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A Neighbourhood-Level Analysis of the Impact of Common Urban Forms On Energy Use in Drinking Water Distribution Systems

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Abstract

This paper examined the link between common urban forms in North America and the energy use of drinking water distribution systems. (The urban form of an urban area relates to its street topology and population density.) Common street topologies and neighborhood population densities were combined to evaluate the impact on pumping energy and embodied energy in drinking water distribution systems. Embodied energy included the life-cycle activities required for the fabrication, transportation, and initial installation of pipes. The results indicated that the gridiron topology had a lower embodied and pumping energy use than the warped parallel and cul-de-sac/loop topologies. The high population density associated with the gridiron topology produced a lower per capita water demand and pumping energy use.

Keywords: water supply and distribution systems; urban form; water demand; pipe flow; embodied energy, pumping energy.

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Introduction

Post war development and urban planning policies have encouraged the sprawling of US and Canadian cities (Southworth and Owens 1993). Cities and their underlying water infrastructure have become more spatially diffuse in the last 70 years. Drinking water systems in particular have evolved in a similar manner as the road system and urban fabric of major metropolitan areas. The distance needed to pump water from source to user has only increased in the intervening decades of urban development. Indeed, Goldstein and Smith (2002) and Sanders and Webber (2012) have reported that 4-12% of electricity use in the US is devoted to the distribution and treatment of water and wastewater. This is hardly surprising given that water is heavy with a density of 1000 kg/m^3 and requires a large amount of energy to convey through pipes with operating pressures ranging between 200-700 kPa. Outside of their operating requirements, water supply and distribution systems also represent a large initial outlay of materials and energy to construct. Prosser et al. (2013) reported large initial embodied energy costs required to fabricate, transport, and install pipes, pumps, and tanks and other components in these systems. The items above point to a need to examine how the geographic shape of neighborhoods and population densities affect the energy use to fabricate and operate drinking water systems.

To document the physical evolution of urban environments, Southworth and Owens (1993) identified neighbourhood street patterns (street topologies) commonly found in North America over the last century (Figure 1). The evolution of street patterns over time is in response to changes in the social, economic, and technological environment. The gridiron topology comprises many intersections and points of access, maximizing the number of possible routes and minimizing trip lengths. This pattern was most common in the early 1900s, when transportation occurred mostly on foot. With the rise of the car as the principal mode of travel, street design was adjusted accordingly with longer blocks and fewer intersections, as seen in the fragmented parallel pattern. Urban planning ideals of the time also sought to emulate more "rural" and "natural" landscapes, resulting in curving streets and more self-contained neighbourhoods. This is most clearly seen in the warped parallel topology of the 1960s. Street patterns in the 1970s and onward departed from the gridiron structure entirely. Cul-de-sacs and small loops were used to maximize privacy by decreasing connectivity and reducing through-

traffic. As a result, these neighbourhoods comprise very few access points, and route choices in these neighbourhoods are limited (Southworth and Owens 1993).

Urban form has also been connected to the variation in residential per capita water use. Sakrison (1997) found that in the Seattle metropolitan area, higher density, gridiron neighbourhoods used less water than conventional suburban developments. Domene and Sauri (2006) found that in the metropolitan region of Barcelona, household size and housing type played a significant role in determining water use. Low-density, single-family homes tended to consume more water because of increased outdoor water uses. Similarly, outdoor water use in North America has been found to be much higher in neighbourhoods with lower densities and larger irrigable areas (Friedman et al. 2013, Van Lare 2005).

There has been a recent interest in examining the impact of urban form on the performance of water infrastructure systems in the urban environment. Jia et al. (2019) examined a number of wastewater and rainwater systems situated in different urban forms and evaluated their performance in terms of economic efficiency, effectiveness and adaptability. They found that urban form has a larger impact on the performance of rainwater systems than it does on the performance of wastewater systems. Huang et al. (2018) examined the impact of factors such as geographic differences and city forms on the energy use in urban water supply systems in China. The authors found that the plane area ratio of a distribution network constrained by the physical layout of the urban environment had an influence on the energy use of water supply systems. Other factors such as the volume of water supplied and the leakage rate also were important factors to consider in the energy use of Chinese water supply systems. Farmani and Butler (2014) examined the urban form of a well-known benchmark distribution network and its economic and hydraulic performance. The authors surveyed a large number of urban growth rates, urban forms that included compact/uniform, monocentric, polycentric and edge forms, and water efficiency strategies and analyzed the benchmark network in terms of total cost, resilience, and water quality performance. The authors found that the urban form and the rate of growth had major implications for the cost and hydraulic performance of their distribution network.

Recently, researchers have examined the link between urban form and the energy use in water supply and distribution systems. Filion (2008) applied life-cycle energy analysis (LCEA) to calculate the energy required for pipe fabrication, pipe break repair, pumping, and pipe disposal in nine network configurations with different population distributions. Here, energy use was lower in compact and highly connected networks with dense population centres near the water source. In a follow-up study, Wong et al. (2017) examined the effect of urban development patterns on the energy use of a water distribution system in the US. The researchers found that lift energy was highest in zones located furthest from the river source and the frictional energy losses were highest in zones nearest the source. Surprisingly, the frictional energy loss in the zone nearest the source was comparable to those in zones near the edge of the system with a lower level of connectivity. In the urban intensification scenario considered by Wong et al. (2017), the reallocation of demand from the edge to the urban core of the system decreased energy use by 50%.

Both Filion (2008) and Wong et al. (2017) commented that since urban growth is incremental, city networks generally do not exhibit a single idealized spatial configuration (e.g., gridiron, radial, satellite). Instead, as cities grow and expand over the course of many decades, they become a patchwork of zones featuring different configurations (Filion 2008). As a result, analysis should be situated where the differences in urban form are found–at the level of the neighbourhood.

The aim of this paper is to examine the impact of urban form on pumping energy and embodied energy in distribution systems at the neighbourhood level. This paper seeks to address two pertinent research questions:

- How do street topologies affect energy use in a neighbourhood?
- How does population density affect energy use in a neighbourhood?

The paper makes an important research contribution to the area as it is the first paper to report a detailed examination of the impact of network topology and population density on the embodied and pumping energy use in water distribution systems at the neighbourhood level. Previous research in this area have only considered these relationships at the level of the entire network.

Methods

Impact of Street Topology and Population Density on Energy Use

Neighbourhood scenarios were created by combining different population density levels with traditional network topologies found in North American cities. A single per capita average water demand was used in all neighbourhood scenarios to isolate for the effects of topology and density. Each neighbourhood scenario was comprised of 750 lots each with a household density of three people/lot (Census 2015) and a population of 2,250 capita in each neighbourhood.

Urban Form Variables–Topology and Population Density

Three popular topologies–gridiron (GR), warped parallel (WP), and cul-de-sac/loop (CL)–were chosen for analysis and are based on the neighbourhood street patterns identified by Southworth and Owens (1993) (Figure 2). To analyze the impact of smaller physical variations within each topology, multiple neighbourhoods in each category were considered. For the gridiron (GR), warped parallel (WP), and cul-de-sac (CL) topologies, three real neighbourhoods were obtained from Google Earth (Google Inc. 2013) (Figure 2). For this study, population density was expressed as net density, which is defined as the number of lots divided by the land area that is used for residential purposes only. Net density does not consider the contribution of green space, roads, and other non-residential space within the neighbourhood to the measured total area. As a result, a variation in net density would be brought about by directly increasing or decreasing the size of residential lots. Lot area values at high, medium, and low densities were based on the urban planning guidelines of a US municipality (City of Miamisburg 2013). In order to apply these densities to each neighbourhood scenario, the length of each original network was scaled up or down to match the lot areas designated for each density.

Although this examination took a systematic approach to consider each combination of topology (GR, WP, CL) and density (high, medium, low), each topology is associated with a certain "native" density in reality. This is because the same social factors that drove the progression from gridiron to cul-de-sac/loop layouts also drove the progression from high to low density neighbourhoods (Southworth and Owens 1993). Barring the recent trend of decreasing density in the last few decades (Knaap et al. 2007), gridiron neighbourhoods tend to be associated with

higher densities while warped parallel and cul-de-sac/loop neighbourhoods have lower densities. This is reflected in the neighbourhood scenarios used for this investigation. Table 1 summarizes the lot area values for each density level as well as the base neighbourhoods associated with each density category.

Embodied Energy and Pumping Energy

The life-cycle energy analysis of Prosser et al. (2013) based on pipe length and diameter was used to quantify the embodied energy associated with each topology considered in the paper. For commercially-available diameters of ductile iron pipe ranging from 150-400 mm, Prosser et al. (2013) reported embodied energy per unit length of 342-789 kWh/m.

The pumping energy use in each neighborhood considered were determined by performing a steady-state hydraulic simulation with the EPANET2 network solver (Rossman 2000). Table 2 summarizes the network parameters used in the models. Changes in elevation throughout the neighbourhood were not considered for two reasons. First, a constant elevation was used to isolate the effect of pipe topology and population density distribution on dynamic losses from friction in the neighborhood systems and removing the effect of static lift driven by changes in elevation or variable topography. Second, a constant elevation was imposed across all neighborhood systems to compare their energy use from dynamic losses only in a fair manner and without the effect of elevation and static lift. In reality, each neighborhood would have its unique topography and pumping energy requirement to overcome its corresponding static lift. The houses in each neighbourhood were assigned to the nearest network node in order to obtain the total water demand at each node. A per capita water consumption rate 400 litres per capita per day (lpcd) typical for North America was used (Environment Canada 2011, MOE 2008). Preliminary testing determined that pumping energy trends were difficult to ascertain at this magnitude of demand since all pipes in the model were set at a minimum diameter of 150 mm to accommodate large fire flows (Walski et al. 2003). To establish the relationship between topology and density and pumping energy, the base demand was increased by a global multiplier of three (1,200 lpcd) to represent peak hour water usage for the simulation. While peak hour demands are not representative of annual energy consumption patterns, they did allow for a clearer comparison of energy use across neighbourhoods.

A node in each neighbourhood was connected to a pump and water supply reservoir, located at the junction where the neighbourhood would be connected to a main road with a feeder main. Each pump had a pump curve with points Q_1=0, H_1 = 4/3 H and Q_2 = 2Q, H_2=0. The flow Q was set at double the total base average demand of each neighbourhood (approximately 21 lps), a value sufficiently large to accommodate the increase in demand due to the global multiplier. It is noted that no Boolean logic rules were used to control the pump and reservoir in the networks considered. As such, the pumping energy use values reported in this paper do not include the added energy associated with pump switches. Further, changes in electricity prices were not considered because the energy analysis is a snapshot in time and does consider energy use over a long-term period. The head H was set at the minimum value required to ensure that the lowest pressure head at any node is 40 m (Great Lakes-Upper Mississippi River Board of State and Provincial Health and Environmental Managers, 2012). All pipe diameters were assigned a starting value of 150 mm (6 inches), with a Hazen-Williams C factor of 130 to represent new ductile-iron pipe (Prosser et al. 2013). If the velocity in the pipe exceeded 1.5 m/s (5 ft/s) during hydraulic analysis, the pipe diameter was increased to the next commercially-available size until its velocity was below this threshold value.

Relationship Between Network Connectivity and Pumping Energy Use: To examine the role of pipe connectivity on pumping energy, the internal connectivity measure developed by Knaap et al. (2007) was used to quantitatively characterize the networks. The internal connectivity of a neighbourhood, was defined by Knaap (2007) as

$$\text{Internal Connectivity} = \frac{\#\text{Intersections}}{\#\text{Intersections} + \text{Dead Ends}}$$

where a high degree of connectivity is represented with a large numerical value of the internal connectivity index. The maximum value for the internal connectivity index is 1, where no cul-de-sacs are present in the neighbourhood.

With a quantitative description of topology established, the degree of correlation between connectivity and pumping energy was quantified with Spearman's rank correlation coefficient (Spearman's ρ). Spearman's rank is a nonparametric measure of the correspondence between two

ranked monotonic variables (Myers et al. 2010). A Spearman coefficient of -1 or +1 indicates a perfect negative or positive monotonic relationship between the two variables. The Spearman correlation coefficient, ρ is computed from the equation:

$$\rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)}$$

where $d_i = x_i - y_i$, with x_i and y_i as the ranks of the variables X_i and Y_i, and n is the sample size. Hypothesis testing is conducted with the null hypothesis H_0: $\rho = 0$ and the alternative hypothesis H_A: $\rho \neq 0$. Significance is tested with the Student '*t*' statistic,

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}}$$

where r is the sample correlation coefficient.

Results and Discussion

Impact of Street Topology and Population Density on Energy Use

For each energy component (embodied energy and pumping energy), the neighbourhood scenarios were compared across topology (density held constant), and then across population density (topology was fixed).

Comparison of Embodied Energy Across Topologies: Figure 3 reports the per capita embodied energy use for each neighbourhood at high, medium, and low densities, as well as for each base scenario, where the original street lengths and lot sizes of the neighbourhood were held constant. Embodied energy is proportional to the total length of pipe, except for in the instances where pipe diameter has been upgraded to meet the maximum velocity criterion. WP-3 was the only neighbourhood that required an increase in diameter. This increase occurred for only one pipe and was applied to all density scenarios. As a result, the main driving force for embodied energy use in this investigation is pipe length. Figure 3 indicates that with the exception of neighbourhood WP-3, gridiron neighbourhoods generally have a lower embodied energy requirement than warped parallel or cul-de-sac/loop neighbourhoods. This result is confirmed by the fact that almost all warped parallel and cul-de-sac/loop networks in this investigation were longer than the gridiron networks.

242 The marked differences in embodied energy across the topologies considered is explained by the
243 extent to which green space is included in the three urban forms. Neighborhoods with warped
244 parallel and cul-de-sac/loop topologies often have buffer zones that separate individual lots and
245 tracts of land from the main road (Southworth and Owens 1993). This means that an additional
246 length of pipe is needed to connect unhoused areas, requiring a longer total length of pipe for the
247 same number of lots, and increasing embodied energy requirements. In gridiron neighbourhoods,
248 lots are usually closely space to each other and to the road and all available space within the
249 neighbourhood is developed. This tends to minimize the length of pipe needed to service the
250 neighborhood population and reduce the embodied energy requirements.
251
252 Comparison of Embodied Energy Across Densities: Figure 4 plots embodied energy against
253 density for each topology. The warped parallel and cul-de-sac/loop neighbourhoods see an
254 increase in embodied energy that ranges between 1.5 and 1.9 kWh/c per m^2 increase in lot area,
255 with the exception of WP-3, as population density is decreased. Gridiron neighbourhoods see a
256 slightly smaller increase of 1.2 kWh/c per m^2, with the exception of GR-3, as population density
257 is decreased. Further, as the population density is decreased, the increase in pipe length, and the
258 corresponding embodied energy, is greater for warped parallel and cul-de-sac/loop networks than
259 for gridiron networks, to accommodate the increase in lot area to accommodate lower densities.
260
261 Increasing the area of narrow lots while maintaining their aspect ratios increases frontage
262 slightly, with the major increase in dimension seen in the depth of an entire row of lots. On the
263 other hand, increasing the area of wide lots means that each lot contributes a major increase in
264 frontage. As a result, moving from high to low density, neighbourhoods with wider lots
265 experienced greater increases in pipe length than those with narrower lots; this resulted in greater
266 increases in embodied energy. The topologies GR-3 and WP-3 saw lower increases in embodied
267 energy across density than the other neighbourhoods in their respective topology categories. This
268 is because both GR-3 and WP-3 neighbourhoods have narrow rectangular lots (with 10 m
269 frontages) and they are not sensitive to density changes.
270
271 Comparison of Pumping Energy Across Topologies: Figure 5 reports the peak hour per capita
272 pumping energy use of each neighbourhood at high, medium and low densities, as well as the

pumping energy use for each base neighbourhood. The results suggest that gridiron neighbourhoods have the lowest pumping energy use compared to the other topologies. This is because gridiron networks are highly interconnected, which allows flow to be distributed more evenly across the network with lower friction losses. It is also noted that the energy use values for pipe layouts within the gridiron topology and pipe layouts within the cul-de-sac/loop topology are clustered together. However, the energy use values for pipe layouts within the warped parallel topology span a wide range. In addition, the energy use values for WP-2 and WP-3 are greater than those of the cul-de-sac/loop neighbourhoods, even though warped parallel pipe layouts are slightly more connected than cul-de-sac/loop pipe layouts.

To further examine the role of pipe connectivity on pumping energy, the connectivity measure developed by Knaap et al. (2007) was used to quantitatively characterize the networks. Table 3 reports the connectivity index of each network. Gridiron networks have no dead-ends and thus have the highest index value. Connectivity decreases as one moves from warped parallel to cul-de-sac/loop networks. This result confirms the trend of decreasing connectivity observed by Southworth and Owens (1993).

For each neighbourhood scenario, the Spearman's rank correlation coefficient was calculated for the correlation between network connectivity and pumping energy and are shown in Table 4. The base models exhibit a negative correlation (ρ = -0.750) between the connectivity index and pumping energy. However, when comparing neighbourhoods at the same density, the correlation between the connectivity index and pumping energy is lower (ρ = -0.583), suggesting that the degree of network connectivity is likely not the primary driving force behind differences in pumping energy consumption.

Flow Splitting: To better understand the differences in pumping energy consumption, the flow paths of each neighbourhood scenario were evaluated. Recall that pumping energy is required to overcome three sources of energy loss–increases in elevation, local losses, and losses due to pipe friction–while fulfilling the minimum pressure head criterion of 40 m.

In this study, the same minimum pressure head criterion was applied to all networks and no change in elevation or local losses were considered. As a result, pumping energy differences are linked to friction loss along pipes which is dependent on pipe length, flow, roughness, and diameter. Since pipe roughness and diameter values were the same for all networks (with the exception of one pipe in WP-3), friction loss is mainly driven by pipe length and flow. Because each network is connected to a single water source, the entire neighbourhood demand flow must pass through this area of connection to the source reservoir. Thus pipes closest to the source convey the largest flows in the network and consequently, friction losses in this area are greatest.

For each network, pipes carrying more than one third of the total neighbourhood demand were identified. As expected, all pipes that met this criterion were located near the water reservoir. The length of pipes that carried more than one third of total demand in each neighbourhood were summed to obtain a metric named "total high flow pipe length" in each network. Spearman's ρ values for the correlation between total high flow pipe length and pumping energy are indicated in Table 4. For comparison, the Spearman's ρ values for the correlation between total pipe length and pumping energy is indicated in Table 4. These results show that pumping energy is more strongly correlated to total high flow pipe length than to the connectivity index or to the total pipe length of the network.

These results suggest that pumping energy use is affected by how quickly large flows that leave the water reservoir are split into smaller flows. The more numerous the intersections are in the area surrounding the water source or connection to transmission pipes, the shorter the distance large flows must travel before being split into smaller flows with lower friction losses. In other words, while "global" network connectivity may not affect pumping energy use significantly, the "local" connectivity of the pipes near the water source has an important impact on pumping energy use.

Figure 2 indicates that WP-2 and WP-3 have very few intersections near their water source connection. Although these networks are better connected downstream, the low connectivity near their water reservoirs drives their pumping energy use past those of the cul-de-sac/loop networks.

WP-1 had significantly lower pumping energy use because the area around the network water reservoir is well connected.

As mentioned above, warped parallel and cul-de-sac/loop topologies were popular at a time when it was common practice to incorporate green buffer zones to separate the main line connection and the neighbourhood proper. So because of this buffer distance, warped parallel and cul-de-sac/loop networks carry high flows for longer distances. On the other hand, gridiron neighbourhoods tend to be directly integrated into heavily urbanized areas, and flows that enter a gridiron neighbourhood has only to be conveyed a short distance before being bifurcated into smaller flows along distribution mains.

Comparison of Pumping Energy Across Densities: Figure 6 plots pumping energy against population density for each topology. As as population density is decreased, the warped parallel and cul-de-sac/loop neighbourhoods see small increases in pumping energy use and the gridiron neighbourhoods see almost no increase in pumping energy use. This indicates that pumping energy use in gridiron neighbourhoods is less sensitive to changes in density than in the other topologies. Since pumping energy use is linked strictly to frictional losses in pipes in this paper, then it follows that the sensitivity of pumping energy to density is thus linked to the magnitude of change in pipe lengths across densities. The distribution of flows along water mains was fixed across all densities in each neighbourhood.

A moderate correlation was found between the change in pumping energy across densities and the change in total pipe length across densities (Spearman's $\rho = 0.450$, H_0: $\rho = 0$ rejected with a confidence level < 80%). However, a stronger positive correlation was found between the change in pumping energy across densities and the change in high flow pipe length across densities (Spearman's $\rho = 0.933$, H_0: $\rho = 0$ rejected with a confidence level of 99.9%). From earlier analysis, it was found that warped parallel and cul-de-sac/loop neighbourhoods tend to have longer high flow pipe lengths due to the lower connectivity in the area near their water reservoirs. Moving from high to low density, these high flow pipes experience a larger increase in length (and thus a larger increase in friction losses) than the shorter pipe segments found near the water source connection of gridiron networks. As a result, neighbourhoods with low

connectivity at their water source connection points are more sensitive to changes in density than neighbourhoods with higher connectivity at their connection points.

In this study, different neighborhood topologies were systematically paired with different levels of population density to examine energy use. In reality, each topology tends to be associated with a certain "native" density in reality. Further, the neighbourhoods in this investigation were assumed to be homogeneously residential when in reality, older gridiron neighbourhoods (and some neotraditional neighbourhoods) tend to have more diversity in land use than newer cul-de-sac/loop subdivisions. This non-homogenous nature of actual neighborhoods can result in a divergence of water demand patterns from a neighborhood where land-use is considered homogenous. As mentioned above, all neighborhood topologies were fixed at a constant elevation to compare their energy use fairly. In reality, each neighborhood has a unique topography and corresponding static lift that will create a difference in energy requirements across neighborhoods. For the sake of a fair comparison, this was not captured in this paper.

This paper has highlighted how the geographic form of neighborhoods mediates the link between water provision and energy use in the urban water-nexus. The neotraditional neighbourhood forms has been identified by researchers as having the potential to reduce energy use in urban areas (Grammenos and Grant 2008; Conway 2009). The neotraditional neighbourhood form integrates the "traditional" gridiron form as the basis for its street layout while incorporating additional design tenets related to "traditional" land use mix, income diversity, and architecture (Grammenos and Grant 2008; Conway 2009). Examples of the neotraditional form include the New Urbanist and Fused Grid topologies that tend to mimic the gridiron pattern by connecting pedestrian walkways, green space, and cul-de-sacs. However, whether neotraditional neighborhood forms are successful at lowering energy requirements relative to their conventional warped parallel and cul-de-sac/loop counterparts will turn on whether they can maintain large population densities and short block lengths to achieve strong "economies of water provision scales" like the traditional gridiron form.

Summary and Conclusions

This paper examined the relationship between urban form and energy use in water supply and distribution systems through the use of neighbourhood scenarios. Urban form was defined in terms of street topology and population density. Energy use was evaluated in two components– embodied energy and pumping energy. Neighbourhood scenarios were created through a combination of three historical topologies (gridiron, warped parallel, and cul-de-sac/loop) and three population densities (high, medium, and low).

Per capita embodied energy requirements were lower in gridiron neighbourhoods than in the warped parallel and cul-de-sac/loop neighbourhoods with longer pipe lengths. Pumping energy was only weakly correlated to the neighbourhood's overall connectivity. Instead, pumping energy was more strongly correlated to the connectivity of the area surrounding the neighbourhood's water source. Flows entering a gridiron neighbourhood tended to split into smaller flows more quickly due to high connectivity near its water source.The-warped parallel and cul-de-sac/loop neighbourhoods had higher pumping energy requirements because of their longer length of pipe that conveyed high flows.

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Fig 1 Neighbourhood street patterns adapted from Southworth and Owens (1993). (Images are not to scale)

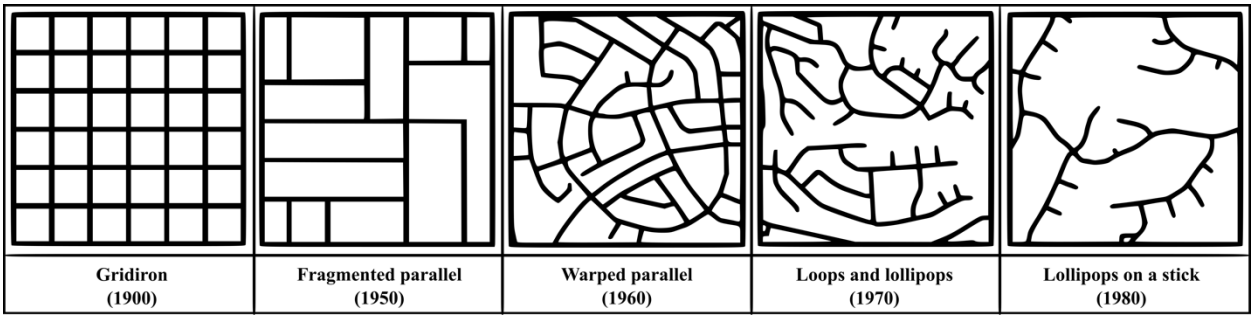


Fig 2 Neighbourhood layouts for each topology category. (Images are not to scale)

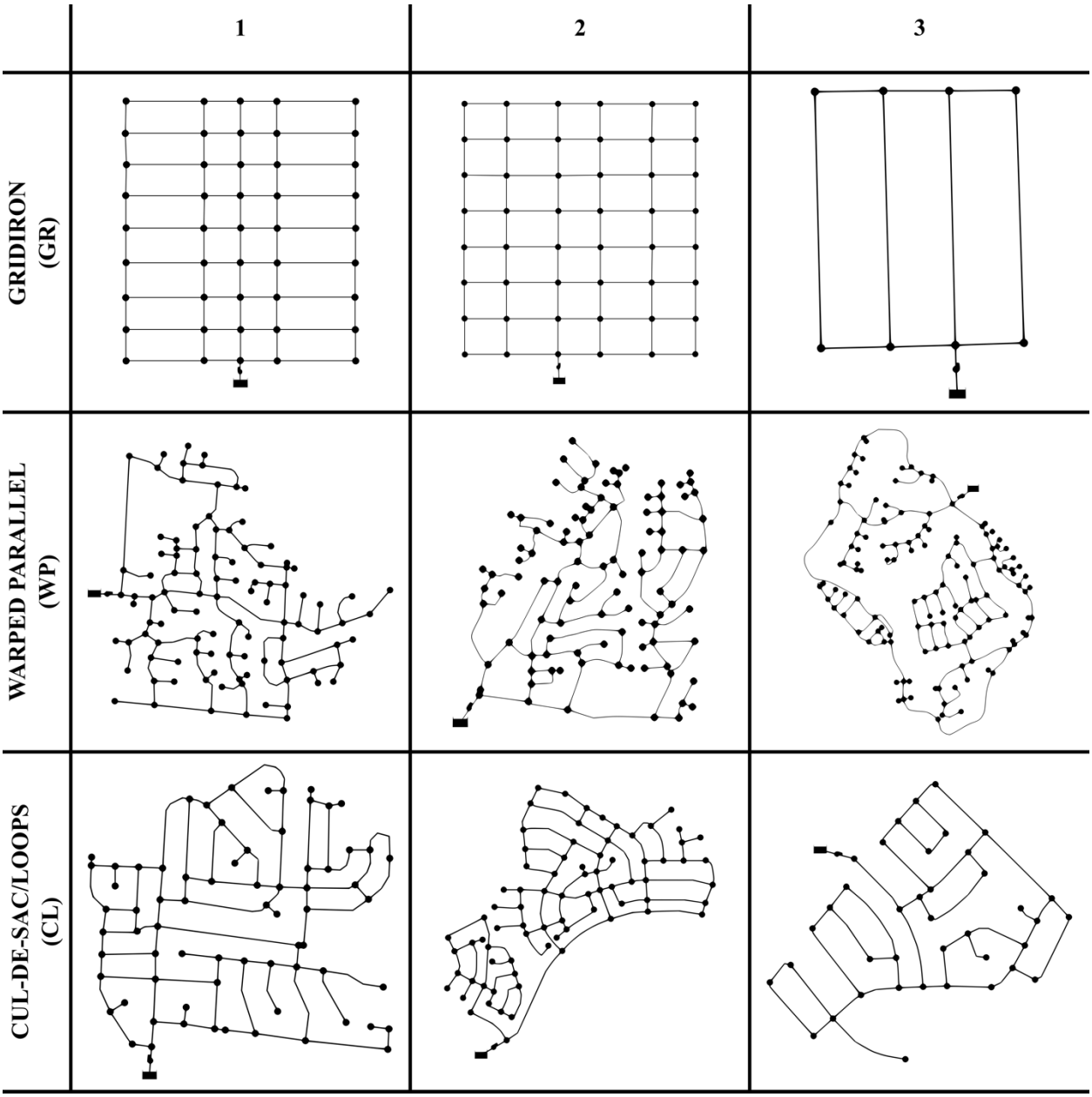
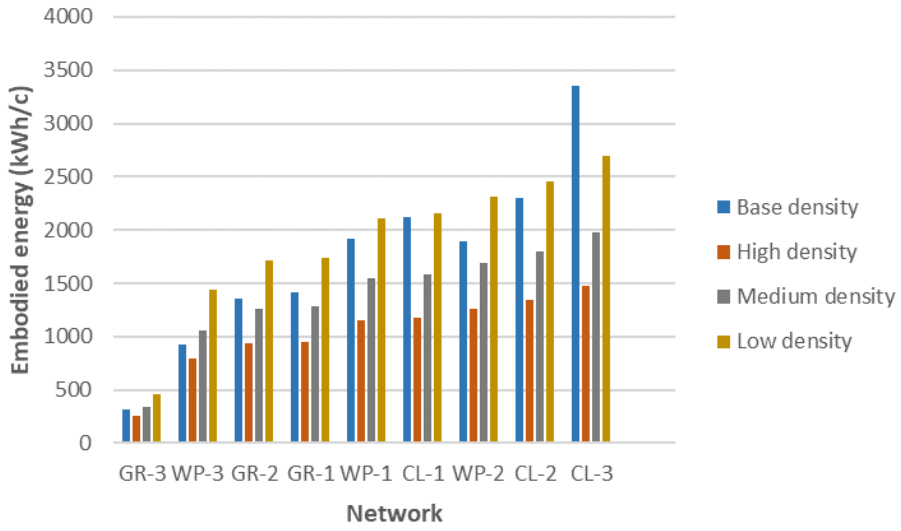


Fig 3 Embodied energy vs topology for high, medium, low, and base density neighbourhoods



535
536 **Fig 4** Embodied energy vs density for a) gridiron, b) warped parallel, and c) cul-de-
537 sac/loop, neighbourhoods. The density values correspond to the lot areas for high, medium, and
538 low density neighbourhoods.

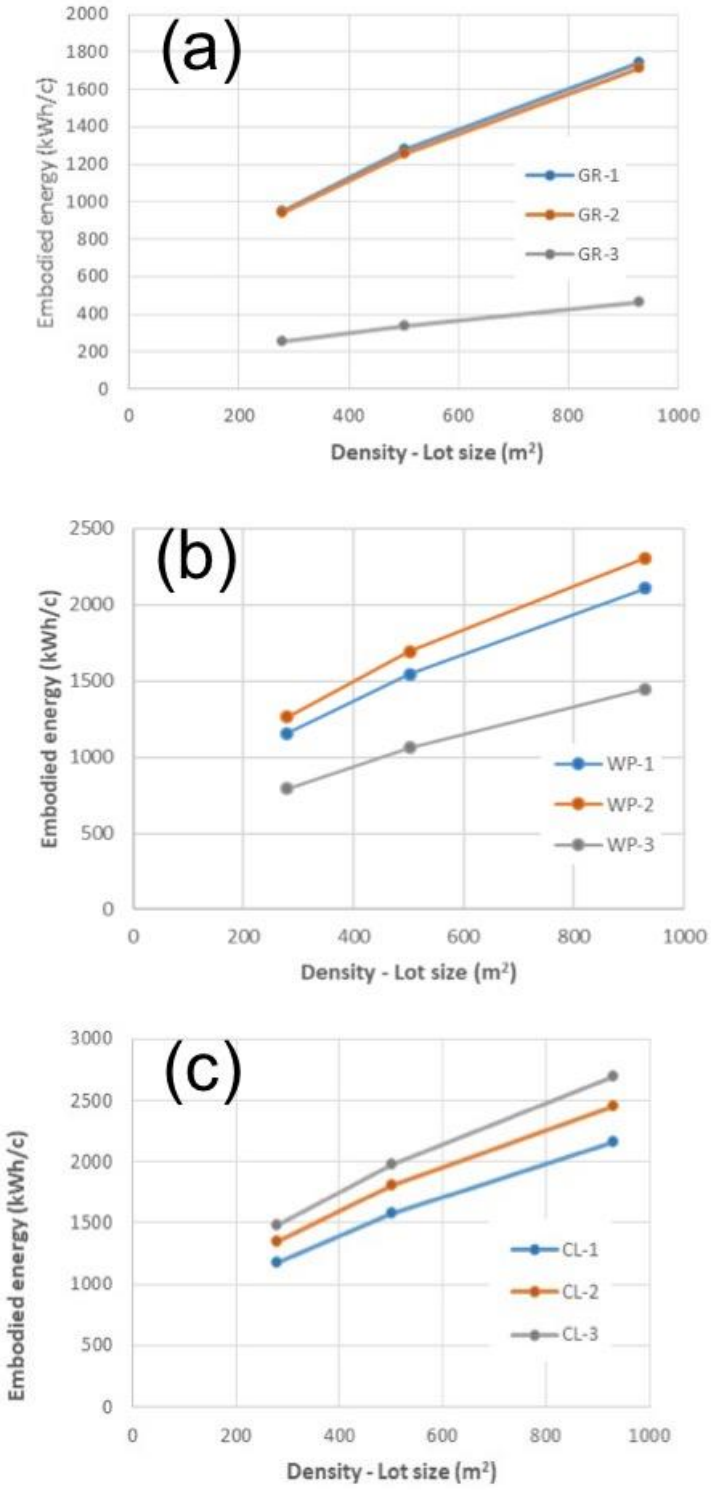


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Fig 5 Pumping energy vs topology for high, medium, low, and base density neighbourhoods

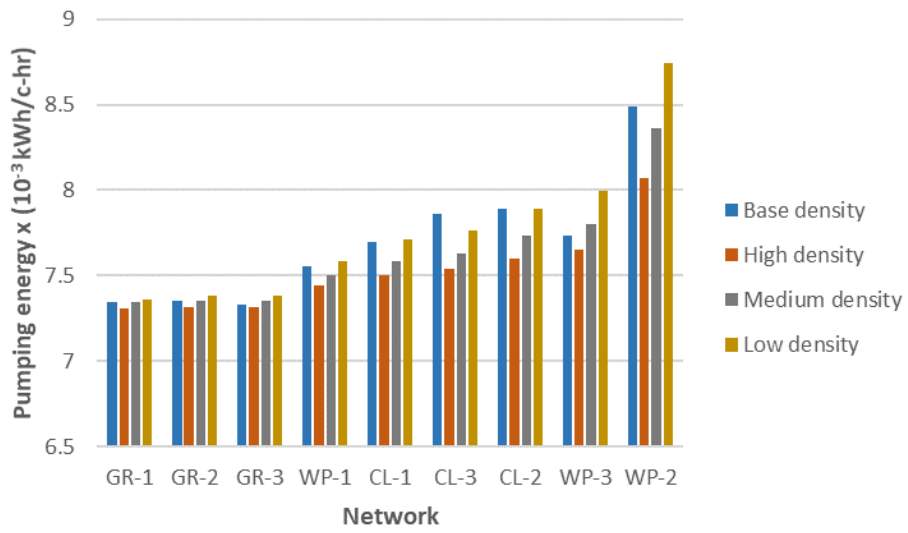
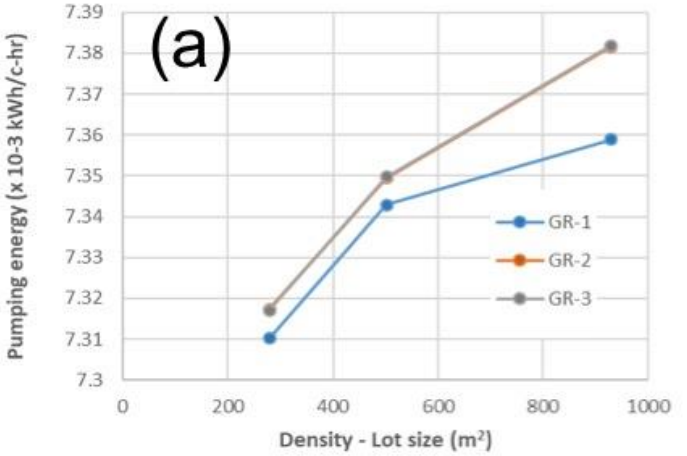
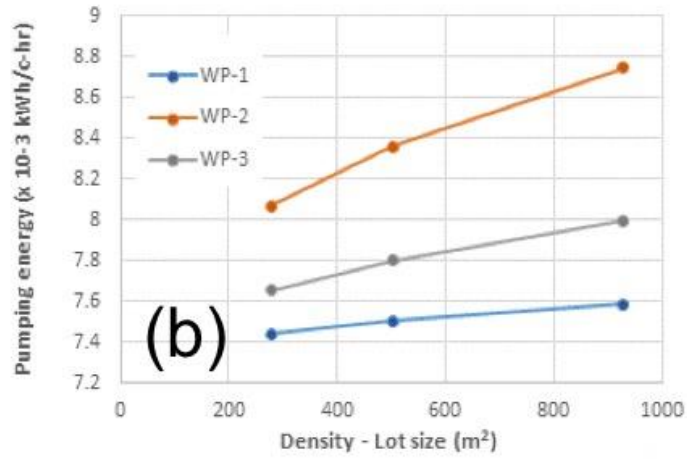
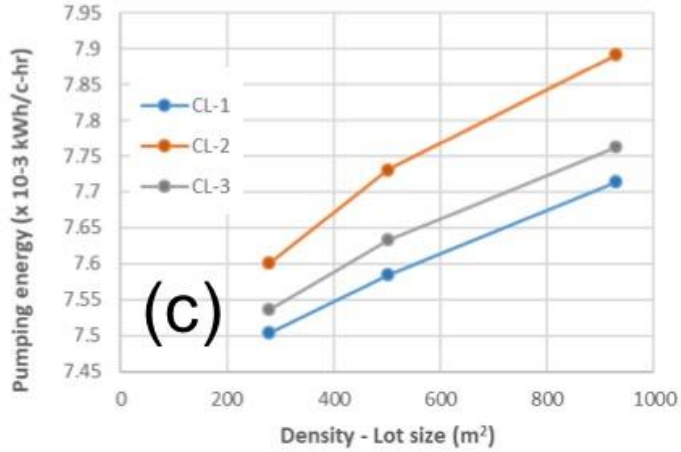


Fig 6 Pumping energy vs density for a) gridiron, b) warped parallel, and c) cul-de sac/loop neighbourhoods. The density values correspond to the lot areas for high, medium, and low density neighbourhoods.







551
552 **Table 1.** Lot areas for high, medium, and low densities

Density	Lot Size (m^2)	Lot Size (ft^2)	Associated Base Neighbourhoods
High	279	3,000	GR-3, WP-3
Medium	502	5,400	GR-1, GR-2, WP-2
Low	929	10,000	WP-1, CL-1, CL-2, CL-3

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555 **Table 2.** Network parameter inputs for hydraulic modelling

Network Parameter	**Input**
Reservoir water level	0 m
Junction elevations	0 m
Pump curve flow, Q	21 lps
Pump curve head, H	Dependent on hydraulic criteria
Pump efficiency, η	75%
Pipe diameter	150 mm; dependent on hydraulic criteria
Pipe roughness (Hazen-Williams C)	130
Base per capita demand	400 lpcd

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558 **Table 3.** Connectivity index value for each neighbourhood

Neighbourhood	Connectivity Index
GR-1	1.00
GR-2	1.00
GR-3	1.00
LL-1	0.40
LL-2	0.45
LL-3	0.35
WP-1	0.75
WP-2	0.74
WP-3	0.85

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561
562 **Table 4.** Correlation between pumping energy and network connectivity, high flow pipe
563 length, and total pipe length
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Density	Network Connectivity		High Flow Pipe Length		Total Pipe Length	
	Spearman's ρ	CL*	Spearman's ρ	CL*	Spearman's ρ	CL*
Base	-0.750	98%	0.883	99.8%	0.700	95%
High	-0.583	90%	0.917	99.9%	0.517	80%
Medium	-0.583	90%	0.967	99.9%	0.467	< 80%
Low	-0/583	90%	0.933	99.9%	0.450	< 80%

565 '* CL = Confidence level.
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