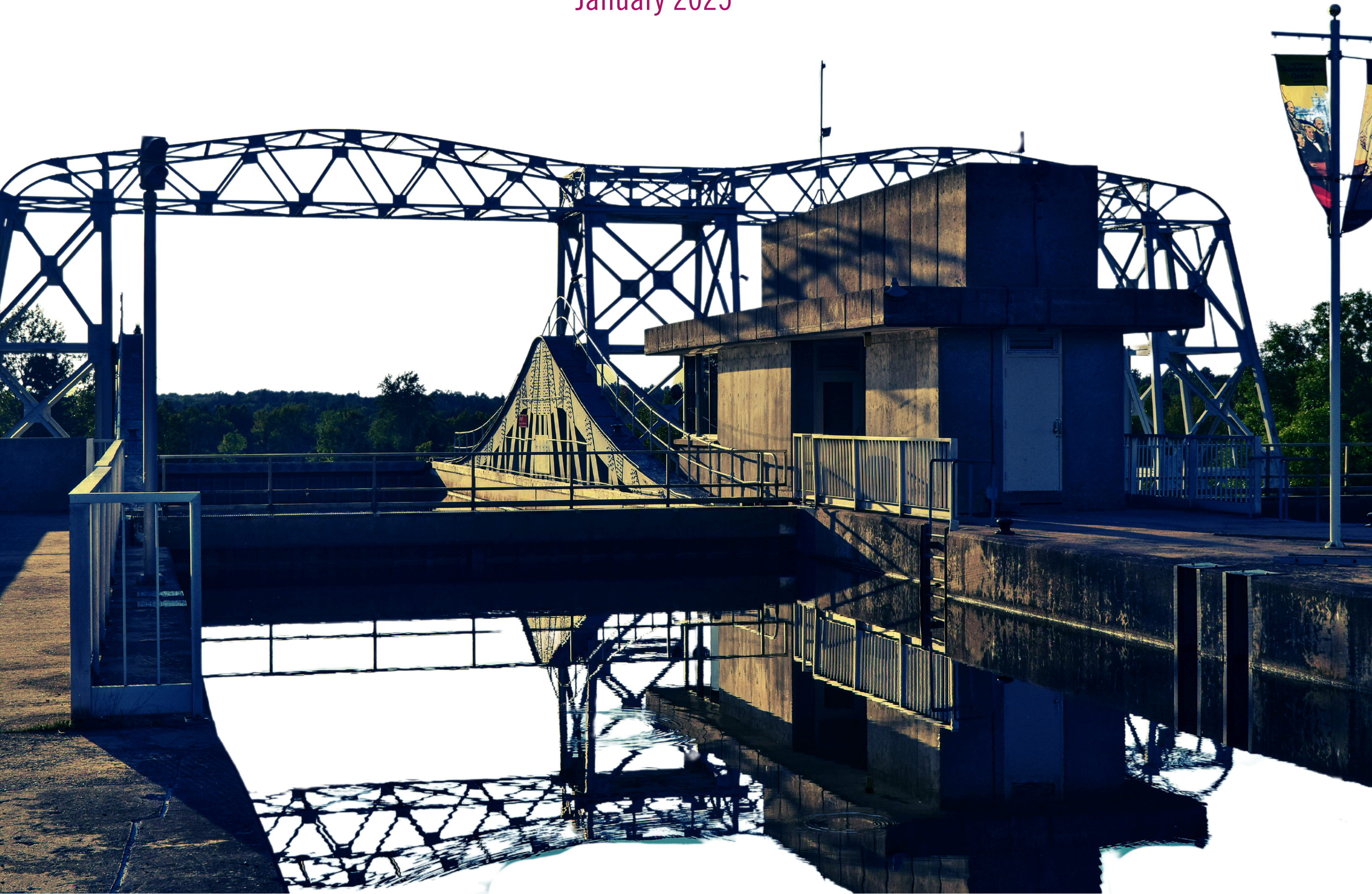

ABSTRACT

Cities across Canada are renewing their water infrastructure in response to growing populations and aging networks. However, greenhouse gas emissions from pipe manufacturing, transportation, installation, and end-of-life treatment – collectively “embodied emissions” – worsen climate change. Greener pathways of construction are required to sustain infrastructural performance and access while minimizing emissions. Using publicly available pipe data from 3,136 neighbourhoods in 11 cities across four Canadian provinces, we evaluate the influence of neighbourhood-level urban design – population density and housing types – on the per capita embodied emissions of water, sanitary, and stormwater networks. Total per capita embodied emissions due to water infrastructure vary 20-fold across the neighbourhoods. Emissions go down when population density goes up and when the percentage of single-family homes decreases; for every 14-fold increase in population density, per capita emissions halve. The research indicates that denser neighbourhoods with fewer single-family homes reduce the environmental cost of water infrastructure.

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INTRODUCTION

In the 21st century, cities must meet two competing challenges to achieve long-term sustainability and prosperity. On one hand, they must minimize greenhouse gas (GHG) emissions to achieve Paris agreement targets by 2050 and avoid worsening global climate change.[1] Cities are currently responsible for 70% of GHG emissions globally, with contributing factors including population and urban form.[2] On the other hand, cities must accommodate massive population growth and urbanization. By 2050, cities around the world are expected to double in population, adding over 4.4 billion new inhabitants.[3] In Canada, 12 million new residents are expected by 2050 by medium growth projections[4] – and over 9 in 10 new Canadians typically reside in cities.[5] Aging infrastructure further increases cities' infrastructure investment needs for this future.[6] To successfully meet both these challenges, planners require a strong understanding of how urban growth and design choices affect greenhouse gas emissions, so that least-emissions pathways can be followed. This paper focuses specifically on identifying low embodied GHG urban forms for piped drinking water, wastewater, and stormwater networks (collectively "water networks").

Water networks convey safe drinking water to residents and collect both sanitary sewer water and stormwater for treatment. In Canada, 60% of urban water infrastructure is more than 25 years old, and one-third requires repair or replacement within the next decade.[7] Further, Canadian cities are rapidly growing, thus increasing the demands on water systems. Canada's eight largest metropolitan areas are projected to add 1.7 to 3.1 million new households collectively by 2041.[8] Like all infrastructures, constructing and maintaining piped water systems generates GHG emissions associated with material manufacturing, transportation, installation, and end-of-life treatment – collectively, "embodied emissions."[9] Buildings and construction have great environmental impact: globally, this sector generates 37% of GHG emissions, with one-sixth of global emissions owed to the manufacturing of materials like cement and metals.[10] In Canada, new infrastructure construction generated over 15 million tonnes of GHG emissions in 2023, of which around 11% was due to water and sewage systems.[11] The embodied emissions of pipe networks relate to decisions on material use: pipe lengths, diameters, thicknesses, and material. Increasing the number of people served by piped systems can distribute the emissions impact, reducing per capita embodied emissions. Considerations of

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[1] Environment and Climate Change Canada, "The Paris Agreement."

[2] Intergovernmental Panel on Climate Change (IPCC), "Summary for Policymakers."

[3] World Bank Group, *Urban Development*.

[4] Statistics Canada, *Population Projections for Canada, Provinces and Territories*.

[5] Statistics Canada, "Canada's Large Urban Centres Continue to Grow and Spread."

[6] Canadian Infrastructure, "Canadian Infrastructure Report Card 2019."

[7] Canadian Infrastructure, "Canadian Infrastructure Report Card 2019."

[8] Canada Mortgage and Housing Corporation (CMHC), "Household Projections for Canada's Major Urban Centres."

[9] Royal Institution of Chartered Surveyors (RICS), "Whole Life Carbon Assessment (WLCA)."

[10] United Nations Environment Programme (UNEP), "2022 Global Status Report for Buildings and Construction"; International Resource Panel (IRP), "Resource Efficiency and Climate Change."

[11] Statistics Canada, "Infrastructure Statistics Hub: Environmental Perspective."

population density, street layout, and building types – collectively, "urban form design decisions" – affect infrastructure functionality and impact.

To ensure that urban water systems perform acceptably while also managing environmental impact, we must renew existing water infrastructure in ways that minimize embodied emissions. However, despite the ubiquity of urban water networks and anticipated growth, the environmental credentials and embodied GHG of these systems are rarely considered. These environmental effects are intimately linked to urban form, but these links represent widely overlooked potential pathways for GHG reductions. While several life-cycle assessment studies have quantified GHG emissions from water systems, a review of these studies from 1998 to 2017 found that only about half considered the construction stage and embodied emissions; most research focused on the operational emissions of these systems.[12] Those studies that did consider construction found embodied emissions ranging widely from negligible to 50% of total life-cycle impacts.[13] Specific studies have quantified the emissions impacts of various decisions – such as pipe replacement frequency;[14] choice of water source;[15] and reuse of nutrients, water, and energy[16] – as well as external factors like climate change and population growth.[17]

However, water network design has generally been taken as a given, with only a handful of papers examining the impact of urban form on embodied emissions to our knowledge.[18] These studies have identified relationships between embodied energy from drinking water pipes and urban form for select, suburban networks. They found that up to 90% reductions in embodied energy could be achieved from denser, more interconnected and grid-like street topologies with the smallest lot sizes.[19] But even these leading studies have explored within a limited scope: focusing only on drinking water networks, generally holding pipe diameter and material fixed, and omitting denser urban forms such as mid- and high-rise buildings. They have left for further study how embodied emissions relate to urban form for drinking water, wastewater, and stormwater networks across real neighbourhoods with greater variation in density. Most recently, a study has modelled the per capita embodied emissions of housing, transportation, and water networks versus population density, household size, and building types for neighbourhoods across Canada.[20] The authors identified 60% reductions in embodied emissions from all infrastructures from higher densities and fewer single-family homes.[21] However, the

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[12] Byrne et al., "Life Cycle Assessment (LCA) of Urban Water Infrastructure."

[13] Byrne et al., "Life Cycle Assessment (LCA) of Urban Water Infrastructure."

[14] Filion, MacLean, and Karney, "Life-Cycle Energy Analysis of a Water Distribution System."

[15] Stokes and Horvath, "Energy and Air Emission Effects of Water Supply"; Mo et al., "Embodied Energy Comparison of Surface Water and Groundwater Supply Options."

[16] Mo and Zhang, "Can Municipal Wastewater Treatment Systems Be Carbon Neutral?"

[17] Mo and Zhang, "Modeling the Influence of Various Water Stressors."

[18] Filion, "Impact of Urban Form on Energy Use in Water Distribution Systems"; Wong, Speight, and Filion, "Impact of Urban Form on Energy Use"; Wong, Speight, and Filion, "Impact of Urban Development on Energy Use in a Distribution System"; Wong, Filion, and Speight, "A Neighbourhood-Level Analysis of the Impact of Common Urban Forms."

[19] Wong, Filion, and Speight, "A Neighbourhood-Level Analysis of the Impact of Common Urban Forms."

[20] Rankin and Saxe, "A Future Growth Model for Building More Housing and Infrastructure."

[21] Rankin and Saxe, "A Future Growth Model for Building More Housing and Infrastructure."

model of water networks relied upon limited data from seven cities in Ontario to predict emissions nationwide, with simplifying assumptions on missing diameters and materials.

As cities across Canada address the age and insufficiency of their water infrastructure, they have a unique opportunity to renew this infrastructure in ways that minimize embodied emissions. Data from existing neighbourhoods with wide ranges of urban form, water system provision, and embodied emissions can help us identify more sustainable growth pathways. In this chapter, we explore these relationships by combining census population and housing data with data for water pipes from 3,136 neighbourhoods in 11 Canadian municipalities. Pipes in denser neighbourhoods may be shorter in length per person but larger in diameter,[22] and as a result may have a different material composition, creating trade-offs in embodied emissions. We hypothesize that urban form meaningfully influences the per capita embodied emissions of drinking water, sanitary, and stormwater networks in real neighbourhoods across Canada. These findings can inform policies that minimize the environmental impact of water infrastructure renewal and growth, improving the outlook for long-term prosperity and environmental sustainability in Canadian cities.

> *“We hypothesize that* ***urban form meaningfully influences the per capita embodied emissions*** *of drinking water, sanitary, and stormwater networks in real neighbourhoods across Canada.”*

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[22] Filion, “Impact of Urban Form on Energy Use in Water Distribution Systems.”

METHODOLOGY

Table 1 summarizes key characteristics of the studied municipalities. Using the recently published Open Database of Infrastructure (ODI),[23] we identified eleven municipalities across four provinces with publicly available data for water, sanitary, and stormwater networks (and combined sewer networks where applicable). With a total population of 2,254,129, the studied municipalities represented 6% of the national census population in 2021.[24] As the ODI lacked some diameter data, we downloaded and processed data for all the cities directly from municipal open data portals.[25]

Table 1. Summary of studied cities and key characteristics by population density, 2021

Municipality (census subdivision)	**Province**	**Population**	**Area (km^2)**	**Density (people per km^2)**	**No. of neighbourhoods⋆**	**Pipe age (years; min/median/max; from network data)**
Greater Sudbury	ON	165,504	3,100	53	265	1 / 43 / 124 [26]
Strathcona County	AB	94,051	870	108	131	0 / 27 / 66 [27]
Langley	BC	138,166	351	394	163	0 / 30 / 124 [28]
Abbotsford	BC	156,568	377	416	224	0 / 29 / 94 [29]
Trois-Rivières	QC	139,163	289	482	237	0 / 38 / 109 [30]
Kelowna	BC	144,576	212	683	167	0 / 25 / 88 [31]
Cornwall	ON	47,845	62	778	97	0 / 42 / 138 [32]
Coquitlam	BC	160,295	132	1,216	193	0 / 35 / 79 [33]
Kitchener	ON	256,885	137	1,877	321	0 / 26 / 170 [34]

⋆ We use census dissemination areas (DAs) as our neighbourhood scale.
Source: Based on data from Statistics Canada, 2021 Census of Population Census Profiles.

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[23] Statistics Canada, *Open Database of Infrastructure*.

[24] Statistics Canada, *Census Profile, 2021 Census of Population*.

[25] Data was last updated between October 2021 and September 2024 and downloaded in GeoJSON format from September 18 to 23, 2024. We conducted all analysis using Python 3.10.9 with the NumPy, Pandas, and GeoPandas packages.

[26] City of Greater Sudbury, *Open Data Portal*.

[27] Strathcona County, *Open Data Portal*.

[28] Township of Langley, *Open Data Portal*.

[29] City of Abbotsford, *Open Data Portal*.

[30] City of Trois-Rivières, *Open Data Portal*.

[31] City of Kelowna, *Open Data Portal*.

[32] City of Cornwall, *Open Data Portal*.

[33] City of Coquitlam, *Open Data Portal*.

[34] City of Kitchener, *Open Data Portal*.

Burnaby	BC	267,825	94	2,859	322	0 / 35 / 125 [35]
Vancouver	BC	683,251	131	5,220	1,016	0 / 49 / 132 [36]
All		**2,254,129**	**5,752**	**392**	**3,136**	**0 / 35 / 170**

We combined city-specific subsystems such as pressurized and gravity mains into four main categories: 1) drinking water distribution, 2) sanitary sewer, 3) storm sewer, and 4) combined sewer systems.[37] Descriptions of pipe materials ranged widely across the studied cities (166 unique material labels); for simplicity we grouped the materials into five broad classes: plastics (i.e., polyvinyl chloride, high density polyethylene, etc.), metals (i.e., ductile iron, cast iron, steel, etc.), ceramics (i.e., clay, brick, etc.), concretes (i.e., reinforced, asbestos, etc.), and unknown (information was missing or an acronym was not identifiable). Where pipe diameters were missing (~20% of data) or invalid (two records of diameter <2 mm), or where pipe materials were classified as unknown, we randomly sampled values with replacement from the distribution of non-missing diameters or material classes for the same water system across all the studied cities (i.e., drinking water, sanitary, storm, or combined). Using an appropriate pipe-sizing standard or manufacturer specification for each material class, we estimated pipe weights. Finally, we applied material-specific pipe manufacturing GHG factors drawn from the Inventory for Carbon and Energy (ICE) database, covering cradle-to-gate life-cycle emissions (Tables A1-3) to estimate the embodied emissions of each drinking water, sanitary, and stormwater pipe.[38] For simplicity, we focused on the pipes themselves, assuming that they constitute most of the material use in the networks, leaving for further study other sources of embodied emissions such as valves and fittings; pipe linings; and treatment facilities, pumping stations, and other buildings.[39]

Having quantified the embodied emissions of each pipe in the 11 municipalities, we assigned pipes to the neighbourhoods using geospatial intersection in GeoPandas. To represent neighbourhoods, we used census dissemination areas (DAs), which are the smallest geographic boundaries for which census data on population and housing types are publicly available, with about 400–700 people in each.[40] We split any pipes travelling between DAs and allocated the impact of pipe segments among the respective DAs, resulting in 604,468 pipe records. We totalled the embodied emissions of each pipe in each DA, then divided by the DA's population for a per capita emissions impact (by water system and in total). We then related these emissions to other publicly available DA-level census data, including population

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[35] City of Burnaby, *Open Data Portal*.

[36] City of Vancouver, *Open Data Portal*.

[37] We omitted pipes explicitly labelled as deactivated (<0.1% of data and only in Kelowna, B.C.).

[38] Circular Ecology, "Embodied Carbon—The ICE Database."

[39] The use of ICE pipe manufacturing factors omits downstream emissions from sources such as transportation to site, installation, and end-of-life; however, we hypothesize that these downstream emissions should generally be proportional to manufacturing emissions (i.e., a neighbourhood with more pipe material and higher manufacturing emissions would generally also have more emissions from transportation, installation, and end-of-life) and will likely be a small proportion of embodied emissions as has been shown in past research, suggesting wider validity for the comparisons between urban forms conducted here. See Hatzav Yoffe et al., "Mapping Construction Sector Greenhouse Gas Emissions."

[40] Statistics Canada, "Dissemination Area Boundary Files."

density, housing types, and median household income.[41] For housing types, we focused on the percentage of single-family homes from the total number of dwellings, following past work.[42]

We made some assumptions due to study limitations. Lacking detailed hydraulic analysis for this study, we allocated the embodied emissions of each pipe based on the neighbourhood of location and not of ultimate use – meaning that neighbourhoods with major trunk lines passing through them might appear to have greater per capita embodied emissions than would otherwise be attributed to the local population. We also did not treat neighbourhoods with high amounts of industrial or commercial activity differently from others, meaning that some neighbourhoods may appear to have higher per capita embodied emissions due to pipe sizing for these non-residential purposes. The embodied GHG factors used are not location specific to Canada or to particular provinces. Finally, we neglected differences in neighbourhood slope or elevation among the studied municipalities, leaving their impacts on per capita embodied emissions for future study.

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[41] Statistics Canada, *Census Profile, 2021 Census of Population*.

[42] Rankin and Saxe, "A Future Growth Model for Building More Housing."

RESULTS

The 3,136 studied neighbourhoods vary widely, often over several orders of magnitude, in population density, percentage of single-family homes, and per capita embodied emissions in drinking water, sewer, and all networks (Table 2). Omitting the most extreme cases by comparing the 5th and 95th percentile values, population density varies by a factor of 162 and per capita embodied emissions for all networks by a factor of 20.

Table 2. Summary statistics for neighbourhood census data and calculated embodied emissions

Category	Variable	Percentile values			Range of values (95th / 5th)
		5th	50th (Median)	95th	
Neighbourhood census data★	Population density (per km^2)	116	3,663	18,745	162x
	% Single-family homes	0	37	97	--
	Median household income ($)	43,200	81,000	118,250	2.7x
Per capita embodied emissions (kg CO$_2$e per person)	Water networks	56.7	261	1,174	21x
	All sewer networks†	42.5	312	1,238	29x
	Sanitary sewers	6.5	87	419	65x
	Storm sewers	6.6	156	672	102x
	Combined sewers	2.5	93	1,050	420x
	All networks	107.4	610	2,151	20x

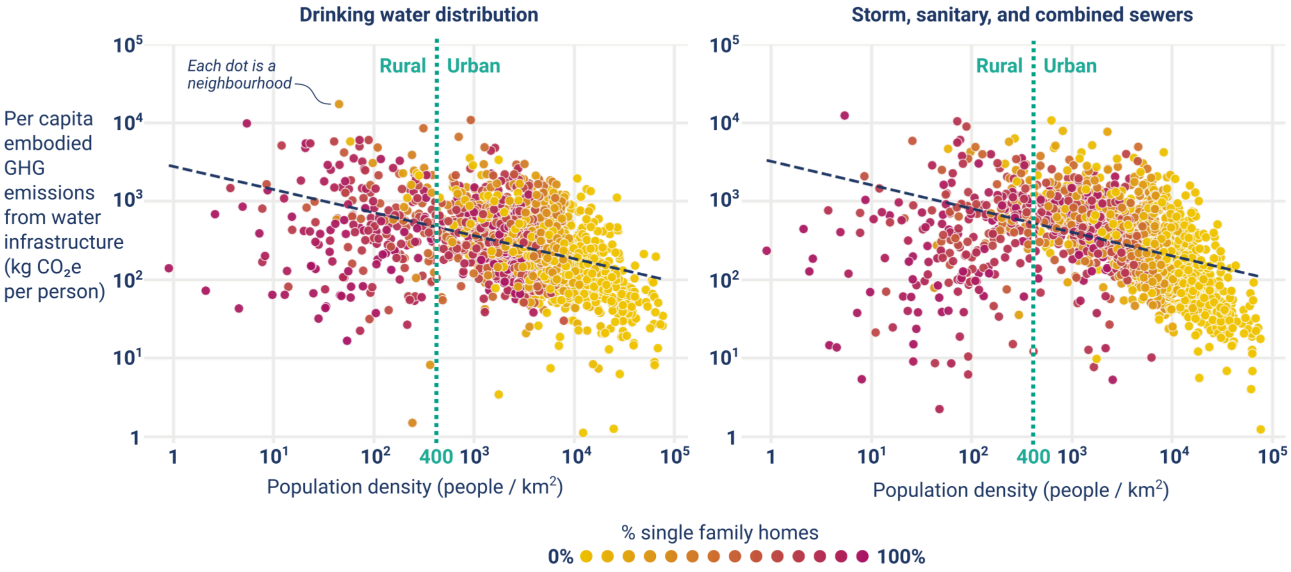
★ Neighbourhood census data is from Statistics Canada, 2021 Census of Population Census Profiles.
† Statistics for sanitary, storm, combined, and all sewers are only for those neighbourhoods that have each of those systems.

Depending on the age of construction, neighbourhoods differ in the prevalence of combined sewers (which accommodate both sanitary and storm flows, largely pre-1970 in the data), creating wide variations in emissions from these systems; accordingly, we combine the emissions of all sewer networks into one metric and see ranges of emissions closer to that of water networks.

In Figure 1, we compare neighbourhood per capita embodied emissions for water and sewer networks with neighbourhood population density and percentage of single-family homes. The figure combines all 11 cities, with each dot representing one neighbourhood. In alignment with past work, we generally see lower per capita embodied emissions with higher population density.[43] By modelling this log-log relationship (see Appendix), we find that every 14-fold increase in neighbourhood population density – for example, going from a neighbourhood with a lot size of 2,800 square metres to one with a lot size of 200 square metres – cuts the total per capita embodied emissions from all water networks in half.

Figure 1. Neighbourhood per capita embodied emissions vs. population density and housing type

Neighbourhood population density and per capita embodied emissions from water infrastructure



Drinking water distribution

Storm, sanitary, and combined sewers

Data Sources: Authors' analysis; Statistics Canada 2021 Census of Population

Each dot is a neighbourhood from one of the 11 study cities. This figure shows lower per capita embodied emissions are associated with higher population density and lower prevalence of single-family homes, especially in urban neighbourhoods above 400 people per km^2 (right of the vertical dotted line).

These reductions in per capita embodied emissions are especially clear in Figure 1 at densities above 400 people per square kilometre, the Statistics Canada threshold for urban regions.[44] It is possible that in more rural neighbourhoods, we may see lower embodied emissions from piped systems due to the presence of alternative management systems, such as septic tanks for sanitary systems. As we only quantified embodied emissions of piped systems, the trade-offs in embodied emissions between piped systems and alternatives (including septic tanks, wells, or even bottled water)[45] remain as gaps for further analysis. The modelled reduction in embodied emissions with population density includes these potential outliers; thus, for the more urban neighbourhoods (~400 people per km^2 or higher), increases in population density will likely yield even greater relative reductions in embodied emissions.

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[43] For past work, see Wong, Filion, and Speight, "A Neighbourhood-Level Analysis of the Impact of Common Urban Forms." Our analysis showed significant, moderate, and negative correlation; R = -0.42 for the log of total embodied emissions versus log of population density.

[44] Statistics Canada, "Population Centre and Rural Area Classification 2016."

[45] Statistics Canada, "Households and the Environment Survey, Primary Type of Drinking Water Consumed."

Despite differences in typical pipe sizing and material choices, Figure 1 shows that the range of embodied emissions for water distribution and all sewers together are quite similar. This suggests potential beneficial trade-offs between sizing and material choice; for example, gravity sewer pipes tend to be larger, but, because they are not pressurized like water pipes, they more frequently use concrete and clay – the two materials with the lowest GHG intensities among the four materials studied.[46] Both water distribution and sewer networks exhibit similar negative relationships between population density and embodied emissions, indicating the potential for reducing emissions with urban form across all types of water networks.

As with increased population density, we see lower per capita embodied emissions with a lower percentage of single-family homes.[47] For every 12% drop in the percentage of single-family homes, per capita embodied emissions from all water networks are reduced by 10% (see Appendix). Figure 1 shows that neighbourhoods with fewer single-family homes have the highest densities and lowest embodied emissions from water networks.

We found a very mild trend of increasing per capita embodied emissions with increasing median household income.[48] This suggests that higher-income neighbourhoods generate greater embodied emissions from water networks and is likely due to links between household income and population density (R = –0.27 for the studied neighbourhoods) and single-family home ownership (R = 0.62). However, the socio-economic situations of neighbourhoods can change with time, meaning that the embodied emissions of pipes first installed decades prior may not relate as strongly with income levels today. Given these mixed influences, population density and percentage of single-family homes appear to be better predictors of neighbourhood-level per capita embodied emissions from water networks than household income.

> *“For every 12% drop in the percentage of single-family homes, per capita embodied emissions from all water networks are* ***reduced by 10%.”***

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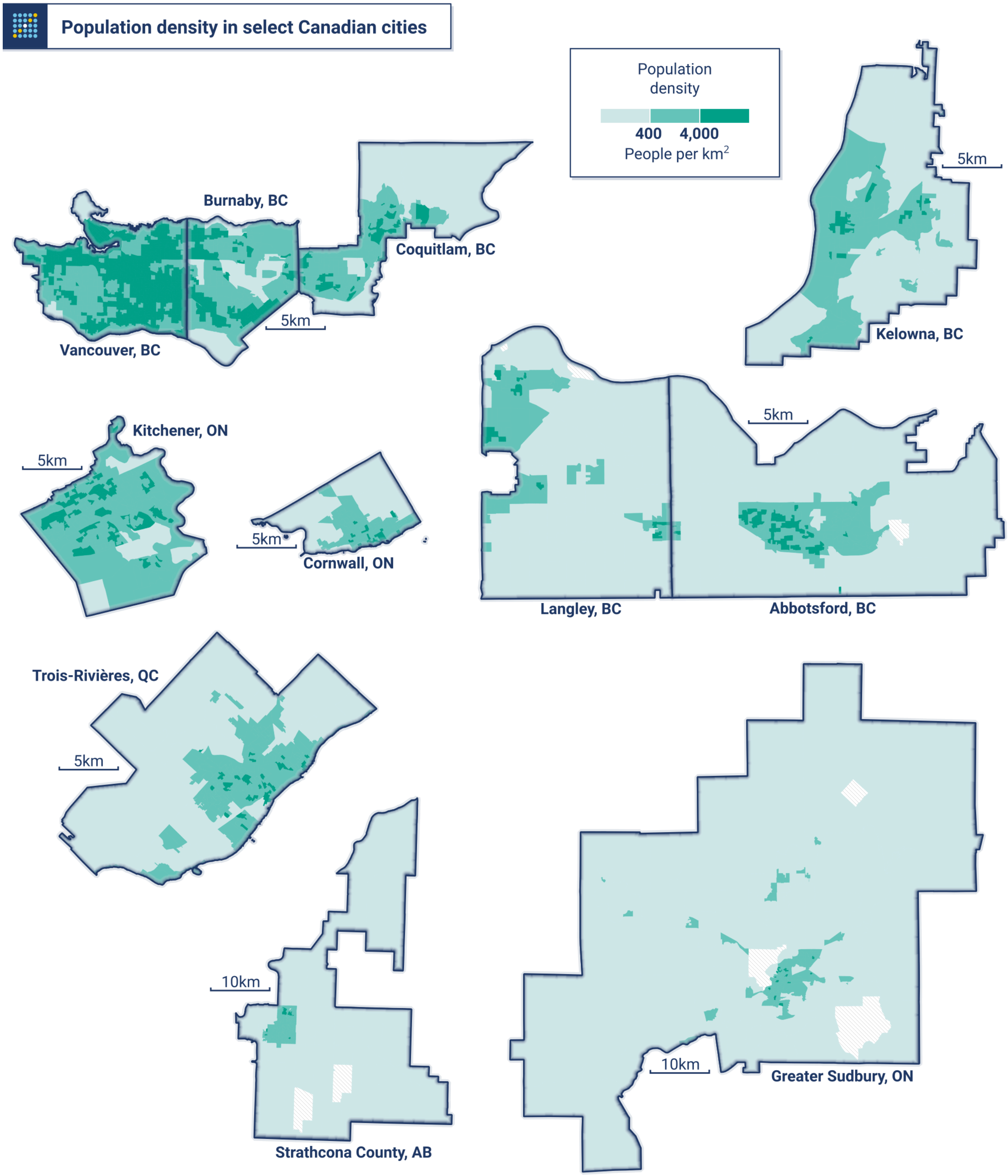
[46] Circular Ecology, “Embodied Carbon—The ICE Database.”

[47] Moderate positive correlation with R = 0.31 for the log of total embodied emissions vs. percentage of single-family homes.

[48] Weak positive correlation with R = 0.16 for the log of total embodied emissions versus median household income.

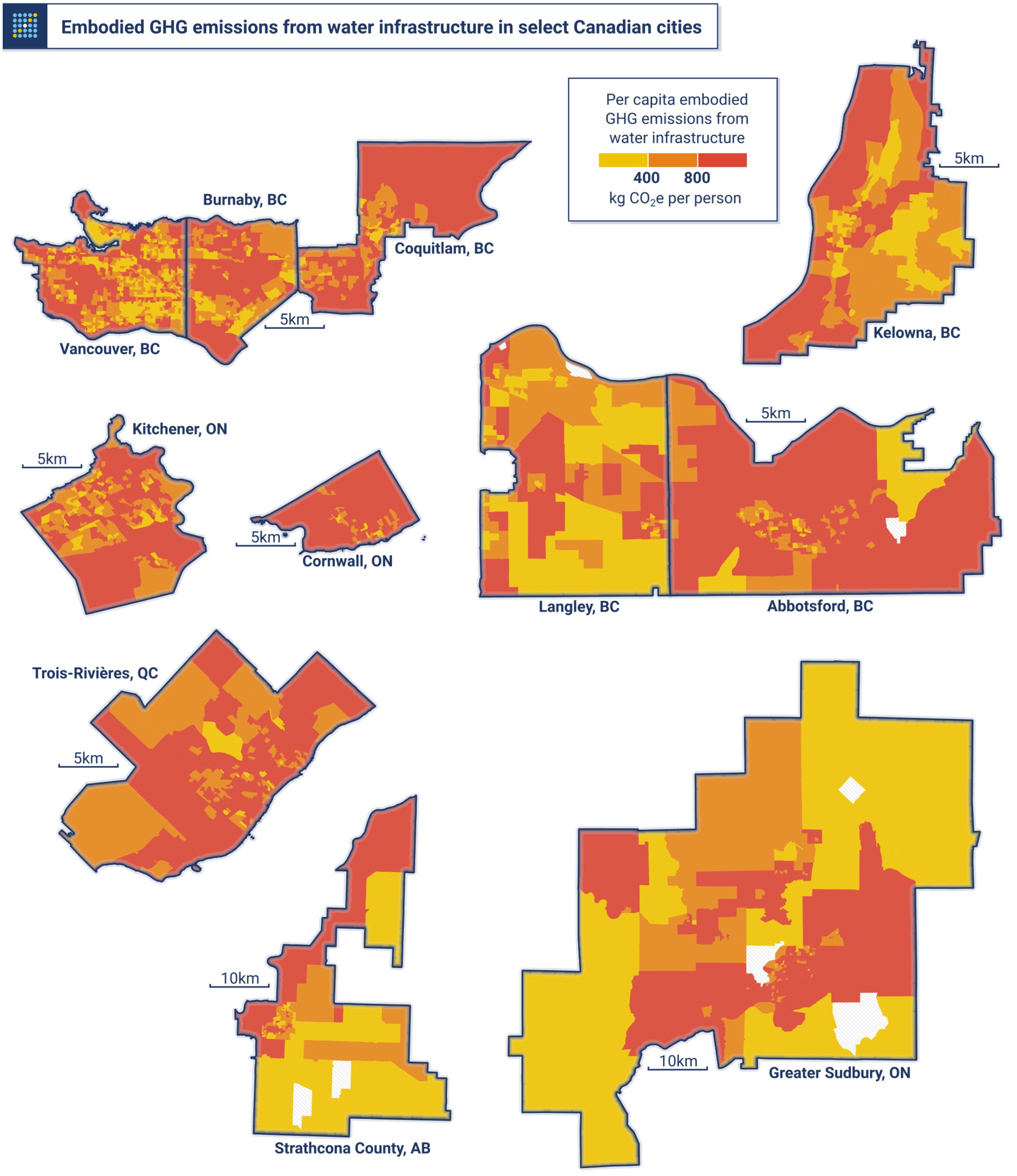
Figure 2(a). Geographic mapping of study neighbourhoods by population density



Data Sources: Statistics Canada 2021 Census of Population; OpenStreetMap

The darkest-coloured neighbourhoods in each city map have the highest population density.

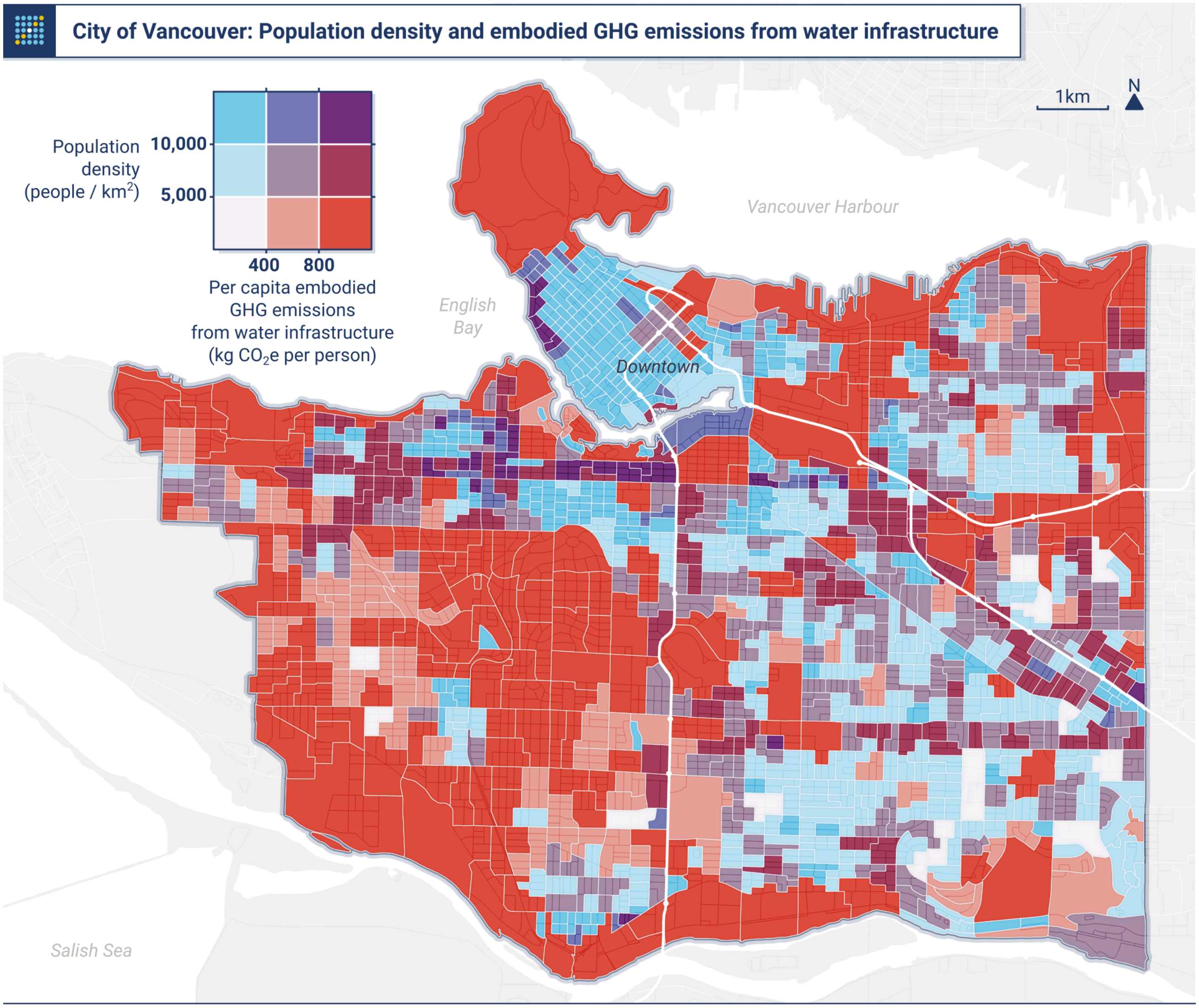
Figure 2(b). Geographic mapping of study neighbourhoods by population density and total per capita embodied emissions



Data Sources: Authors' analysis; Statistics Canada 2021 Census of Population; OpenStreetMap

The colour gradient indicates lowest (light) to highest (dark) per capita embodied emissions.

Figure 2(c). Geographic mapping of study neighbourhoods by population density and total per capita embodied emissions



Data Sources: Authors' analysis; Statistics Canada 2021 Census of Population; OpenStreetMap

Figure 2c presents the neighbourhoods of Vancouver by population density and embodied GHG emissions from water infrastructures. Neighbourhoods shown in light blue are high in population density and low in per capita embodied emissions, while those shown in red are low in population density and high in per capita embodied emissions, both in alignment with the modelled relationship. The neighbourhoods in purple are high in both population density and per capita embodied emissions, suggesting other factors at play for future study.

Figure 2 maps the neighbourhoods of the 11 studied cities by population density and total per capita embodied emissions from all piped networks. In Figure 2a, the darkest coloured neighbourhoods have the highest population density. In Figure 2b, the colour gradient indicates lowest (light) to highest (dark) per capita embodied emissions. While all cities exhibit unique geospatial patterns of development and population distribution, as well as local elevation and slope impacting network design, the densest neighbourhoods tend to consistently reduce embodied emissions, suggesting wider generalizability. Further analysis on neighbourhood characteristics, including age, street layout, and slope, could help to understand variations not fully explained by density and housing.

To better understand what these numbers represent, Figure 3 shows aerial views of three example neighbourhoods in the 5th, 50th, and 95th percentile of total per capita embodied emissions, close to the trendline modelled relationship (see Appendix for visualization). The neighbourhoods decrease in population density (from 39,036 to 5,332 to 334 people per per km^2 respectively) and increase in prevalence of single-family homes (from 0% to 40% to 71% respectively). Any opportunities to build more like the 5th percentile of per capita embodied emissions from piped networks (such as photo A) instead of the 95th percentile (such as Photo C) would reduce these emissions by an average of 95% (a 20-fold variation, as shown in Table 2). Similarly, building like the 5th percentile of per capita embodied emissions instead of the 50th percentile (such as Photo B), would reduce emissions by an average of 82% (a 5.7-fold variation). In absolute terms, we estimate that embodied emissions from water networks could generate 830,000 tonnes of CO_2e per year, or 6% of emissions from all new infrastructure construction in Canada in 2023, indicating the scope for emissions reduction (see Appendix).

Figure 3. Aerial views of three studied neighbourhoods close to the modelled trendline

Comparative aerial views of neighbourhoods at 5th, 50th, and 95th percentiles of GHG emissions

5th percentile of GHG emissions from water infrastructure

Vancouver
-123.126, 49.272

50th percentile of GHG emissions from water infrastructure

Burnaby
-122.947, 49.222

95th percentile of GHG emissions from water infrastructure

Trois-Rivières
-72.605, 46.295

Population density (per km^2): **39,036**
% single-family homes: **0%**

Population density (per km^2): **5,332**
% single-family homes: **40%**
Average lot size (m^2): **188**

Population density (per km^2): **344**
% single-family homes: **71%**
Average lot size (m^2): **2,910**

Data Sources: Authors' analysis; Statistics Canada 2021 Census of Population; Google Maps

Despite the strong relationships between population density, prevalence of single-family homes, and per capita embodied emissions from water networks, these factors do not explain all observed variation in per capita embodied emissions. We recommend that future studies consider additional factors related to embodied emissions, including street layout, pipe sizing and material design practices, and location-specific elevation and slope impacts. Future work should also explore and mitigate confounding variables such as the presence of non-residential water uses such as industry or parks impacting per capita embodied emissions.

DISCUSSION

Looking at real, current data on water, sanitary, and sewer pipe networks from over 3,000 neighbourhoods across Canada, we observe reduced per capita embodied emissions from all water networks with higher neighbourhood-level population density and with lower prevalence of single-family homes. This suggests that building housing types that are denser than single family homes (e.g. multiplexes, mid- and high-rises) would help to reduce per capita embodied emissions of water infrastructures. These density benefits appear in both water and sewer networks, emphasizing the reduced per capita emissions from all types of systems. We find that these results hold across cities of different geospatial population distributions and geographic locations in Canada (i.e., different climatic needs, from British Columbia to Quebec).

The wide range of per capita embodied emissions seen in the data, as well as the urgency of the climate crisis, implies that consideration of GHG emissions in water networks should be factored into choices on urban growth. Currently, environmental impact assessments for municipal infrastructures in Canada do not generally consider GHG emissions and climate impacts. This is a major gap: our work describes the scope for improvement that could be achieved through urban form choices if these emissions were considered in planning processes. For example, we show that the per capita embodied emissions from water networks in a neighbourhood vary greatly depending on the urban form of its housing: the lowest-emission neighbourhoods saved up to 95% compared to the highest-emission neighbourhoods. Since we estimate that water-network-embodied emissions could contribute 6% of national new infrastructure construction emissions, consideration of these savings could yield meaningful GHG reductions on the national scale.

Further, our work emphasizes the interconnected nature of the different stages of urban planning and infrastructure delivery: urban form, which can be one of the earliest decisions made for new developments and can be strongly influenced through choices around infill development, critically influences all downstream infrastructure delivery and impacts. We strongly recommend that at the earliest stages of development, the complete impacts of all infrastructures needed to service neighbourhoods, including their GHG emissions and climate impacts, are assessed and included in decision-making processes. Our work provides a set of methods to aid in these assessments and suggests that, based upon historical data, managing anticipated urban growth by building through denser neighbourhoods with fewer single-family homes will reduce embodied emissions and help in meeting climate targets. Confirming these historical findings with direct consideration of planned water infrastructure and urban growth strategies can further inform future emissions estimates and policy implications.

Recognizing that not all the variation in embodied emissions is explained by the variables we have considered, and that some reductions in embodied emissions are possible without large changes in population density or housing type, we suggest further analysis that includes considerations of street layout, neighbourhood age and design practices, and local geographic conditions (elevation and slope as well as ground permeability for stormwater management) to further elucidate reduction pathways. For example, past research has indicated gridiron street layouts reduce embodied GHG in water networks.[49] We also recommend greater consideration of how to allocate the impact of trunk water and sewer mains based on neighbourhoods of use rather than location. Methods of fairly allocating non-residential water infrastructure impacts such as for industry or parks should also be considered. As alluded to previously, non-network systems such as bottled water, wells, or septic tanks present interesting trade-offs in embodied emissions not yet considered here.

Urban growth and form decisions can be politically charged, as evidenced by recent controversies over allowing housing expansion into the rural Greenbelt region in Ontario.[50] Data-driven research approaches such as those explored in this work can help inform policy-makers and the public about the real impacts of different urban form choices, helping to make more evidenced-based decisions. To move these findings towards practical implications on where in our cities urban growth should be accommodated for minimized environmental impacts, we recommend further research into how much density existing neighbourhoods can reasonably accommodate given the already-built water infrastructures, reducing additional embodied emissions. In the meantime, we recommend that urban planners, policy-makers, and developers consider sunk costs and GHG emissions in water and other infrastructures when choosing between strategies such as infill housing and expansion.

> *"…urban form, which can be one of the earliest decisions made for new developments and can be strongly influenced through choices around infill development,* ***critically influences all downstream infrastructure delivery and impacts."***

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[49] Wong, Filion, and Speight, "A Neighbourhood-Level Analysis of the Impact of Common Urban Forms."

[50] *CBC News*, "A Timeline of Key Events in Ontario's Greenbelt Controversy. "

CONCLUSION

An estimated 12 million new Canadians are anticipated by 2050,[51] 90% of whom are likely to live in cities.[52] As planners and policy-makers consider water infrastructural renewal in the coming decades to meet growing demand, it is imperative that considerations of environmental impact and embodied GHG emissions are taken into account. In parallel to embodied emissions reductions, adopting material efficiency strategies can reduce economic capital costs, enabling spending elsewhere and helping to shrink the infrastructure deficit into the future. With cities differing considerably in population, layout, and water resources, neighbourhood form provides a lens to disaggregate municipal systems, compare between cities, and understand both current practices and future infrastructure needs across Canada.

In this study, we use real pipe network data from 3,136 neighbourhoods from 11 municipalities from four Canadian provinces, covering 2.3 million residents or 6% of the national population, to demonstrate that the total per capita embodied emissions associated with drinking water, sanitary, storm, and combined sewer networks can vary 20-fold across neighbourhoods. We find that even though increased pipe diameters are generally needed to service higher population densities, the efficiencies of serving more people result in reduced per capita embodied emissions with increased population density and fewer single-family homes.

These wide variations in per capita embodied emissions represent both a challenge and a solution. The challenge is that some neighbourhoods – generally lower density, with more single-family homes – inequitably create far more embodied GHG emissions to deliver the same infrastructural service to residents, worsening global climate change, which disproportionately affects the most vulnerable. The solution is that planning future urban growth like the least-emitting, denser neighbourhoods can help reduce overall embodied emissions significantly into the future, minimizing these inequities in emissions generation and helping us meet sustainability goals. From our findings, we recommend urban forms that increase population density and reduce the percentage of single-family homes to minimize the embodied emissions of urban water systems, thus helping to mitigate global climate change while promoting the continued health, well-being, and economic prosperity of tomorrow's cities.

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[51] Statistics Canada, *Population Projections for Canada, Provinces and Territories*.

[52] Statistics Canada, "Canada's Large Urban Centres Continue to Grow and Spread."

APPENDIX

1.1 Pipe data preparation

In addition to replacing missing diameters and materials as described in the main text, the following data cleanup steps were taken:

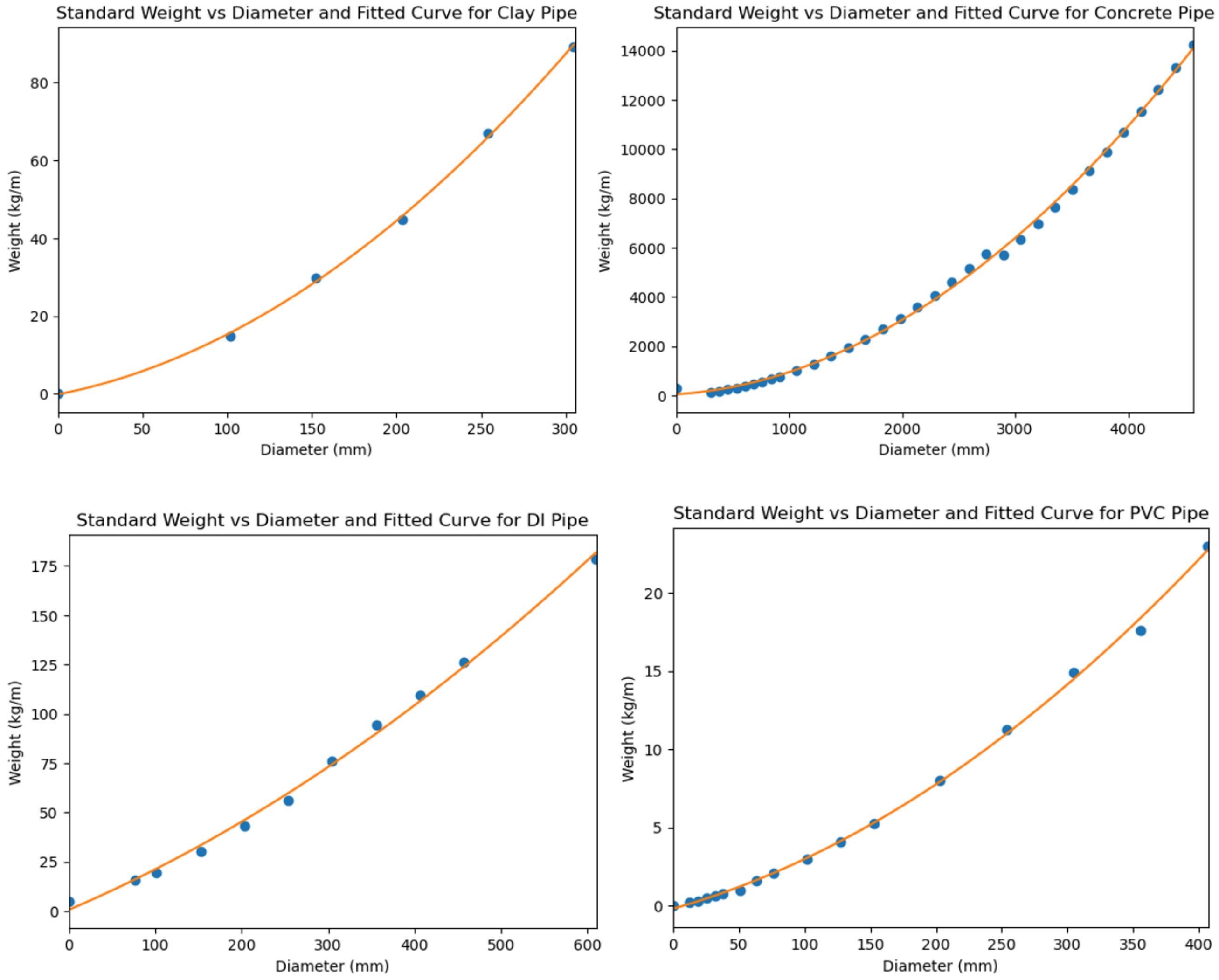
1. We omitted 11 pipe records with incomplete geometry data (all in Vancouver) due to the small number of records and difficulty of determining pipe length and location.
2. We excluded the one census DA with a census population of zero (in Greater Sudbury) to avoid infinite embodied emissions per person values.

We filtered relevant fields of geometries (allowing for geospatial joining with census data as well as the calculation of pipe lengths), diameter, material, and year of installation for each pipe. We combined all records from all systems and cities into one table for simplified geospatial intersection with census dissemination area boundaries.

1.2 Pipe sizing and embodied emissions estimates

Materials required special consideration for estimating pipe weight and embodied emissions. As each material class possessed slightly different pipe sizing and thickness standards (for example, plastics and metals are sized differently due to strength and durability differences), we identified an appropriate pipe sizing standard for the most common material of each class (for plastics, polyvinyl chloride; for metals, ductile iron; for ceramics, clay; and for concretes, standard concrete). This provided a relationship between pipe diameter and typical weight per unit length for that material (Table A-1). We fit material-specific curves (Figure A-1) to these standard values using the Numpy polyfit function with a 2nd-order function. We added an artificial data point at $x = 0$ and a material-specific y value (seen in Figure A) to ensure that the function remained positive for all diameter values. We applied these functions to all pipes of the respective material class, allowing us to reasonably estimate the weight per unit length of every pipe based on their material class and diameter. Lastly, we multiplied by the length of the pipe to estimate the weight of each pipe. We ignored pipe lining materials and their associated embodied emissions for this analysis.

Figure A-1. Standard weight per unit length vs. diameters and fitted curves for the four representative pipe materials: clay, concrete, ductile iron (DI), and polyvinyl chloride (PVC)



These curves were used to estimate pipe weight.

Table A-1. Pipe-sizing standards for the four representative materials

Class	Material	Standard
Concretes	Concrete	ASTM C76 – Reinforced Concrete Culvert, Storm Drain and Sewer Pipe[53]
Plastics	PVC	AWWA C900 – Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings[54]
Metals	DI	AWWA C151/A21.51 – Ductile-Iron Pipe, Centrifugally Cast[55]
Ceramics	Clay	ASTM C700 – Standard Specification for Vitrified Clay Pipe[56]

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[53] Illinois Concrete Pipe Association, "Concrete Pipe Use Manual."

[54] American Water Works Association (AWWA), "Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings."

[55] McWane Ductile, "McWane Ductile Iron Pipe."

[56] Mission Clay Products, "Pipe Dimensions & Specifications."

For ductile iron, following Toronto design guidelines as a proxy for the cities studied, we applied special thickness Class 52 for sizes up to 300 mm and Class 53 above 300 mm.[57]

We used material weight to quantify embodied emissions by scaling by material-specific pipe-manufacturing GHG factors drawn from the Inventory for Carbon and Energy (ICE) database, covering cradle-to-gate life-cycle emissions (Tables A1-3).[58] Although ICE was developed for the United Kingdom, we used these factors due to a lack of third-party-validated environmental product declarations (EPDs) for clay and iron pipes from North America. To validate the use of ICE factors, we compared ICE emissions intensities for concrete and PVC pipe with available North American EPDs for these materials and found the differences could range from 18% to 73% (Table A-2);[59] this remains a potential source of error, and future study would benefit from North America–specific emissions intensities where possible. We also note that the ICE factors are manufacturing-specific, omitting transportation to site, installation, and end-of-life treatment. Additionally, our analysis focuses on pipe networks, leaving other sources of embodied emissions, including treatment facilities, pumping stations, and other buildings, for further study.

Table A-2. Comparison of ICE GHG intensities with available North American EPDs

ICE material category	ICE embodied GHG Intensity (kg CO_2e/kg)	North American embodied GHG Intensity (kg CO_2e/kg)	% Difference
Precast concrete pipe, DN600 unreinforced per kg	0.146	0.179-0.234[60]	18-38%
Vitrified clay pipe DN 200 & DN 300	0.5		
General iron	2.03		
PVC Pipe	3.23	1.87-2.55[61]	27-73%

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[57] City of Toronto, "Design Criteria for Sewers and Watermains."

[58] Circular Ecology, "Embodied Carbon—The ICE Database."

[59] Canadian Concrete Pipe and Precast Association (CCPPA), "A Regionalized Industry Average EPD for Concrete Pipe"; Uni-Bell PVC Pipe Association, "Environmental Product Declaration."

[60] Canadian Concrete Pipe and Precast Association (CCPPA), "A Regionalized Industry Average EPD for Concrete Pipe."

[61] Uni-Bell PVC Pipe Association, "Environmental Product Declaration."

2.1 Fitted models for population density, % single-family home, and total per capita embodied emissions from all water networks

To relate population density and total per capita embodied emissions from all water networks, given the fitted intercept of 3.65 and slope of –0.26, we can model the power law:

$$\log(EE_{total}) = 3.69 - 0.26 \log(PD)$$
$$EE_{total} = 10^{3.69}(PD)^{-0.26} = 4898(PD)^{-0.26}$$

where EE_{total} is the total per capita embodied emissions from all water and sewer networks (kg CO_2e), and PD is the neighbourhood population density (per km^2).

We can use this relationship to estimate the increase in density needed to halve emissions.

$$\frac{EE_{total,\ new}}{EE_{total,\ old}} = \frac{4898(PD_{new})^{-0.26}}{4898(PD_{old})^{-0.26}}$$
$$0.5 = \left(\frac{PD_{new}}{PD_{old}}\right)^{-0.26}$$
$$\left(\frac{PD_{new}}{PD_{old}}\right) = (0.5)^{-\frac{1}{0.26}} \approx 14$$

Thus, for every 14-fold increase in population density, the modelled total per capita embodied emissions from all water networks is halved.

Similarly, we can relate % single-family homes and total per capita embodied emissions. With the fitted intercept of 2.62 and slope of 0.004, we can model the relationship:

$$\log(EE_{total}) = 2.62 + 0.004(\%SFH)$$
$$EE_{total} = 10^{2.62}10^{0.004(\%SFH)} = 417(1.009)^{\%SFH}$$

where EE_{total} is the total per capita embodied emissions from all water and sewer networks (kg CO_2e), and %SFH is the neighbourhood percentage of single-family homes from the total number of dwellings.

We can use this relationship to estimate the decrease in the percentage of single-family homes needed to reduce emissions by 10%.

$$\frac{EE_{total,\ new}}{EE_{total,\ old}} = \frac{417(1.009)^{\%SFH_{new}}}{417(1.009)^{\%SFH_{old}}}$$
$$0.9 = (1.009)^{\%SFH_{new} - \%SFH_{old}}$$
$$\%SFH_{new} - \%SFH_{old} \approx -12$$

Thus, every 12% reduction in the percentage of single-family homes reduces the modelled total per capita embodied emissions from all water networks by 10%.

Table A-3 provides sample values of %SFH and modelled total per capita embodied emissions from this relationship, highlighting the 10% decrease in emissions with every 12% decrease in the prevalence of single-family homes.

Table A-3. Example values of % single-family homes, modelled emissions, and % changes

% single family homes	Modelled total per capita embodied emissions (kg CO_2e)	% incremental decrease in single family homes	% incremental decrease in modelled emissions
100	1,022		
88	917	12%	10%
76	824	12%	10%
64	740	12%	10%
52	664	12%	10%
40	597	12%	10%
28	536	12%	10%
16	481	12%	10%
4	432	12%	10%
*0	417	4%	4%

* The final row is an odd case for the final value to be capped at 0% single-family homes

2.2 Neighbourhoods selected as representative in Figure 3

Figure A-2 visualizes the modelled relationship between population density and embodied emissions among the studied neighbourhoods (blue line), with the three representative neighbourhoods shown in Figure 3 in the main text highlighted (red dots).

Figure A-2. Log-log plot of population density versus total per capita embodied emissions

The three representative neighbourhoods pictured in Figure 3 are shown in red.

2.3 Estimation of national embodied emissions from water networks

Given the national urban population in Canada of 34 million in 2023, we apply the median total per capita embodied emissions for all water networks of 610 kg CO_2e from this study and assume a 25-year pipe replacement rate.[62] Thus, national embodied emissions from water networks are estimated as:

$$\frac{\left(34{,}000{,}000\; people * 610 \frac{kgCO2e}{person}\right)}{25\; yrs} * \left(\frac{1\; tonne}{1000\; kgCO2e}\right) = 829{,}600\; tCO2e/yr$$

In 2023, GHG emissions from new infrastructure construction totalled 15 million tonnes.[63] Thus, water networks are estimated to contribute around 6% of national new infrastructure construction emissions, indicating a sizable potential for reduction through urban form.

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[62] Statistics Canada, *Annual Demographic Estimates, Rural and Small Town and Functional Urban Areas*.

[63] Statistics Canada, *Infrastructure Statistics Hub: Environmental Perspective*.

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