INVESTIGATION OF THE RELATIONSHIP BETWEEN
URBAN FORM AND THE ENERGY USE OF WATER
DISTRIBUTION SYSTEMS

by

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Abstract

The physical configuration of water distribution systems is closely tied to the layout of the urban areas they serve. Over the last century, urban areas in North America have changed significantly in design, moving from high-density grid-based neighbourhoods to low-density suburban developments. The objective of this thesis is to examine the impact of urban form on the energy use in water distribution systems. This relationship was investigated at the neighbourhood-level through an energy analysis of scenarios characterized by different street topologies and population densities. The results suggest that gridiron neighbourhoods have lower energy requirements than warped parallel or cul-de-sac/loop neighbourhoods because their networks are highly connected. Gridiron neighbourhoods also have lower irrigation requirements due to their native high population densities, resulting in lower pumping energy requirements.

The link between long-term urban development and energy use was investigated at the city-level through an energy analysis of a real-world, complex water distribution system. The system’s three pressure zones corresponded well with areas from different periods of development, with distinctly different urban form characteristics. An energy balance approach was used to quantify the operating energy inputs and
outputs for each of the system’s pressure zones. The results suggest that there is an increasingly large “energy penalty” associated with expanding the city’s urban fringe due to the sharp increase in ground elevation moving away from the water source. An alternative development scenario was also investigated, where instead of expanding outward, an existing urban area was intensified through an increase in population density. The results suggest that intensification can contribute to significant energy savings because more of the system’s overall demand is met nearer to the water source, at lower elevation. Although the results obtained from this analysis are specific to the case study system, the general trends identified in the study can be relevant to other systems with similar characteristics, and could be used to guide future urban development plans.
Co-Authorship

Hannah Wong is the primary author of this thesis. Chapters 2, 3, and 4 were written as independent manuscripts. Dr. Yves Filion and Dr. Vanessa Speight provided intellectual supervision and editorial comment for all chapters, and are co-authors of all the manuscripts.
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* * *

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Chapter 1

Introduction

Water supply and distribution systems provide urban areas with many services, from our most basic need for drinking water, to a variety of other applications that ensure everyday comfort and economic well-being. Cities consume large amounts of resources and also produce large amounts of waste. With the population of urban areas increasing rapidly, there is impetus to consider how future development of new or existing urban areas will impact the natural environment and our changing climate.

Minne et al. (2011) emphasized the need for a holistic view on the many components of city infrastructure when planning for future development. Although studied in great detail in isolation, water infrastructure, transportation networks, energy infrastructure, and land use influence and are influenced by each other, and are thus intertwined. Further complexity is added with the presence of equally influential socioeconomic, cultural, and political factors that also shape the built environment of cities (Minne et al., 2011).
Water supply and distribution systems are spatially linked to transportation networks and land development by the physical layout of underground pipe networks that run parallel to roadways. Energy is consumed in the initial fabrication and installation of the pipe networks as well as in day-to-day operational activities such as pumping and maintenance. Socioeconomic, cultural, and political factors permeate every aspect, affecting land development decisions, the layout of neighbourhoods and roads, and the water demand exacted on water supply and distribution systems.

1.1 Urban Development in North America

During and following the Industrial Revolution, North American city cores were home to a highly diverse mix of manufacturing and commercial activities. Because travel by foot or horse-drawn carriage in the mid-nineteenth century were the principle modes of transportation, most of the urban population lived in or very near the central city (Anas, Arnott, & Small, 1998).

The advent of electric streetcar systems in the latter decades of the nineteenth century bolstered the gradual migration of middle and upper-class families out of the city core into outer residential areas. The first appearance of the Model T motor vehicle in 1908 marked the beginning of another key shift in city development (Anas et al., 1998). The growing popularity of the automobile spurred the improvement and expansion of transportation networks. With this significant expansion of personal mobility, lower density neighbourhoods far from the city core were able to be developed, pushing city boundaries rapidly outward (Southworth & Ben-Joseph, 2003).
With suburban growth largely unchecked, the need for comprehensive city planning became clear. Notable planning strategies included Ebenezer Howard’s Garden City model that, in the process of being adapted from England for the automobile-dominated streets of North America, contributed to the trend of separating residential neighbourhoods from high-traffic streets. Suburban neighbourhoods soon became wholly separated from arterial roads, with limited entry and exit points (Moudon, 1992). The growing influence of the building industry standards coupled with the desire for privacy and traffic control led to the replacement of gridded neighbourhood streets with curves, loops, and cul-de-sacs (Southworth & Ben-Joseph, 2003).

The adverse impacts of the suburban developments that now dominate the North American landscape soon became apparent. Low density development occupied large swathes of greenspace areas. Large amounts of resources were required to first establish these neighbourhoods and then sustain the suburban lifestyle. The need for cars in these automobile-oriented streetscapes resulted in increased air pollution and discouraged physical activity. The resultant highly private lifestyle led to social and community disconnect and isolation (Squires, 2002).

In response to the negative aspects of suburban neighbourhoods, planners began to look to neotraditional development - design that sought to emulate “premodern” neighbourhoods with higher densities, mixed uses and walkable streets (Hirt, 2009). A large branch of neotraditional development is the New Urbanism movement, which rose to prominence in the 1980s as an alternative for conventional suburban neighbourhoods. New Urbanist neighbourhoods design principles advocated
for regional-, neighbourhood-, and street-level development that encouraged and nurtured community-building (The Congress for the New Urbanism, 2015). Many New Urbanist communities have since been established in North America. However, the movement’s design tenets have yet to completely dominate more conventional suburban design approaches. In addition, the efficacy of its design in reducing the negative impacts of suburban development remains uncertain (Skaburskis, 2006; Talen, 2010).

1.2 Water Infrastructure in North America

The development of water infrastructure in North America is closely linked to the growth and development of the cities they serve. Historically, the availability of clean water has always been a constraining factor for urban growth. Significant technological advancements throughout the last century have allowed clean water to be transported from a supply source to further and further destinations downstream. Pipe materials have evolved from wood to cast-iron to ductile iron, concrete and polyvinyl chloride (PVC). The appearance of electric centrifugal pumps in the 1920s accelerated the development of water supply systems in many urban areas (Anderson, 1988).

Water supply and distribution systems face a critical set of challenges today, as many of the physical components in these systems have reached or exceeded their service life. Aging and deteriorated water infrastructure lead to a host of performance issues and compromise the ability of the system to deliver water at the quality expected by users. Internal corrosion and tuberculation of the inner wall decreases the diameter of pipes, leading to higher frictional losses and potentially higher pumping
energy requirements. Significant water losses are also seen in deteriorated systems. A study by Brothers (2001) found that water loss in many North American systems ranges from 20 – 50%.

North American water infrastructure also faces a fiscal challenge due to several decades of deferred investment for infrastructure repair, maintenance and expansion. An estimate of the water supply, wastewater and stormwater deficit was found to be in the billions of dollars for Canada (Mirza, 2007).

1.3 Energy in Water Supply and Distribution Systems

Energy and water infrastructure intersect at many points – water is an important medium in energy production, while the establishment and operation of water infrastructure requires energy inputs. A study by Goldstein and Smith (2002) reports that 4% of total electricity use in the United States goes to the conveying and treating of water and wastewater. With the additional energy required for end-uses (such as residential water heating) and various commercial and industrial uses, it has been estimated that water-related activities occupy 12% of the nation’s energy use (Sanders & Webber, 2012).

In light of the aging water distribution infrastructure, the embedded energy in leakage from water systems is particularly relevant. The water lost from the system carries with it the energy required to treat and distribute the water. A study on 275 utilities in the United States estimated that the energy embedded in real water losses ranged from 400 to 50,000 MWh of electricity annually (Aubuchon & Roberson, 2014).
As utilities begin to replace and rehabilitate deteriorated pipe stock, energy trade-off decisions exist between the investment in capital infrastructure and operational considerations. While pipe replacement can result in operational energy savings, there is a significant initial energy cost embodied in the material production, construction and transportation activities of the pipes themselves (Prosser, Speight, & Filion, 2013).

1.4 Thesis Objectives

Cities and urban areas continue to increase in population while simultaneously facing many challenges in the management of their existing water infrastructure. As water supply and distribution systems are also expanded to accommodate increases in demand, an understanding of how urban growth affects water systems is needed. As seen earlier, the form which urban development takes has changed much over history and continues to evolve. This thesis seeks to understand how urban form affects the energy use in water supply and distribution systems. This investigation will draw from a perspective that acknowledges the close links between water infrastructure and the social, economic and political environment it exists in. The main objectives of this thesis are:

1. To gather and consolidate literature from the fields of urban planning and engineering for the purpose of identifying the essential connections between urban form and energy use in water supply and distribution systems, and with this understanding,
2. To examine the effect of different street layouts and population densities on a
neighbourhood’s energy use,

3. To consider the heterogeneity of household water demand due to spatial differ-
ences of the neighbourhood and its resultant effect on energy use, and

4. To generate new knowledge concerning the impact of long-term urban devel-
opment on the energy use of a water system, by analyzing the urban form
characteristics and energy profile of a case study system.

1.5 Thesis Organization

The remainder of this thesis is organized as follows:

Chapter 2 brings together and reviews literature from the disciplines of civil
engineering and urban planning in order to investigate the relationship between urban
form and energy use in water supply and distribution systems. The contributions
and limitations of each area of research are discussed, as is the need for integration
between different disciplines of study.

Chapter 3 presents the research methods and results related to the second and
third objective of the thesis. Neighbourhood scenarios are developed based on a
combination of street topologies and population densities. Variation in water con-
sumption due to urban factors are also considered. Energy use is analyzed in two
components – the pumping energy needed for operation and the embodied energy
required for the fabrication, transportation, and initial installation of pipes.

The fourth objective of this thesis is addressed in Chapter 4. The energy use of
a case study system is analyzed in the context of its long-term urban development. The energy audit approach developed by Cabrera, Pardo, Cobacho, and Cabrera Jr (2010) was used to compare the energy profiles of the case study system’s three pressure zones.

Chapter 5 summarizes the research results and major contributions of this thesis, as well as recommendations for future research directions.

1.6 Publications

Sections of the work in this thesis have been published or will be submitted for publishing to international conferences and journals. They include:


1.7 Research Contributions

The research contributions made in this thesis are as follows:

1. Consolidation and organization of research literature from the fields of urban planning and civil engineering for the purpose of understanding the relationship between urban form and energy use in distribution systems and identifying key urban form variables of interest,

2. New knowledge on how the urban form variables affect the energy use of water distribution systems at a neighbourhood level, and

3. New knowledge on how long-term urban development affects the energy use of an actual, complex water distribution system.

1.8 References


Chapter 2

Literature Review

The link between urban form and energy use in water supply and distribution systems remains relatively unexplored. This chapter examines this relationship through a review of research literature in three areas: urban morphology, sustainable urban forms, and the connections between urban form and water system design performance. The combined findings from the three research areas provide context and identify variables of interest for analysis in the following chapters.

2.1 Introduction

Energy use and anthropogenic climate change are closely connected to urban development given the energy-intensive nature of activities that take place in urban areas – from the operation of physical infrastructure to the movement of people, goods, and disposal of waste. This connection has only been made stronger with the gradual migration of rural populations to urban areas. Today, 54% of the world’s population now lives in urban areas, and in North America, more than 80% of the population
is located in urban areas (United Nations, 2014).

In the years following the Second World War, much of North America’s urban expansion was focused on low-density suburban development (Anderson, Kanaroglou, & Miller, 1996). These urban forms and the physical configuration of their transportation and other infrastructure systems have since been associated with a number of negative environmental impacts (e.g., poor urban air quality, contaminated runoff) and high energy and material resource use (Cieslewicz, 2002). This has led many researchers to examine the impact of the urban form of infrastructure systems such as transportation networks on factors such as energy use, resource consumption, and environmental impacts. In this chapter, the starting definition of urban form is the physical configuration of a city and its infrastructure systems, and the spatial distribution of the population served by these systems in a city.

While the relationship between urban form, transportation infrastructure, and energy has been extensively studied in the past, little research has examined the impact of urban form on the energy use and environmental impacts associated with water supply and distribution systems. This is a potentially important link to address, given that water and wastewater services together with residential water heating and commercial/industrial water consumption account for 12% of total energy use in the United States (Sanders & Webber, 2012). There are compelling reasons why urban form and the geographic shape of water infrastructure systems can have a large influence on energy use. For example, new growth often takes place at the periphery of cities and can increase the distance that water must be pumped from the source to the users across one or multiple pressure zones of a system. The recent
trend towards the densification of existing urban cores also stands to increase urban densities and change the energy use patterns of the water infrastructure of existing urban cores. Another example is the temporal and spatial changes to land-use in a city (e.g., redevelopment of existing urban areas and development of green fields) and the impact that land-use has on water use and energy use in those areas.

While this link is potentially very important, the relationship between urban form and energy use in water systems is complex and difficult to establish for a number of reasons. For one, urban form patterns are always in flux and are a product of the decisions made by many different contributors, from individual households to broad planning policies (Anderson et al., 1996). Decisions concerning the planning, construction, and maintenance of water infrastructure are almost always made in relation to other decisions concerning city growth plans, land-use development and transportation system development and cannot be divorced from these broader considerations. In addition, urban form does not only affect the spatial configuration of a water system and its water main assets, but may also play a role in influencing the characteristics of the water demand exerted on the system. As a result, the relationship between urban form and energy use in water supply and distribution systems draws from both urban planning and engineering, and cannot be addressed exclusively within the context of just one area of research. Investigating this relationship further is challenging as there is a lack of sufficient connection between these two areas of research. For example, engineering researchers may not have sufficiently in-depth knowledge of urban development, while urban planning researchers may not be well-equipped with a technical understanding of the hydraulic complexity of
water supply and distribution systems.

In this context, the aim of this chapter is to review the research literature in the areas of urban morphology, sustainable urban forms, and the connections between urban form and water system design and performance. These three research areas share many points of commonality and can all contribute to further understanding the link between urban form and energy use in water supply and distribution systems. The literature will also be reviewed with the aim of exploring potential research avenues to develop new modeling approaches to better characterize the link between urban form and energy use in water supply and distribution systems.

The chapter is organized as follows: First, the linkages between urban form and energy use in supply and distribution systems are discussed in the context of previous work. Second, research in urban morphology, sustainable urban forms, and the connections between urban form and water system design and performance is reviewed to further elucidate the links between urban form and energy use in water supply and distribution systems. The review of research literature in each of the three fields is used to explore new modeling approaches to better characterize the impact of urban form on energy use in water systems.

2.2 Establishing the Connection Between Urban Form and Energy Use in Water Supply and Distribution Systems

Filion (2008) was the first to directly examine the impact of urban form on the energy use of water supply and distribution systems. In this study, the urban form of water systems was defined as the physical configuration of these systems and the spatial
distribution of water users across these systems. The author posed the following research question: What is the impact of the physical configuration and population distribution in a water system on the annual per capita energy use of that water system?

This question was addressed by analyzing the gridiron, radial, and satellite urban forms indicated in Figure 2.1 for a water system serving a fixed population of 100,000 people. The gridiron configuration is found in many North American cities whose water supply and distribution system infrastructure was developed in the late 1800s and early 1900s. The radial configuration is found in European cities of medieval origin that extend outward from a well-defined city centre in concentric circles that are connected by transportation corridors. Modern examples of the radial layout include the Boulevard Périphérique in Paris (Frey, 2005). The satellite configuration is representative of a car-centric city with a high-density city centre connected to outlying low- to-mid-density communities by major transportation corridors (Anas, Arnott, & Small, 1998).

For the chosen urban forms, Filion (2008) also examined three realistic population distributions: uniform, monocentric, and polycentric. In the uniform population distribution, water demand was distributed evenly over all water network nodes. In the monocentric distribution, 60% of the overall demand was allocated to the centre of each layout, while the remaining 40% of demand was distributed evenly over the other nodes. In the polycentric distribution, 60% of the demand was allocated to high-density nodes at the centre and the periphery of the system, with the remaining 40% of demand allocated to the other nodes.
Figure 2.1: Combinations of network configurations and population distributions (Filion, 2008).

The results of the study showed that the radial network configuration had the lowest annual per capita energy use due to its more compact shape, requiring shorter pipe lengths to reach the furthest nodes. The radial configuration also provided the
largest number of pipe paths to users and thus required smaller pipe diameters. The results also showed that the monocentric distribution had the lowest annual per capita energy use because most of the demand could be met near the source, thereby reducing frictional headloss in the system and reducing the size of pipe diameters required to meet minimum service requirements.

Filion (2008) provides a foundation for continued investigation of the relationship between urban form and energy use in water supply and distribution systems. From a quantitative standpoint, fundamental questions about the link between the geographic form and the spatial distribution of users in a water system and its per capita annual energy use have been addressed on a macro, city scale. Most importantly, Filion (2008) draws attention to important issues arising from the multidisciplinary nature of urban form research as it pertains to water and other physical infrastructure systems. The urban form of a city – which is the product of a complex web of political, social, and historical forces – drives the geographic shape of water systems and other physical infrastructure systems. For example, the morphology of North American cities (and thus the spatial configuration of their water networks) has been strongly shaped by the rise of the car as a means of transport, which increased mobility and facilitated low-density development (Anas et al., 1998). Planning policies following the Second World War also supported the development of these low-density suburban areas connected by large commuter highways (Southworth & Ben-Joseph, 1995). The urban landscape today continues to be shaped by current social, political, and economic forces.

A second issue is that in addition to the broader social, political, and economic
forces present, urban growth is incremental, with changes happening gradually over time. Cities are often a patchwork of neighbourhoods with different pipe configurations (and also pipe ages) as they develop over the course of many decades. As a result, studies involving idealized spatial configurations at the city-scale (i.e. gridiron, radial, satellite) do not adequately capture the diverse and changing nature of cities and their water network systems. The research of Filion (2008) thus paves the way for future work that integrates the non-engineering (but non-negligible) forces that shape the urban form of cities, and by extension, their water systems and their energy use.

Two points of departure from the research of Filion (2008) should be considered to gain a deeper understanding of the link between urban form and energy use in water supply and distribution systems. First, there is a need to examine additional historical urban forms beyond the city forms (i.e. gridiron, radial, satellite configurations) used in the research of Filion (2008). More recently developed urban forms should also be examined. For example, there has been a growing interest in “sustainable” urban form design alternatives, such as the Fused Grid layout (Grammenos & Grant, 2008) and New Urbanist design (Conway, 2009). Investigating the energy use of water supply and distribution systems within a more developed urban form context could bolster the planning community’s understanding of urban sustainability while contextualizing engineering studies on the energy use of water systems. Second, there is a need to recognize the incremental nature of urban growth by exploring energy use in water systems at the scale at which decisions are being made and growth is occurring, that is, at the scale of neighbourhoods. As neighbourhoods
and other urban developments are added to cities, a number of questions arise as to how these new developments influence energy use in water systems. For example: What are the spatial configurations of these new developments? How far are these new developments from the existing urban fringe? How is per capita water demand and energy use affected by the urban form of these new developments?

2.3 Review of Urban Morphology Research

Urban morphology is the study of the urban landscape (Whitehand & Larkham, 1992) and deals with how the spatial structure and patterns of urban areas change over time. This section reviews the most pertinent research in the urban morphology of North American cities with the intent of further understanding the links between urban morphology and the energy use patterns in water supply and distribution systems.

2.3.1 Historical Patterns of Fringe Development

While the social, economic and environmental implications of suburban development have long been of interest to researchers and decision-makers, the physical properties of suburbs have largely been overlooked in the research. In response to this research gap, Southworth and Owens (1993) used a case study approach to examine the morphology of eight urban areas over time at three different spatial scales descending in size – community, neighbourhood, and individual street and house lot. The community scale deals with road patterns at a coarser, regional scale as well as growth patterns over time. The neighbourhood scale analyzes finer street networks within
subdivisions, while the street and house lot scales address the characteristics of lots and buildings. Table 2.1 summarizes the elements that were analyzed in each spatial scale. Based on the study, spatial pattern types (topologies) were then developed for the urban periphery.

Table 2.1: Summary of scales defined by Southworth and Owens (1993)

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<th>Elements</th>
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<td>Community</td>
<td>6,000 acres (2,340 ha)</td>
</tr>
<tr>
<td></td>
<td>Large street patterns</td>
</tr>
<tr>
<td></td>
<td>Large land use patterns</td>
</tr>
<tr>
<td></td>
<td>Growth patterns over time</td>
</tr>
<tr>
<td>Neighbourhood</td>
<td>100 acres (41 ha)</td>
</tr>
<tr>
<td></td>
<td>Single-family neighbourhoods</td>
</tr>
<tr>
<td></td>
<td>Block, street, intersection patterns</td>
</tr>
<tr>
<td>Street and house lot</td>
<td>Street cross-sections</td>
</tr>
<tr>
<td></td>
<td>Lot configurations</td>
</tr>
<tr>
<td></td>
<td>Building types</td>
</tr>
</tbody>
</table>

Contrary to many assumptions, suburbs do not sprawl out as incoherent and haphazard landscapes, but instead bear the marks of a variety of influences, including real estate interests, city planning, engineering standards and market preferences (Southworth & Owens, 1993). The concept of a “suburb” can be traced back to the Garden City movement championed by Ebenezer Howard in the late 1800s in England, which advocated for communities contained in greenbelts. Safe and walkable neighbourhoods were envisioned, with mixed uses in each community to ensure their self-sufficiency (Stephenson, 2002). Rising land values and development pressures reduced these idealized planning principles to residential-only developments consisting of single-family homes placed on large green lots. The quintessential suburban curving street patterns owe their popularity to planners influenced by English countryside landscapes (Southworth & Owens, 1993). These design ideals were reinforced
by traffic engineers who set standards for minimum road widths, cross-sections, and traffic control patterns (Southworth & Ben-Joseph, 1995).

At the community scale, several distinct street patterns were found, classified as “speculative gridiron”, “interrupted parallels”, and “incremental fill and cul-de-sacs/loops”. Each street pattern is linked to a particular time period and reflects the economic, cultural, and technological changes that occurred throughout the twentieth century. Table 2.2 describes specific features of each community scale street pattern. One case study city – Concord, US – consisted of a hybrid of these patterns, demonstrating the change in patterns over space and time. Gridiron streets are found in Concord’s old city core, while the interrupted parallels/incremental fill and cul-de-sacs/loops developed during the 1960s are found in the outlying areas of the city.

Table 2.2: Community scale patterns identified by Southworth and Owens (1993).

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speculative gridiron</td>
<td>Pre-WWI&lt;br&gt;Continuous grid gradually filled in&lt;br&gt;High connectivity&lt;br&gt;Diverse uses</td>
</tr>
<tr>
<td>Interrupted parallels</td>
<td>Disconnected subdivisions&lt;br&gt;Loops and curves in streets&lt;br&gt;Blocks elongated to reduce street building&lt;br&gt;Tracts of homes built by one developer</td>
</tr>
<tr>
<td>Incremental infill</td>
<td>Development process more gradual due to WWII&lt;br&gt;Random and fragmented streets</td>
</tr>
<tr>
<td>Cul-de-sacs/loops</td>
<td>1960s and 1970s&lt;br&gt;Complete shift from gridiron layout&lt;br&gt;Isolated neighbourhoods connected to large arterials</td>
</tr>
</tbody>
</table>

Three growth patterns at the community scale were also identified: “concentric growth”, “instant growth”, and “scattered growth” (Southworth & Owens, 1993).
Concentric growth describes an outward expansion in concentric circles from an urban core. Instant growth describes the development of multiple large-scale projects and/or subdivisions within a short period of time. Scattered growth depicts urban development supported by the increased mobility provided by major road transportation corridors. This growth is typified by non-contiguous developments separated by vacant or undeveloped areas bridged by major roadways.

Southworth and Owens (1993) also examined their eight urban areas at the neighbourhood scale to gain a more detailed understanding of the relative length of streets and number of intersections and dead-ends of different street topologies in these areas (Figure 2.2). In general, neighbourhood streets tended to decrease in connectivity over time. Older topologies such as the “gridiron” layout contained many intersections and points of access to accommodate pedestrian travel. Safety and traffic control became a larger concern with the growing prevalence of car transport, leading to a reduction in the number of intersections, as seen in the “fragmented parallel” topology. The new preoccupation with safety, coupled with preferences for more “rural” and “natural” landscapes led to the disconnected, car-oriented curving and looping streets seen in the “warped parallel” topology. Privacy in the neighbourhood was further maximized by increasing the number of dead-end streets (cul-de-sacs), as seen in the “loops and lollipops” and “lollipops on a stick” topologies. At the street and lot scale, it was found that road and lot widths increased over time, implying a decreasing population density in urban fringe developments.

The street topologies and design principles identified by Southworth and Owens (1993) through their case studies provide a valuable lens through which to examine
energy use in water supply and distribution systems. Mapping these topologies and
growth patterns over time captures the dynamic and incremental growth of cities
in a series of snapshots. These snapshots could then be modeled and added to
larger existing network models in order to more accurately capture the impact of
change and growth. The observations made at the community scale demonstrate
trends in city growth and how developments are located relative to the urban fringe.
This can be directly related to how far new water demand is located from existing
water supplies and the length of pipes needed to reach and service these areas. The
observations of street patterns made by Southworth and Owens (1993) provides a
detailed classification of different spatial patterns found in urban areas and highlights
the pertinent topologies (and consequently, water network designs) that could be
analyzed. The street and house lot measurements provide a context for varying
population densities, and consequently, water demand in a distribution system.
2.3.2 More Recent Trends in Urban Morphology Research

In their analysis of the evolution of suburban streets over the last two centuries, Southworth and Ben-Joseph (2003) examined the recent renewal of interest in traditional (gridiron) urban forms, also known as neotraditional street designs and patterns. While conventional cul-de-sac and looped suburbs continue to dominate current development landscapes, planning movements such as New Urbanism have been credited for advocating and popularizing a return to more compact, grid-like neotraditional designs (Grant, 2002; Wheeler, 2008). More recent case studies have confirmed this growing interest in new forms (or the return to old forms), but also demonstrate the overall prevalence of conventional suburban designs (Smith & Randall, 2008; Song & Knaap, 2007; Wheeler & Beebe, 2011).

A move towards intensification of inner cities has also been observed, particularly for some larger North American cities that are reaching the limits of physical growth. For example, the Greater Toronto Area is constrained by greenbelt policies (Eidelman, 2010), encouraging developers to intensify inner city cores through high density developments (Lehrer, Keil, & Kipfer, 2010; Rosen & Walks, 2013). Research on the energy implications of these high-density (and often high-rise) developments is still emerging. In particular, little is known about the impact of these development trends on the energy use of water distribution networks. Pertinent research questions include: Will intensification concentrate water demand in high-density zones near water sources and reduce pumping distance and energy? What is the trade-off in energy between the concentration of demand in high-density “intensified” zones near the source and the additional energy required to pump water to meet the additional...
lift requirement of high-rise buildings?

2.3.3 Measuring Urban Forms

While Southworth and Owens (1993) incorporated some quantitative measures for urban form (e.g., length of roads, number of intersections per unit area), their primary focus was identifying – through qualitative means – the spatial typologies and organizing principles in suburban developments. Urban form patterns are inherently difficult to quantify and define, and most past attempts to measure urban form patterns have focused more on central city areas than suburban developments (Knaap et al., 2007). A study by Knaap et al. (2007) developed a variety of measures to quantify the urban form properties of suburban neighbourhoods. Table 2.3 summarizes the measures developed within three categories – street network design, land use intensity, and land use patterns. Each category addresses an element of suburban development that is commonly criticized. Street network design measures are focused on street connectivity, while land use intensity measures address population density. Land use pattern measures address the homogeneity of land uses and the subsequent decrease in accessibility in suburban developments.

The measures were then applied to five urban areas in the United States. The results showed that from the 1940s to the 1970s, single-family lot sizes increased and internal connectivity decreased. This trend was reversed for both measures between the 1970s and the 2000s, indicating a reduction in “sprawling” neighbourhoods. However this improvement is countered by the continued increase in single-family house sizes and decrease in external connectivity from the 1940s and onwards (Knaap
For the purpose of exploring the relationship between urban form and energy use in water supply and distribution systems, quantitative measures like those in Table 2.3 could be used to categorize and define different urban forms for comparison. For example, the street network design measures (internal and external connectivity) could be calculated for the neighbourhood street topologies identified by Southworth and Owens (1993). These measures could then be used in a quantitative analysis of the impact that network design has on the energy use of the water supply and distribution systems of different neighbourhoods.

Table 2.3: Urban form measures developed by Knaap et al. (2007).

<table>
<thead>
<tr>
<th>Category</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Street network design</strong></td>
<td>Internal (within neighbourhood) connectivity</td>
</tr>
<tr>
<td></td>
<td>External (neighbourhood to neighbourhood) connectivity</td>
</tr>
<tr>
<td><strong>Land use intensity</strong></td>
<td>Lot size</td>
</tr>
<tr>
<td></td>
<td>House size</td>
</tr>
<tr>
<td><strong>Land use pattern</strong></td>
<td>Diversity index</td>
</tr>
<tr>
<td></td>
<td>Accessibility to commercial use</td>
</tr>
<tr>
<td></td>
<td>Pedestrian accessibility</td>
</tr>
</tbody>
</table>

Overall, the findings from urban morphology research provide an important basis for investigating the link between urban form and the energy use in water supply and distribution systems. Urban morphology research provides a comprehensive spatial context by identifying and situating spatial trends in history while also identifying the drivers of development. The literature also provides insight on how cities grow and expand. By identifying the cultural, political, and economic forces that shape urban growth, urban morphology literature helps ground an engineering study of water supply and distribution systems in a more realistic context.
2.4 Review of Research on Sustainable Urban Forms

While there has been little research that links sustainable urban form and design to water supply and distribution systems, previous research has examined urban form in relation to the sustainability of other infrastructure systems and the urban environment. A review of this research shows how researchers in other fields have chosen to define and characterize urban form and define and measure sustainability. This in turn provides insight on how to approach the relationship between urban form and the energy performance of water supply and distribution systems.

2.4.1 Urban Form and Waste Collection Infrastructure

Di Nino and Baetz (1996) compared the pollutant emissions produced by the collection and transportation of wastes between two hypothetical cities with markedly different urban forms. The “Spread city” resembled a conventional cul-de-sac suburb with low-density residential neighbourhoods interspersed with several commercial and institutional centres. The “Nodal city” served the same population but with approximately half the land area of the Spread city. The Nodal city resembled a traditional gridiron neighbourhood with a diverse mix of higher-density housing and commercial and institutional developments. The street layouts of each city were taken from a report by Paehlke and Dart (1991), which produced typical layouts for conventional suburbs and gridiron neighbourhoods. These layouts were replicated multiple times to form each respective city. The results showed that the Nodal city produced significantly fewer emissions than the Spread city, largely due to the shorter distances traveled in the compact, well-connected street configuration of the Nodal
city.

The work of Di Nino and Baetz (1996) shares a similar conceptual framework to that presented in Filion (2008) which connected urban form to energy use in water supply and distribution systems. Where shorter travel paths and higher connectivity reduced emissions associated with the collection and transport of waste, Filion (2008) showed that water systems with a radial configuration reduced energy use due to shorter pipes lengths and more pipe paths leading to each node. Both examinations also share similar assumptions. Di Nino and Baetz (1996) assumed that per capita waste generation is fixed and constant for both urban forms. Similarly, Filion (2008) assumed that per capita water consumption is fixed and constant for all spatial configurations. Both examinations could be further developed by considering whether waste production or water demand is actually constant or whether they can also be influenced by urban form. Research that addresses the question of whether urban form can influence water use will be reviewed in the following research area on the connections between urban form and water system design and performance.

2.4.2 Urban Form Defined by Density

The study by Di Nino and Baetz (1996) is unique in that their approach to urban form considers the spatial configuration of neighbourhoods. In most studies, the relationship between urban form and sustainability has largely been approached by focusing on an environmental indicator (e.g., energy, carbon emissions) and defining urban form by population density alone. For example, Norman, MacLean, and Kennedy (2006) compared the energy use and greenhouse gas (GHG) emissions of
two developments in Toronto – a high-density development in the city core and a low-density development at the edge. Using life cycle analysis, the energy use and GHG emissions associated with construction materials, building operations, and transportation were estimated. It was found that the low-density development used more energy and produced more GHG emissions, largely attributed to an increased contribution from the transportation network.

A study by Stephan, Crawford, and De Myttenaere (2013) applied life cycle energy analysis (LCEA) to a low-density suburban neighbourhood over a 100-year time frame. Scenarios were developed by varying parameters such as dwelling size, car types, and housing typologies. It was found that higher densities produced savings in building materials, shared infrastructure and reduced operational and transportation energy requirements. However, it was also acknowledged that the benefits of a high density neighbourhood can be exaggerated if the production of most of the neighbourhood’s needs occurred outside of the area (Stephan et al., 2013).

2.4.3 Socioeconomic Factors

An additional complexity in population density research was addressed by a series of investigations in Finland that considered the socioeconomic status of their areas of study. Through a hybrid life cycle analysis approach, Heinonen, Kyrö, and Junnila (2011) estimated the per capita carbon load of two different regions in Helsinki – the high-density downtown consisting of apartment buildings with a higher-income population, and the low-density suburbs consisting of single-family homes with a
lower-income population. Although downtown Helsinki had a density three times higher than that of the suburbs, it was found that downtown Helsinki had a higher carbon load. This was attributed to the higher standard of living in Helsinki’s downtown that negated any density-related efficiency gains. A similar investigation across the two largest metropolitan areas in Finland (Helsinki and Tampere) supported this finding, reporting a weaker correlation between urban density and carbon consumption compared to the correlation between income and carbon consumption (Heinonen & Junnila, 2011).

A third investigation (Heinonen, Jalas, Juntunen, Ala-Mantila, & Junnila, 2013) explored this finding further by introducing the “parallel consumption” phenomenon: while the physical living space in the dense downtown of urban areas was smaller, the “actual living space” of the higher-income, downtown population was much bigger due to the time spent consuming energy outside of the home. This phenomenon, coupled with higher cottage or second home ownership and an affluent lifestyle, resulted in a higher per capita carbon load, offsetting any efficiencies gained from living on a high-density urban form.

These findings provide an important counter-perspective to the widely accepted assumption that higher density urban forms are more sustainable. While this assumption is not necessarily incorrect, these three studies suggest that socioeconomic factors can contribute significantly to the sustainability of an urban area. It should be noted that while North American suburbs are largely inhabited by a higher-income population, many inner city neighbourhoods are now undergoing gentrification, as higher-income individuals begin to move back to downtown cores – and often into
high-rise buildings (Lees, Slater, & Wyly, 2013). Thus, the questions raised by the investigation in Finnish metropolitan areas are also relevant for the sustainability of North American cities. In particular, to what extent does the higher consumptive patterns of a higher-income population negate the efficiencies gained by higher density urban forms?

Overall, research in the area of sustainable urban form provides insight in two ways on how to approach the relationship between urban form and the energy use in water supply and distribution systems. First, sustainable urban form research provides examples of how urban form has been defined and connected to the concept of sustainability. Street topology was a principle differentiator for the cities compared by Di Nino and Baetz (1996) and would be very relevant for an examination of energy use in water supply and distribution systems. However, with the exception of Di Nino and Baetz (1996), the overwhelming majority of sustainable urban form research characterizes urban form by population density only. This single focus was also noted by Knaap et al. (2007) when they observed that population density tends to be the primary quantitative measure for urban form. As a result, there is a need for more research that also considers the spatial configuration component of urban form in relation to sustainability.

On the other hand, population density remains an important property of urban form that can potentially affect the energy use of water distribution systems. For example, a lower density neighbourhood with a longer pipe network might consume more material resources in its construction and would require water to be pumped longer distances. Sustainable urban form research thus provides a second form of
insight by contributing new knowledge on how population density affects sustainability. As seen in the research that was reviewed, this relationship can be complex. Although the works of Norman et al. (2006) and Stephan et al. (2013) found that higher density neighbourhoods were generally more sustainable, the works of Heinonen et al. (2013, 2011) and Heinonen and Junnila (2011) found that socioeconomic factors such as income (leading to differences in consumption behavior in households) can dominate over population density factors. In examining the impact of population density on the energy use of water supply and distribution systems, it is important to recognize that socioeconomic factors could potentially play a similarly significant role in affecting energy use, and should be considered in future studies.

2.5 Review of Literature on the Connections Between Urban Form and Water System Design and Performance

While there is little research on the relationship between urban form and the energy use of water supply and distribution systems, a number of studies have examined the relationship between water system performance, including cost and water usage, and urban form.

2.5.1 Cost - Regional/City-scale Approach

Sitzenfrei, Moderl, Mair, and Rauch (2012) examined the impact of system design and expansion on the hydraulic performance, water quality, and costs of construction of water systems. An urban development model (incorporating population and land use changes) was linked to an infrastructure development model. One hundred case
studies of water system expansion were considered, each with scenarios involving looped or branched water distribution systems and different levels of planning and control regarding water demand. Branched systems were found to have lower costs of construction due to a reduction in total required pipe length. Sitzenfrei et al. (2012) also found that incorporating a master plan for infrastructure development resulted in water systems that were more cost efficient to construct while maintaining the same hydraulic and water quality performance.

Burchell et al. (2002) examined the costs of sprawl in regions within the United States, and in particular, the cost of water and sewer infrastructure under controlled and uncontrolled-growth scenarios. The growth scenarios were developed at multiple scales (region, state, county, and economic area) and were based on an analysis of the historical context of sprawl as well as projected growth trends. The model results indicated that inter-county and intra-county control of growth could reduce 150 million gallons of water demand per day. The savings were attributed to increasing building density and making outdoor water use (lawn irrigation) more efficient.

It is important to note that both studies examined urban form and water from a macro-area, regional standpoint. While much research on sustainability and urban form is indeed approached at the city scale (or larger), urban areas grow incrementally (Anderson et al., 1996; Filion, 2008). As a result, while both studies provide valuable insight for large-scale policy approaches and development regulations, there is a need to examine the relationship between urban form and energy use in water supply and distribution systems at a smaller scale.
2.5.2 Cost - Neighbourhood-scale Approach

Through a review of literature on sustainable neighbourhood design, Engel-Yan, Kennedy, Saiz, and Pressnail (2005) outlined a neighbourhood design process that emphasizes the need to integrate considerations for all multiple urban infrastructure systems (transportation, water, buildings, forestry). It was found that there is a need to consider sustainability at a neighbourhood scale, noting that the problems seen at the larger, city level are often the summation of poor planning decisions at much smaller spatial scales (Engel-Yan et al., 2005). In their examination of water infrastructure design, it was noted that the impact of urban form elements such as lot size and street layout should be considered in evaluating the cost and the performance of water infrastructure.

One particularly detailed example of analysis that includes smaller-scale elements is Speir and Stephenson (2002)’s investigation of the costs of water and sewer infrastructure in relation to spatial patterns. The study considered the costs of pipes, valves, hydrants, manholes, and booster pumps, as well as pumping costs. The effects of three spatial attributes – lot size, tract dispersion and distance from existing water and sewer centers – were isolated and examined using a spreadsheet-based cost model. A total of 60 scenarios were developed, each possessing a combination of the three spatial attributes. The study found that the reduction of lot size, distance separating tracts, and distance from existing water centers all resulted in lowered capital and operational costs. An additional examination of demand as a function of lot size indicated a potential for cost savings by reducing lot sizes. It should be noted that all 60 scenarios in this investigation featured a gridiron road layout, and
thus did not consider the effect of other spatial configurations.

Mondaca, Andrade, Choi, and Lansey (2015) developed a model to estimate the capital and operating cost of water supply and distribution systems in residential subdivision settings. Pipe design at the neighbourhood level was included in the hydraulic models, acknowledging that aggregating multiple low-demand junctions or entire neighbourhoods into a single node (“skeletonizing” the model) results in a hydraulic model that may not reflect system performance issues occurring within the neighbourhood (Mondaca et al., 2015). To develop their cost model, Mondaca et al. (2015) synthetically generated a number of gridiron subdivision networks with varied population density, area, and change in elevation. The authors then compared the costs across the synthetically-generated gridiron layouts and two actual subdivision layouts, with significant differences noted between them.

As a metric, financial cost sometimes does not adequately capture environmental impacts because of the existence of market externalities (Filion, MacLean, & Karney, 2004; O’Neill, 2007). However, the literature that details the relationship between urban form and water infrastructure costs does provide examples of methodological frameworks, as well as insights on how the elements of urban form can be related to the properties of a water supply and distribution system. Engel-Yan et al. (2005) support the need to examine the impact of urban form at the smaller neighbourhood scale. The work of Speir and Stephenson (2002) as well as Mondaca et al. (2015) provide examples of experimental set-ups for a neighbourhood-scale examination of urban form. A similar methodological framework could be applied to examine the relationship between urban form and the energy use of water supply and distribution
systems by substituting cost with energy. Although regional/city-scale studies may not provide guidance on specific methodology, they provide important context by highlighting the potential impact that policy and management schemes could have on the design of water systems, as well as the cumulative effect of neighbourhood policy choices. This can aid in identifying the variables of interest in an examination of the impact of urban form on the energy use of water supply and distribution systems. For example, from the work of Burchell et al. (2002), population density and outdoor water use are two variables of interest that can be influenced by policy and should be incorporated into future research.

2.5.3 Demand

Water demand has been studied extensively in relation to many factors – price policies, conservation or consumption attitudes, technological improvements, local climate, and irrigation practices (Friedman, Heaney, Morales, Palenchar, et al., 2013; Tanverakul & Lee, 2012) – but seldom in relation to urban form. Some of these studies that have sought to connect urban form to water demand are reviewed next.

Domene and Saurí (2006) used disaggregated data to examine the influence of housing type, household size, and consumer behavior on residential water use. These factors were examined through a case study of the metropolitan region of Barcelona. Housing was differentiated by density, with the availability of an outdoor garden or swimming pool in low-density housing also considered. Results showed that household size and housing type were important factors in water consumption. In particular, single-family homes tended to consume more water due to outdoor irrigation
uses. While income also affected water use, its impact was found to be smaller than the presence of outdoor uses.

While per capita indoor water use does not vary much across all geographic regions in North America, outdoor water use varies greatly. In their study, Friedman et al. (2013) found that the water used for irrigation can vary from 10% of indoor water use (Waterloo, Ontario) to 270% of indoor water use (southern California). In warmer climates and drier seasons, outdoor water use can be the primary component of total water use, particularly for single family residential areas. Friedman et al. (2013) explored patterns in potable irrigation in Florida by using a modeling approach that combined a land parcel-based database and billing data to estimate outdoor water use. From the billing data used, it was found that 75% of the annual water use and 80% of peak water use for the month of May was attributed to irrigation. Additionally, the increasing popularity of in-ground sprinkler systems caused irrigation rates to grow in the study area. It was also found that outdoor water use was higher in households with larger irrigable areas.

The impact of urban form – and more specifically, lot size and irrigable area – on water demand is potentially significant. The work of Domene and Saurí (2006) and Friedman et al. (2013) demonstrates the need to consider per capita water use when examining the impact of urban form on energy use in water supply and distribution systems. Per capita water use is often assumed to be a single fixed value when water supply and distribution systems are designed or modeled. However, a neighbourhood with a lower population density could include lots and irrigable areas that are larger than those of a neighbourhood with a higher population density.
Larger irrigable areas require more water to maintain and increases outdoor water use. Higher per capita water use in a low density neighbourhood would require more water to be pumped through the water distribution system, having direct impacts on operational energy use. As a result, there is a need to further characterize per capita water demand with respect to population density and urban form in the design and modeling of water supply and distribution systems.

The research that connects urban form to water system design and performance reviewed above stands to further our understanding of the relationship between urban form and the energy use in water supply and distribution systems. Large or regional-scale cost studies provide policy context and help identify important variables of interest that can be affected through management and planning decisions. For example, Burchell et al. (2002) found that the costs associated with outdoor water demand and infrastructure needed for low density development could be lowered by encouraging more efficient lawn irrigation and higher density developments. As a result, outdoor water demand and population density are relevant variables that should be considered in future modeling and analysis of distribution systems. Small or neighbourhood-scale cost studies provide examples of existing methodological approaches to relate urban form to water supply and distribution systems. For example, the systematic approach used by Speir and Stephenson (2002) to isolate for the effects of three different urban form variables on cost could be applied by replacing the cost metric with energy use in distribution systems. Finally, studies that examine the impact of urban form on water demand can provide new insights into the relationship between per capita water use and population density and how
this relationship can influence pumping energy use in distribution systems.

2.6 Future Research Directions

Future research should extend from the points of departure identified in the previous research reviewed in this chapter. First, the spatial configurations of the urban areas to be modeled should more closely match real-life street topologies that are typically found in cities. Second, since the neighbourhood is the basic building block for change and growth in cities, neighbourhood-scale models should be developed to examine the relationships between urban form and energy use in distribution systems. Future work should include the creation of scenarios that examine the influence of the neighbourhood form on energy use in water mains that supply water to those neighbourhoods.

The literature from all three research areas – urban morphology, sustainable urban forms, and the connections between urban form and water system design and performance – all inform the future research directions of urban form and the energy use of water supply and distribution systems. The water supply and distribution network configurations that are examined should be based on the street topologies and growth patterns identified by urban morphology research. In addition, the quantitative measures developed in the research area of urban morphology should be applied to differentiate and compare the network configurations. The review of the research in sustainable urban forms has shown that the urban form of a city is often characterized only by population density. A more complete assessment of the urban form of water supply and distribution systems should include street topology and
its impact on energy use alongside population density. Based on the review of the research in the connections between urban form and water system design and performance, per capita water use should not be considered a fixed value when examining different urban form scenarios, as a wide range of per capita water uses can exist across different urban forms. Future research that examines the link between urban form and energy use in distribution systems would benefit from attaching realistic per capita water demand values to lot sizes (and population densities) in different neighbourhood forms.

2.7 Summary

Increasingly, there is a recognition that the geographic shape and the distribution of population in urban areas – in short the urban form – can have a large impact on energy use in infrastructure systems and, in particular, water systems that serve users in an urban context. The aim of this chapter was to review the research literature in the areas of urban morphology, sustainable urban forms, and the connections between urban form and water system design and performance to further the understanding of the link between urban form and energy use in water supply and distribution systems. The review of research literature in each of the three areas formed the basis to suggest potential approaches to better characterize the impact of urban form on energy use in water systems.

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Economic Literature, 1426–1464.


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Chapter 3

Urban Form and Energy Use in Water Supply and Distribution Systems: A Neighbourhood-Level Analysis

The main objective of this chapter is to understand the relationship between urban form and the energy consumption of water supply and distribution systems at the neighbourhood level. Variables identified in Chapter 2 such as street topology, population density, and per capita outdoor water use are combined to create neighbourhood scenarios. The energy use of each scenario is analyzed in two components – pumping energy required for operation and the embodied energy required for the fabrication, transportation, and initial installation of pipes.

3.1 Introduction

In the decades following the Second World War, much of North America’s urban growth consisted of low-density suburban developments which steadily pushed city
boundaries outward. These urban forms have since been associated with a broad spectrum of negative consequences – from poor social cohesion and reduced health to the inefficient use of land and increased levels of automobile congestion and emissions (Anderson, Kanaroglou, & Miller, 1996). How cities continue to develop is an increasingly important consideration, particularly with the global trend of rapid urbanization over the last few decades. The United Nations (2014) reports that 54% of the world’s population and more than 80% of North America’s population now live in urban areas.

As cities respond to growth pressures and develop, it is important to consider the drinking water infrastructure that supports them. Much of the pipe stock in North America’s water distribution systems has reached or exceeded its expected service life (American Society of Civil Engineers, 2013). Aging pipes are less efficient in delivering water, where over time, tuberculation and internal corrosion in the pipes increases friction losses and pumping costs (Prosser, Speight, & Filion, 2013). In addition, leakage rates are significant, with typical water losses ranging from 20 to 50% (Brothers, 2001).

Water supply and distribution systems also require a significant input of energy. In the United States, 4% of the nation’s electricity use is attributed to the distribution and treatment of water and wastewater (Goldstein & Smith, 2002). A study by Sanders and Webber (2012) that accounted for additional direct water-related activities (residential water heating, commercial, and industrial uses) puts this number up at 12% of the overall energy consumption in the United States. In addition to the energy associated with operation, water supply and distribution systems also have
an initial “capital” energy cost which is embodied in fabrication, transportation, and installation activities (Prosser et al., 2013).

This chapter brings the current context of drinking water infrastructure and urban growth together by investigating the link between the spatial rendering of the pipes that make up water distribution systems, and the cities and neighbourhoods they serve. In particular, the impact of urban form on the energy use of water supply and distribution systems is examined at the geographical scale of the neighbourhood, reflecting the scale at which existing cities are expanding.

3.2 Background

Filion (2008) was the first to directly investigate the relationship between urban form and the energy use of water supply and distribution systems. Urban form was defined at the spatial scale of cities, as a combination of two components – the physical configuration of the water network’s pipes and the spatial distribution of the water users over the network. Energy use was quantified through life-cycle energy analysis (LCEA), considering the energy required for pipe fabrication, pipe break repair, pumping, and pipe disposal. Nine urban forms were created by combining different network configurations with different population distributions. Energy consumption was found to be lower in networks that were more compact and highly interconnected. Distributing most of the population near the water source was also found to reduce energy use.

In addition to providing quantitative analysis at the city level, Filion (2008) also identified two important issues that can steer the direction of future research.
First, city street configurations are rarely based on what is most efficient for physical infrastructure. Instead, urban environments take shape under the influence of a complex web of political, social, and economic forces. Road configurations – and consequently water network configurations – are often driven by transport and land-use policies, as well as the interests of various agents in the private and public sector. The second issue discussed is that because 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.

Southworth and Owens (1993) identified neighbourhood street patterns (street topologies) commonly found in North America over the last century, as shown in Figure 3.1. The evolution of street patterns over time are in response to changes in the social, economic, and technological environment. The gridiron topology contained 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 automobile as the principle mode of travel, street design adjusted accordingly with longer blocks and fewer intersections, as seen in the fragmented parallel pattern. Urban planning ideals of the time also looked 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 contain very few access points, and route choices in these neighbourhoods are limited (Southworth & Owens, 1993).

![Figure 3.1: Neighbourhood street patterns adapted from Southworth and Owens (1993). Images are not to scale.](image)

Interest in “greener”, more pedestrian-friendly urban design surfaced in the 1980s. This shift was most clearly encapsulated by the New Urbanist movement, which grew in popularity in the following decades (Ellis, 2002). From a spatial context, New Urbanism (or neotraditional planning) advocated for higher densities and more walkable, interconnected streetscapes (Southworth, 1997) that resemble traditional gridiron neighbourhoods.

In the United States, more than 400 New Urbanist neighbourhoods have since been built or are under construction (Trudeau, 2013). An evaluation of 106 of these projects found that although the neighbourhoods differed significantly in their incorporation of New Urbanist design elements, one common feature that was observed was the use of gridded street configurations (Trudeau, 2013).

The “Fused Grid” is another more recent street configuration. As shown in Figure 3.2, the Fused Grid merges a gridiron network with cul-de-sacs. Gridiron connectivity
is achieved for pedestrians through walkways and green space connecting cul-de-sacs together, while route choices for automobiles are limited. Fused grid neighbourhoods have since been applied in Stratford, Ontario and Calgary, Alberta (Grammenos & Grant, 2004, 2008).

![Fused Grid street layout](image)

**Figure 3.2:** Fused Grid street layout adapted from Grammenos and Grant (2004).

While Southworth and Owens (1993) focused on the qualitative differences between different neighbourhood street topologies, Knaap, Song, and Nedovic-Budic (2007) developed quantitative measures of urban form at the neighbourhood level. One such measure is the internal connectivity of a neighbourhood, which was defined as

\[
\text{Internal connectivity} = \frac{\#\text{intersections}}{\#\text{intersections} + \#\text{dead ends}} \tag{3.1}
\]

where greater connectivity is indicated by a higher ratio. This measure is particularly relevant for the neighbourhood street patterns identified by Southworth and Owens (1993) because connectivity was an important differentiator between the five neighbourhood street patterns.

Urban form has also been connected to 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 Saurí (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, Heaney, Morales, Palenchar, et al., 2013; Van Lare, 2005).

The literature highlighted in this section provides the context needed to investigate the link between urban form and the energy use of water distribution systems at the neighbourhood-level. Key urban form variables of interest such as neighbourhood topologies and outdoor water use are also identified. The relationship between urban form and energy use is examined by way of a number of neighbourhood scenarios typically found in North American cities. In particular, this chapter seeks to address four pertinent research questions:

- How do street topologies affect energy use in a neighbourhood?
- How does population density affect energy use in a neighbourhood?
- How is energy use in a neighbourhood affected when variation in outdoor water use due to differences in urban form is considered?
- How can the findings from the above analysis be applied to neotraditional developments?
3.3 Methods

3.3.1 Impact of Street Topology and Population Density on Energy Use

Neighbourhood scenarios were created by combining different population density levels with topologies based on neighbourhood street patterns commonly found in North American cities in the last century. To isolate for the effects of topology and density, the same per capita average water demand was applied to all neighbourhoods. Variation in per capita water demand due to differences in outdoor water use will be addressed in a subsequent analysis. Each neighbourhood scenario was set to contain approximately 750 lots (household units). Further discussion on the choice in neighbourhood size can be found in Appendix A. It was assumed that each household consisted of three people, which is the approximate household density for the US (United States Census Bureau, 2015), for a total population of 2,250 people per neighbourhood.

Urban Form Variables – Topology and Population Density

Three topologies – gridiron (GR), warped parallel (WP), cul-de-sac/loop (CL) – were chosen for analysis and are based on the neighbourhood street patterns identified by Southworth and Owens (1993). To analyze the impact of smaller physical variations within each topology, three neighbourhoods in each category were considered, for a total of nine neighbourhoods, shown in Figure 3.3. Each neighbourhood was modeled after an actual North American neighbourhood by tracing its street topology with Google Earth (Google Inc., 2013) and AutoCAD (Autodesk Inc., 2011). Physical
properties such as street length and average lot sizes were also obtained. For the purposes of water network modeling, it was assumed that pipe configurations followed street patterns exactly.

<table>
<thead>
<tr>
<th>Neighbourhood</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GRIDIRON</strong></td>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
<td><img src="image3.png" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>WARPED PARALLEL</strong></td>
<td><img src="image4.png" alt="Diagram" /></td>
<td><img src="image5.png" alt="Diagram" /></td>
<td><img src="image6.png" alt="Diagram" /></td>
</tr>
<tr>
<td><strong>CUL-DE-SAC/LOOPS</strong></td>
<td><img src="image7.png" alt="Diagram" /></td>
<td><img src="image8.png" alt="Diagram" /></td>
<td><img src="image9.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

**Figure 3.3:** Neighbourhood layouts for each topology category (drawings are not to scale). The nodes, pipes, pump and reservoir of each neighbourhood’s hydraulic model network are also shown. For the subsequent discussion, each neighbourhood will be referred to by their topology and number (e.g., GR-1 refers to the top left neighbourhood in this figure).
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. Total pipe lengths of the original (base) neighbourhoods as well as their high, medium, and low variations can be found in Table A.1 in Appendix A.

Although this investigation took a systematic approach to consider each combination of topology (GR, WP, CL) and density (high, medium, low), each topology tends to be 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 & 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 3.1 summarizes the lot area values for each density level as well as the base neighbourhoods associated with each density category.
### Table 3.1: Lot areas for high, medium, and low densities.

<table>
<thead>
<tr>
<th>Density</th>
<th>Lot size (m²)</th>
<th>Lot size (ft²)</th>
<th>Associated base neighbourhoods</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>279</td>
<td>3,000</td>
<td>GR-3, WP-3</td>
</tr>
<tr>
<td>Medium</td>
<td>502</td>
<td>5,400</td>
<td>GR-1, GR-2, WP-2</td>
</tr>
<tr>
<td>Low</td>
<td>929</td>
<td>10,000</td>
<td>WP-1, CL-1, CL-2, CL-3</td>
</tr>
</tbody>
</table>

**Energy Consumption – Embodied and Pumping**

Energy use in this investigation consisted of two components – the pumping (operational) energy needed to supply water to the neighbourhood, and the embodied energy required to fabricate, transport, and install the network pipes.

Embodied energy was calculated as a function of pipe length and diameter. This approach is based on the metrics of Prosser et al. (2013) that applied life cycle energy analysis (LCEA) to quantify the embodied energy associated with replacing pipes in a water distribution system. The energy required per length of ductile iron pipe at various commercially-available diameters ranged from 342 kWh/m for pipes with a diameter of 150 mm to 789 kWh/m for pipes with a diameter of 400 mm (Prosser et al., 2013).

Pumping energy requirements were calculated by modeling each neighbourhood scenario as a pipe network with EPANET2 (Rossman, 2000) and running steady-state hydraulic analyses. Headloss due to pipe friction was determined by the Hazen-Williams formula,

\[
h_f = \frac{10.68L}{C^{1.85}D^{4.87}Q^{1.85}}
\]

where \( h_f \) is the headloss across the pipe in question in meters, \( L \) is the length of the pipe in meters, \( C \) is the unitless Hazen-Williams ‘C’ factor that describes the
roughness of the pipe, $D$ is the diameter of the pipe in meters, and $Q$ is the flow within the pipe in cubic meters per second. Table 3.2 summarizes the network parameters used in the models. Changes in elevation throughout the neighbourhood were not considered for this analysis in order to isolate the effects of friction losses on energy. As a result, all nodes were set at the same elevation. The houses in each neighbourhood were assigned to the nearest network node in order to obtain the total water demand at each node. As in the work of Filion (2008), an average baseline water demand of 400 litres per capita per day (lpcd) was used. This value is within the range of average per capita water consumption in North America (Environment Canada, 2011). 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). This resulted in low velocities and minimal friction loss under average (no fire flow) demand conditions. To more clearly discern the relationship between topology/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. It should be noted that peak hour demands are not truly representative of annual energy consumption, but allow for a clearer comparison of urban form topologies.

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 neighbourhood’s pump was characterized by a pump curve with a single point (flow $Q$, head $H$). From this single point, EPANET2 automatically generates a pump curve with two additional points at $Q_1 = 0$, $H_1 = \frac{4}{3}H$. 

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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. 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 a new ductile-iron pipe (Prosser et al., 2013). If a pipe’s velocity 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.

### Table 3.2: Network parameter inputs for hydraulic modeling.

<table>
<thead>
<tr>
<th>Network parameter</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reservoir water level</td>
<td>0 m</td>
</tr>
<tr>
<td>Junction elevations</td>
<td>0 m</td>
</tr>
<tr>
<td>Pump curve flow, $Q$</td>
<td>21 lps</td>
</tr>
<tr>
<td>Pump curve head, $H$</td>
<td>Dependent on hydraulic criteria</td>
</tr>
<tr>
<td>Pump efficiency, $\eta$</td>
<td>75%</td>
</tr>
<tr>
<td>Pipe diameter</td>
<td>150 mm; dependent on hydraulic criteria</td>
</tr>
<tr>
<td>Pipe roughness (Hazen-Williams C)</td>
<td>130</td>
</tr>
<tr>
<td>Base per capita demand</td>
<td>400 lpcd</td>
</tr>
</tbody>
</table>

#### 3.3.2 Impact of Variation in Per Capita Water Demand on Energy Use

Per capita water use can vary due to the density of the neighbourhood as a result of differences in outdoor water use (Friedman et al., 2013; Van Lare, 2005). Low-density neighbourhoods, which tend to have larger irrigable areas, may require more water to maintain these areas. The neighbourhood scenarios of the previous section considered variation in population density and street topology only. Here, to evaluate
the effect that variation in water demand has on energy use, per capita water use was broken into two components – indoor water use and outdoor water use.

Indoor water use was assumed to be homogeneous across all neighbourhoods of all densities and remain constant throughout the year. The value used for per capita indoor water demand was 262 lpcd, a value taken from a study by Friedman et al. (2013) that logged the water use of 1,188 homes in 12 different North American cities.

Outdoor water use was assumed to vary across neighbourhoods of different densities. For this study, it was assumed that the outdoor water use of each neighbourhood was based on the volume of water required to maintain healthy turfgrass on the irrigable area of each lot. In reality, water may also be used for other outdoor uses, such as filling swimming pools and car-washing. In addition, the volume of water used for irrigation can also be affected by other factors that are beyond the scope of this investigation. These include weather variability, water pricing, irrigation methods, irrigation restrictions, and various social factors (Askew & McGuirk, 2004; Endter-Wada, Kurtzman, Keenan, Kjelgren, & Neale, 2008; Friedman et al., 2013; Ouyang, Wentz, Ruddell, & Harlan, 2014).

The irrigable area of each lot was defined as

\[ \text{Internal area (} m^2 \text{)} = \text{lot area (} m^2 \text{)} - \text{built area (} m^2 \text{)} \]  

where built area refers to the area of the lot covered by structures (houses, garages, sheds) and paved areas (driveways, walkways) in square meters. The average built area per lot for each neighbourhood was determined through measurements taken...
of the original neighbourhood lots on Google Earth (Google Inc., 2013). In the same way that each original neighbourhood’s lot sizes were scaled to meet the high, medium, and low density designations, irrigable area was increased or decreased proportionately with the increase or decrease in lot size. As a result, the ratio between irrigable area and lot area remains constant for all density scenarios.

Outdoor water use was approximated through the evapotranspiration (ET) method developed by the US Department of Energy (2010). The water required to maintain an area of healthy turfgrass is determined given the plant type and the climate and precipitation characteristics of the location. Total annual water use for a certain area can be calculated using the following equation provided by the US Department of Energy (2010), adapted for SI units:

\[
\text{Outdoor water use (m}^3/\text{yr}) = \frac{AIF \times IA}{IE}
\]

where \(AIF\) is the annual irrigation factor \((m^3/m^2 \cdot \text{yr})\) and \(IA = \) the irrigable area \((m^2)\), and \(IE = \) the inefficiency of the watering method.

\(IE\) was set to 1 as no inefficiencies related to watering methods were considered in this investigation. Annual irrigation factor \((AIF)\) values for different turfgrass types are provided by the US Department of Energy (2010) for 36 different cities in the United States located in ten different climate zones. According to the procedure provided by the US Department of Energy, for a location not listed in the report, the annual irrigation factor of the city closest in distance and climate zone is used.

For this investigation, the location of the municipality in the Midwestern United States from which neighbourhood density designations were taken earlier was used.
Cincinnati, Ohio was the closest of the 36 cities to the municipality in proximity and climate zone. For this investigation, it was assumed that turfgrass was the only vegetation present on each lot. Table 3.3 summarizes the inputs used to select the appropriate annual irrigation factor.

The total water demand of each neighbourhood was calculated by summing the indoor and outdoor water demand components. Pumping energy requirements were calculated by modeling each neighbourhood pipe network with EPANET2 (Rossman, 2000). Each pump was characterized with the same single point pump curve with flow $Q$ and head $H$. Flow $Q$ was set at the total demand of each neighbourhood. Head $H$ was set at the minimum head required to maintain a pressure head of 40 m at all junctions.

### Table 3.3: Annual irrigation factor inputs.

<table>
<thead>
<tr>
<th>Annual irrigation factor parameter</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closest city</td>
<td>Cincinnati, OH</td>
</tr>
<tr>
<td>Climate zone</td>
<td>Humid continental – warm summer</td>
</tr>
<tr>
<td>Peak ETo*</td>
<td>158 mm/month</td>
</tr>
<tr>
<td>Peak Rainfall</td>
<td>85 mm/month</td>
</tr>
<tr>
<td>Turfgrass type</td>
<td>Kentucky bluegrass</td>
</tr>
<tr>
<td>Turfgrass season type</td>
<td>Cool</td>
</tr>
<tr>
<td><strong>Annual irrigation factor</strong></td>
<td><strong>0.15 m³/m²-yr</strong></td>
</tr>
</tbody>
</table>

*peak reference evapotranspiration

### 3.3.3 Application to Neotraditional Neighbourhoods

Neotraditional neighbourhoods are developed from many diverse design principles, integrating physical design elements with socially-based decisions. In accordance with its name – “neotraditional” – many neotraditional neighbourhoods tend to employ some form of “traditional” gridiron network as the basis for their street
layouts while incorporating additional design tenets related to “traditional” land use mix, income diversity, and architecture. As a result, neotraditional neighbourhoods are not always differentiated entirely by a particular physical characteristic, and thus do not fit easily into the systematic approach of the previous sections that isolated for the impact of street topology and population density.

Instead, based on the observations from the analysis of the impact of population density/street topology on energy use, neotraditional neighbourhood scenarios were created to investigate the impact of the urban form factors that were most relevant to neotraditional design. Two general types of neotraditional neighbourhoods were considered – New Urbanist neighbourhoods and Fused Grid neighbourhoods. No variation in outdoor water use was considered in this analysis.

3.4 Results and Discussion

3.4.1 Impact of Street Topology and Population Density on Energy Use

For each energy component (embodied energy and pumping energy), the neighbourhoods scenarios are compared across topology (density held constant), and then across density (topology held constant).

Embodied Energy

Figure 3.4 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 maintained. Embodied energy – as defined for this study – is proportional to the total length of pipe, except for
Figure 3.4: Embodied energy use of each neighbourhood at base, high, medium, and low densities. The networks are sorted from highest to lowest energy user at medium density.

the instances where a pipe’s diameter is 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 3.4 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.

In the historical context of urban form, warped parallel and cul-de-sac/loop topologies emerged alongside a dominant urban design approach that favours the
segregation of land uses. Attempts were also made to emulate the rolling and curving rural landscapes of country homes (Southworth & Owens, 1993). As a result, these neighbourhoods often contained buffer zones separating the neighbourhood from the main road. Even within a single subdivision, undeveloped tracts of land separated clusters of houses to promote privacy. As a result, warped parallel and cul-de-sac/loop networks must devote an additional length of pipe to connect unhoused areas, requiring a longer total length of pipe for the same number of lots, and increasing embodied energy requirements. In contrast, gridiron neighbourhoods are usually closely connected with the surrounding urban area, and all available space within the neighbourhood is developed, decreasing embodied energy requirements.

**Density Comparison for Embodied Energy**

Figure 3.5 plots embodied energy against density for each topology category. Moving from high to low density, warped parallel and cul-de-sac/loop neighbourhoods see an increase in embodied energy that ranges between 1.5 and 1.9 kWh/c per m² increase in lot area, with the exception of WP-3. Gridiron neighbourhoods see a slightly smaller increase of 1.2 kWh/c per m², with the exception of GR-3. Since embodied energy is almost solely proportional to the length of the network for all scenarios, in moving from high to low density, the increase in pipe length is greater for warped parallel and cul-de-sac/loop networks than for gridiron networks to accommodate the increase in lot area.

The difference in increase in embodied energy is due to the different lot shapes associated with each topology. Southworth and Owens (1993) note that lot frontage
Figure 3.5: Embodied 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.

has increased over time, with the shift from narrow, rectangular lots in the early 1900s to wider, square lots from the 1960s onwards. As a result, older gridiron neighbourhoods tend to feature narrow lots while newer warped parallel or cul-de-sac/loop neighbourhoods feature wider, square lots. This is reflected in the neighbourhoods chosen for this investigation – Figure 3.6 shows typical rectangular lots in GR-1 and square lots in CL-3, with frontage lengths of 16 m and 26 m respectively.

Increasing the area of narrow lots while maintaining their aspect ratios increases frontage slightly, with the major increase in dimension is seen in the depth of an entire row of lots. On the other hand, increasing the area of wide lots results in each lot contributes a major increase in frontage. As a result, moving from high to low density, neighbourhoods with wider lots experience greater increases in pipe length than narrow lots, resulting in greater increases in embodied energy. The earlier noted exceptions – GR-3 and WP-3 – experienced significantly lower increases in embodied
energy across density than the other neighbourhoods in their respective topology categories. This is because both neighbourhoods contain particularly narrow rectangular lots (with 10 m frontages), resulting in their weaker sensitivity to density changes.

**Pumping Energy**

Figure 3.7 reports the peak hour per capita 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 evenly across the network, resulting in lower friction losses. It can also be observed 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 wider 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.

**Connectivity Index**

To more closely investigate this observation, the connectivity measure developed by Knaap et al. (2007) was used to quantitatively characterize the networks. The maximum value for the connectivity index is 1, where no cul-de-sacs are present in the neighbourhood. Table 3.4 reports the connectivity index of each network. Gridiron networks have no dead-ends and thus have the highest possible index value. Connectivity decreases moving from warped parallel to cul-de-sac/loop networks.
This result confirms the trend of decreasing connectivity observed by Southworth and Owens (1993).

**Table 3.4:** Connectivity index value for each neighbourhood.

<table>
<thead>
<tr>
<th>Neighbourhood</th>
<th>Connectivity Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>GR-1</td>
<td>1.00</td>
</tr>
<tr>
<td>GR-2</td>
<td>1.00</td>
</tr>
<tr>
<td>GR-3</td>
<td>1.00</td>
</tr>
<tr>
<td>LL-1</td>
<td>0.40</td>
</tr>
<tr>
<td>LL-2</td>
<td>0.45</td>
</tr>
<tr>
<td>LL-3</td>
<td>0.35</td>
</tr>
<tr>
<td>WP-1</td>
<td>0.75</td>
</tr>
<tr>
<td>WP-2</td>
<td>0.74</td>
</tr>
<tr>
<td>WP-3</td>
<td>0.85</td>
</tr>
</tbody>
</table>

With a quantitative description of topology established, the degree of correlation between connectivity and pumping energy was analyzed. The degree of correlation was quantified with Spearman’s rank correlation coefficient (Spearman’s $\rho$), which is a nonparametric measure of how well the relationship between two ranked variables are described as a monotonic function (Myers, Well, & Lorch, 2010). A Spearman coefficient of -1 or +1 indicates a perfect negative or positive monotonic relationship between the two variables. The Spearman correlation coefficient, $\rho$ is computed from the equation:

$$\rho = 1 - \frac{6\Sigma d_i^2}{n(n^2 - 1)}$$  \hspace{1cm} (3.5)

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,
\[ t = \frac{r \sqrt{n - 2}}{\sqrt{1 - r^2}} \]  

(3.6)

where \( r \) is the sample correlation coefficient.

For each neighbourhood scenario, Spearman’s rank correlation coefficient was calculated for the correlation between network connectivity and pumping energy and are shown in Table 3.5. The base models exhibit a fairly high negative correlation \( (\rho = -0.750) \) 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 weaker \( (\rho = -0.583) \), suggesting that the degree of network connectivity is likely not the primary driving force behind differences in pumping energy consumption.

**Table 3.5:** Correlation between pumping energy and network connectivity, high flow pipe length, and total pipe length.

<table>
<thead>
<tr>
<th>Density</th>
<th>Network connectivity</th>
<th>High flow pipe length</th>
<th>Total pipe length</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spearman’s ( \rho )</td>
<td>CL*</td>
<td>Spearman’s ( \rho )</td>
</tr>
<tr>
<td>Base</td>
<td>-0.750</td>
<td>98%</td>
<td>0.883</td>
</tr>
<tr>
<td>High</td>
<td>-0.583</td>
<td>90%</td>
<td>0.917</td>
</tr>
<tr>
<td>Medium</td>
<td>-0.583</td>
<td>90%</td>
<td>0.967</td>
</tr>
<tr>
<td>Low</td>
<td>-0.583</td>
<td>90%</td>
<td>0.933</td>
</tr>
</tbody>
</table>

*Confidence level at which the null hypothesis \( (\rho = 0) \) can be rejected

**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 which, from the Hazen-Williams equation, 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 neighbourhood’s entire 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 a third of the neighbourhood’s total demand were identified. As expected, all identified pipes were located near the water reservoir. The lengths of these pipes were summed to obtain each network’s “total high flow pipe length”. Spearman’s $\rho$ values for the correlation between total high flow pipe length and pumping energy can be found in Table 3.5. For comparison, the Spearman’s $\rho$ values for the correlation between total pipe length and pumping energy can also be found in Table 3.5. From these results, it can be seen 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.

The results suggest that pumping energy use is significantly affected by how quickly large flows leaving 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 splitting, resulting in 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 a significant impact on pumping energy use.

From Figure 3.3, it can be seen 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’s water reservoir is well connected, as shown in Figure 3.3.

In the context of urban form, warped parallel and cul-de-sac/loop neighbourhoods are more likely to have low connectivity near their connection points. As previously mentioned, warped parallel and cul-de-sac/loop topologies were popular at a time when it was common practice to segregate residential neighbourhoods and incorporate green space buffer zones separating the main line connection and the neighbourhood proper. As a result, it is more likely that warped parallel and cul-de-sac/loop networks carry high flows for longer distances. In contrast, gridiron neighbourhoods tend to be nested into the surrounding urban area, and flows that enter the network are split relatively quickly.

**Density Comparison for Pumping Energy**

Figure 3.8 plots pumping energy against population density for each topology. Moving from high to low density, warped parallel and cul-de-sac/loop neighbourhoods
see small increases in pumping energy use, while gridiron neighbourhoods see almost no increase. This result suggests that pumping energy requirements in gridiron neighbourhoods are less sensitive to changes in density than the other topologies. Pumping energy use for the neighbourhood scenarios in this investigation is linked to the energy lost to friction. Of the four pipe properties driving friction loss – flow, diameter, roughness, and length – length is the only variable that changes across densities in every neighbourhood. Flow distribution also remained the same across all densities for every neighbourhood. The sensitivity of pumping energy to density is thus linked to magnitude of change in pipe lengths across densities.

Some 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

![Figure 3.8: 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.](image)
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.

3.4.2 Impact of Variation in Per Capita Water Demand on Energy Use

For the particular geographical location used, outdoor water ranges from 6% (WP-3) to 52% (CL-3) of indoor water use. The indoor and outdoor water use values for each neighbourhood can be found in Table A.2 in Appendix A. It should be noted that the AIF value for the chosen geographical location is quite small compared to other geographical locations in the United States. For example, in San Francisco, California, the AIF has a value of $0.576 \text{ m}^3/\text{m}^2\cdot\text{yr}$ for cool season turfgrass. Outdoor water requirements to maintain healthy turfgrass in that climate would be almost four times that of the geographical location used in this investigation.

Table 3.6 compares the neighbourhoods ranked from highest to lowest pumping energy consumers for constant and varied water demand. The rankings show that accounting for varied outdoor water use yields a significantly different makeup of top energy users than the constant water use results. For example, WP-3 moved from
being one of the top energy users to one of the lowest because its irrigable area was smallest relative to its total lot size. Irrigable area and pumping energy are strongly correlated, with a Spearman’s $\rho$ of 0.9 ($H_0: \rho = 0$ rejected at a confidence level of 99.8%). In contrast, the correlation between high flow length – the primary driver for pumping energy from earlier the earlier analysis – and pumping energy is now very weak, with a Spearman’s $\rho$ of -0.033.

Table 3.6: Neighbourhoods ranked from highest to lowest pumping energy users.

<table>
<thead>
<tr>
<th>Variation in outdoor not considered</th>
<th>Variation in outdoor considered</th>
<th>Variation in outdoor not considered</th>
<th>Variation in outdoor considered</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP-2</td>
<td>CL-3</td>
<td>WP-2</td>
<td>CL-1</td>
</tr>
<tr>
<td>CL-3</td>
<td>CL-1</td>
<td>WP-3</td>
<td>CL-3</td>
</tr>
<tr>
<td>CL-2</td>
<td>CL-2</td>
<td>CL-2</td>
<td>WP-2</td>
</tr>
<tr>
<td>WP-3</td>
<td>WP-1</td>
<td>CL-3</td>
<td>GR-2</td>
</tr>
<tr>
<td>CL-1</td>
<td>WP-2</td>
<td>CL-1</td>
<td>WP-1</td>
</tr>
<tr>
<td>WP-1</td>
<td>GR-2</td>
<td>WP-1</td>
<td>CL-2</td>
</tr>
<tr>
<td>GR-2</td>
<td>GR-1</td>
<td>GR-3</td>
<td>GR-1</td>
</tr>
<tr>
<td>GR-1</td>
<td>GR-3</td>
<td>GR-2</td>
<td>GR-3</td>
</tr>
<tr>
<td>GR-3</td>
<td>WP-3</td>
<td>GR-1</td>
<td>WP-3</td>
</tr>
</tbody>
</table>

The results suggest that for the chosen geographic location, the magnitude of outdoor water use is significant enough to be the dominant determinant for pumping energy consumption. These results also highlight the potential importance of considering variation in water demand due to spatial heterogeneities. Urban form factors – particularly population density – can be associated with variation in outdoor water use and thus act as an important driver in determining pumping energy requirements.

Accounting for the variation in outdoor water use due to population density has a
number of implications for energy use in the base density neighbourhoods. As noted
earlier, gridiron neighbourhoods tend to have higher “native” population densities
than warped parallel or cul-de-sac/loop neighbourhoods. This suggests that the “na-
tive” outdoor water demand of gridiron neighbourhoods tends to be much lower than
the “native” outdoor water demand of cul-de-sac/loop neighbourhoods due to differ-
ences in irrigation area. As a result, a gridiron neighbourhood with its native high
density encourages lower energy use by the lower outdoor water use associated with
its smaller irrigable area and, as seen from the street topology/population density
investigation, by the connectedness of its street topology. On the other hand, a cul-
de-sac/loop neighbourhood, with its native low density tends to have higher energy
requirements because of its topology and its higher water demand.

3.4.3 Application to Neotraditional Neighbourhoods

New Urbanist Neighbourhoods

As noted by Trudeau (2013), the majority of New Urbanist projects incorporate
gridiron street configurations into their design and are thus expected to have sim-
ilar energy requirements to traditional gridiron neighbourhoods. However, some
New Urbanist neighbourhoods were found to have a gridiron topology along with
conventional suburban “superblocks” that are much longer than traditional blocks
(Trudeau, 2013). The presence of superblocks – even in a gridiron neighbourhood
– could result in high flows traveling longer distances through the neighbourhood,
increasing pumping energy requirements.
In order to investigate the impact of superblocks, roads in the base neighbourhoods GR-1 and GR-2 were removed to create longer blocks, shown in Figure 3.9. Additional lots were added to the neighbourhood to fill in the area previously occupied by these roads. Table 3.7 compares the embodied and pumping energy requirements of the New Urbanist and original neighbourhoods, assuming constant water demand.

A shorter total pipe length is required for a network with longer blocks, and more area is freed up for additional lots. As a result, the per capita embodied energy requirements of both New Urbanist neighbourhoods are lower than their associated traditional gridiron neighbourhoods. However, high flows travel longer distances in the New Urbanist neighbourhoods because of their longer blocks, leading to an increase in per capita pumping energy requirements. This suggests that the extent to which a New Urbanist neighbourhood behaves like a traditional neighbourhood depends not only on their adherence to the traditional gridiron topology but also on whether they maintain traditional magnitudes of scale.

Table 3.7: Comparison of energy use in base and neotraditional neighbourhoods, NU=New Urbanist and FG=Fused Grid.

<table>
<thead>
<tr>
<th>Neighbourhood</th>
<th>Embodied energy (kWh/c)</th>
<th>Pumping energy ($\times 10^{-3}$ kWh/c-hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base</td>
<td>NU</td>
</tr>
<tr>
<td>GR-1</td>
<td>1,414</td>
<td>1,168</td>
</tr>
<tr>
<td>GR-2</td>
<td>1,353</td>
<td>988</td>
</tr>
</tbody>
</table>
Figure 3.9: Neotraditional pipe network configurations. The nodes, pipes, pump and reservoir of each network are also shown.

**Fused Grid Neighbourhoods**

There are two potential ways to configure the water network of Fused Grid neighbourhoods. First, the water network could be made to follow the street layout closely, with numerous cul-de-sacs and dead ends. The second approach is to maintain a traditional gridiron network by connecting pipes across the pedestrian walkways and green spaces between cul-de-sacs.

Neighbourhoods GR-1 and GR-2 were altered to produce both Fused Grid configurations and are shown in Figure 3.9. Demand was lowered accordingly to account for the replacement of lots by greenspace and pedestrian walkways. Table 3.7 compares the embodied and pumping energy requirements of the Fused Grid neighbourhoods.
and the original neighbourhoods, assuming constant water demand.

The use of cul-de-sacs in Fused Grid A shortens overall network length and reduces per capita embodied energy requirements. However, per capita pumping energy requirements are increased because the low connectivity in the network results in high flows traveling longer distances. Connecting cul-de-sacs together in Fused Grid B results in a larger per capita embodied energy requirement than the base neighbourhoods. This is because the presence of green space and pedestrian walkways reduce the number of lots that can be served by the network. Although there is also a similar increase in per capita pumping energy requirements, the increase is very small because the network is more highly connected than Fused Grid A.

Overall, neotraditional topologies have the potential to provide lower energy consuming alternatives to conventional warped parallel and cul-de-sac/loop neighbourhoods. However, the extent to which embodied and pumping energy use is reduced depends on whether other urban form elements such as higher densities and shorter block lengths are also incorporated.

3.5 Summary and Conclusions

This chapter 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 due to their shorter total pipe lengths. Warped parallel and cul-de-sac/loop neighbourhoods had longer pipe lengths because they tended to be coupled with urban design features such as buffer zones and undeveloped tracts in order to maximize privacy and traffic safety. The additional pipe length required to connect these sections added to the overall length of the neighbourhoods and increased per capita embodied energy requirements.

Neighbourhood topology was characterized through a connectivity index in order to quantitatively assess the correlation between topology and pumping energy requirements. Analysis showed that 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. On the other hand, the segregating urban design features such as green space in warped parallel and cul-de-sac/loop neighbourhoods increased the length of pipe that conveyed high flows, driving up pumping energy requirements.

Another set of scenarios accounted for the differences in outdoor water use at different population densities. Outdoor water use for the chosen geographical area added a significant demand volume to the neighbourhoods, ranging from 6% (at high density) to 52% (at low density) of indoor water demand. As a result, differences in the neighbourhoods’ pumping energy requirements were more strongly driven by
their water demand than their topology.

Overall, the results suggest that historical urban design factors play a large role in determining the physical layout of a neighbourhood and its consequent energy use. Social factors such as the desire for privacy and the need for traffic safety (due to increased automobile dependence) manifest themselves in the spatial configuration of warped parallel and cul-de-sac/loop neighbourhoods, leading to higher embodied and pumping energy requirements. Similar factors are also responsible for the lower densities in these neighbourhoods, which can lead to increased outdoor water use, reinforcing their high energy requirements. As a result, while this investigation systematically considered all combinations of topology, population density and outdoor water demand, it should be recognized that certain neighbourhood combinations (such as low-density cul-de-sac/loop and high-density gridiron) are more likely to occur in reality.

Future research can expand this investigation in two ways. First, additional urban form components and energy measures could be added to better characterize the neighbourhood scenarios. Neighbourhoods in this investigation were assumed to be entirely 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. Differences in land use mix can lead to different diurnal demand patterns (Walski et al., 2003). The additional impact of different diurnal demand patterns on energy use could be analyzed through extended period analysis. In addition, this investigation did not consider leakage in pipe networks. Leakage rates are affected by both the length of the network and network pressure (Cabrera,
Pardo, Cobacho, & Cabrera Jr, 2010) and can contribute significantly to the energy use of a water network (Aubuchon & Roberson, 2014). Further analysis could examine how the different network lengths and levels of excess pressure in the neighbourhood scenarios contribute to leakage and as a result, additional pumping energy requirements. Second, while this investigation provides an initial assessment of how urban form affects neighbourhood water networks in isolation, a another direction for future research could look at the energy response of an existing city network as it expands through the addition of new neighbourhoods with different urban forms.

3.6 References

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Autodesk Inc. (2011). AutoCAD.


Chapter 4

The Impact of Long-Term Development on the Energy Use of a Water Distribution System: A Case Study

In the previous chapter, the impact of urban form on energy use was examined through the analysis of isolated neighbourhoods. The main objective of this chapter is to understand the impact of long-term urban development on the energy use of an actual water supply and distribution system. While the results of this study are specific to the case study system, the overall trends observed can be relevant to other systems with similar characteristics, and provide guidance for future urban development planning.
4.1 Introduction

Over the last century, the layout of urban areas in North America has changed considerably. The expansion of existing cities and the development of new urban centres has been markedly shaped by the economic, technological, and social changes of the last century. Where neighbourhoods once grew slowly over time, house by house, entire residential-only subdivisions can now be constructed on a much shorter timescale (Moudon, 1992). Where neighbourhoods streets were once closely integrated into the surrounding urban fabric, residential neighbourhoods now tend to be more self-contained (Knaap, Song, & Nedovic-Budic, 2007). As a result, modern cities are a patchwork of areas and neighbourhoods containing different street patterns. Accordingly, the water distribution networks laid beneath the roads, supplying water to urban areas, have also changed in configuration. The transformation of the spatial shape of these systems is of interest in light of the significant energy costs associated with the construction and operation of urban water infrastructure (Goldstein & Smith, 2002; Sanders & Webber, 2012).

The relationship between urban form and the energy use of water supply and distribution systems was investigated in the previous work of Filion (2008) and Wong, Speight, and Filion (2015). Filion (2008) analyzed the per capita annual energy consumption of three idealized network patterns (gridiron, radial, satellite) at the city-scale with three different population distributions (monocentric, uniform, polycentric). The study found that due to its shorter flow paths, a radial network configuration had the lowest energy use compared to gridiron or satellite networks. In addition, the monocentric population distribution required less energy than uniform
or polycentric distributions because most of the network’s demand could be met near the water source. In the study by Wong et al. (2015), neighbourhood-level scenarios were created based on combinations of street topologies (gridiron, warped parallel, cul-de-sac/loop) and population densities (high, medium, low). The energy consumption of each scenario was analyzed in two components – the pumping energy required for operation and the energy embodied in the initial fabrication, transportation and installation of pipes. Results showed that the higher density and higher connectivity of gridiron neighbourhoods resulted in lower embodied and pumping energy requirements compared to warped parallel or cul-de-sac/loop neighbourhoods.

How cities deal with future population growth pressures is also an important question, in light of the rapid urbanization of the world’s population. In North America, more than 80% of the population live in urban areas (United Nations, 2014). Will cities continue to expand their urban boundaries into greenfield areas, as was the trend after the Second World War (Anderson, Kanaroglou, & Miller, 1996)? Will cities consider intensification of existing urban areas as an alternative growth scenario? For example, the Greater Toronto Area, having reached physical limits to outward expansion due to greenbelt policies (Eidelman, 2010) has seen an increase in high-rise development in its inner city core (Lehrer, Keil, & Kipfer, 2010). Intensifying cities instead of expanding would result in populations being distributed differently on the water distribution network, which could have implications on the energy use of the system.

The aim of this chapter is to generate new knowledge concerning the connection between the long-term development of urban areas and the energy use of their water
supply and distribution systems. The objective of the chapter is to examine whether long-term changes to the urban form of an actual, complex distribution system have produced corresponding changes to the energy use of that distribution system over time. The new knowledge from this examination can provide direction and guidance for future urban growth. In particular, this chapter seeks to answer the following three research questions:

- How have urban form patterns changed over time in the case study network?
- How does operational energy use in the water distribution system differ between areas characterized by different urban form patterns in the case study network?
- How does increasing the population density of the existing city core (through intensification) instead of expanding the urban fringe to accommodate future growth affect energy use in the case study system?

4.2 Description of the Case Study and Development Scenarios

The case study system indicated in Figure 4.1 is an actual, complex water supply and distribution system that serves an urban area of 20,000 people in the Midwestern United States (United States Census Bureau, 2012). For privacy, the system name will be withheld in the subsequent analysis. The city, which is situated along a river, has grown outward from the eastern bank, expanding further up the river valley from the 1900s and onwards. An additional small expansion was also made on the western bank of the river between the 1960s and the 1970s. The total average system demand is 10 MLD (mega litres per day).
The system is comprised of three pressure zones: low elevation (Pressure Zone 1), medium elevation – further subdivided into east (Pressure Zone 2) and west (Pressure Zone 2a) and high elevation (Pressure Zone 3). Water is pumped from the river (modeled as the reservoir) and processed by a water treatment plant on the eastern bank within Pressure Zone 1. Pressure Zones 2, 2a and 3 each contain a booster pump station. The pumps in each pressure zone are controlled by the water level of their respective tanks, turning on when a minimum level is reached and shutting off when a maximum level is reached. A hydraulic model representing all pipes in the distribution system has been developed by the city. The river from which water is pumped is not included in the hydraulic model. Instead, the reservoir models the system’s water treatment plant clearwell. The head of the clearwell varies between 212.6 m and 214.1 m, with the average head being 213.3 m. Headloss due to pipe flow friction in the model was determined by the Hazen-Williams formula,

\[ h_f = \frac{10.68L}{C^{1.85}D^{4.87}}Q^{1.85} \]  

(4.1)

where \( h_f \) is the headloss across the pipe in question in meters, \( L \) is the length of the pipe in meters, \( C \) is the unitless Hazen-Williams 'C' factor that describes the roughness of the pipe, \( D \) is the diameter of the pipe in meters, and \( Q \) is the flow within the pipe in cubic meters per second. Table 4.1 summarizes the network model properties.
Table 4.1: Case study system network properties.

<table>
<thead>
<tr>
<th>Network property</th>
<th>Input</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water treatment plants</td>
<td>1</td>
</tr>
<tr>
<td>Pumping stations</td>
<td>4</td>
</tr>
<tr>
<td>Storage tanks</td>
<td>4</td>
</tr>
<tr>
<td>Pressure zones</td>
<td>4</td>
</tr>
<tr>
<td>Total average system demand (MLD)</td>
<td>10</td>
</tr>
<tr>
<td>Total length of pipe (m)</td>
<td>166,360</td>
</tr>
<tr>
<td>Hydraulic model nodes</td>
<td>956</td>
</tr>
<tr>
<td>Hydraulic model pipes</td>
<td>1,183</td>
</tr>
</tbody>
</table>

4.2.1 Scenario 1: Historical Expansion - Early 1900s to Present

Significant differences in elevation throughout the network are one of the main reasons for establishing different pressure zones in a water supply and distribution system (Walski et al., 2003). In the case of the study system where the city expanded eastward from the river, three pressure zones have been established, as elevation increases with distance from the river bank (water source). As a result of expanding outward and upward over time, the study system’s pressure zones overlay areas of different ages. Pressure Zone 1, located at the lowest elevation, covers areas of the city developed before the 1950s. Pressure Zones 2 and 2a cover a higher elevation area further up the river bank that was developed between the 1950s and the 1990s, and Pressure Zone 3, located furthest from the river and at the highest elevation, corresponds with neighbourhoods established in the 1990s and onwards. Historical maps of the area can be found in Figures B.1 and B.2 in Appendix B. An additional consequence of pressure zones being spatially well-matched to urban areas from different historical periods is that each zone also reflects the street topology that was historically dominant at the time that that particular urban area was established.
Table 4.2 summarizes the network properties of each pressure zone.

**Table 4.2:** Network properties of each pressure zone.

<table>
<thead>
<tr>
<th>Property</th>
<th>Pressure Zone</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Average demand (lps)</td>
<td>32</td>
</tr>
<tr>
<td>Minimum elevation (m)</td>
<td>209</td>
</tr>
<tr>
<td>Maximum elevation (m)</td>
<td>250</td>
</tr>
<tr>
<td>Average elevation (m)</td>
<td>220</td>
</tr>
<tr>
<td>Total pipe length (m)</td>
<td>56,920</td>
</tr>
<tr>
<td>Average Hazen-Williams C factor</td>
<td>111</td>
</tr>
<tr>
<td>Approximate period of development of urban area</td>
<td>&lt;1950s</td>
</tr>
</tbody>
</table>

### 4.2.2 Scenario 2: Intensification in Pressure Zone 1

The case study city has grown through expansion, where over time, the urban fringe has been pushed outward from the river where the city was initially established. However, an alternative form of urban development can take place through intensification, where the population density of existing urban areas is increased through redevelopment. Here, the third research question of the chapter is addressed by modeling an intensification scenario, where instead of expanding outward, an increase in population is accommodated by intensifying the inner city core. In this scenario, the area within Pressure Zone 1 is intensified through an increase in population density as an alternative to developing the urban area served by the network in Pressure Zone 3. Figure 4.2 displays the hydraulic model of the water supply and distribution network for the intensification scenario.
Figure 4.1: Case study water supply and distribution network. The three pressure zones as well as the smaller west bank zone are shown with their respective hydraulic components (pumping station and tank).
Figure 4.2: Intensification scenario water supply and distribution network. Pressure Zone 3 has been removed and its total water demand distributed to the yellow nodes located in Pressure Zone 1.
4.3 Methods

Analysis in this investigation was based on comparisons between the three pressure zones. First, the urban form of each pressure zone is characterized by quantifying each zone’s topology. The pumping energy use in each pressure zone is then quantified for both scenarios. Lastly, the embodied energy use for the intensification scenario is determined.

4.3.1 Urban Form Characterization

In the work of Wong et al. (2015), the urban form of the neighbourhood scenarios was characterized by a combination of street topology and population distribution. This investigation focused on characterizing the street topology of each pressure zone only. Characterizing population density is beyond the scope of this project because unlike the residential-only neighbourhoods in the study by Wong et al. (2015), the pressure zones in this case study contain a diverse mix of residential and other land uses, making for an unequal comparison of population density across the zones. The spatial pattern of each pressure zone was characterized through the connectivity index developed by Knaap et al. (2007). The connectivity index was defined as:

\[ Internal\ connectivity = \frac{\#\text{intersections}}{\#\text{intersections} + \#\text{cul de sacs}} \]  \hspace{1cm} (4.2)

where an intersection was defined as a junction where three or more roads that do not end as a cul-de-sac converge, and cul-de-sacs were defined as dead ends. The
maximum value for the connectivity index is 1, where the urban area contains no cul-de-sacs or dead ends. For this investigation, the connectivity index was determined for each of the pressure zones.

4.3.2 Pumping Energy Use Analysis

EPANET2 (Rossman, 2000) was used to create hydraulic models of the baseline (Scenario 1) and intensification (Scenario 2) system configurations. For Scenario 2, all hydraulic components (pumping station, tanks, pipes and nodes) in Pressure Zone 3 were removed from the original hydraulic model and the water demand associated with Pressure Zone 3 was added to seven existing nodes in Pressure Zone 1. This roughly approximates the construction of 28 ten-storey residential buildings, each containing 100 units with a house density of 2.3 persons per unit. The value chosen for house density was based on housing and population census data (United States Census Bureau, 2012). The per capita water demand chosen for this calculation was 588 lpcd, which is the mean water use value found in the study by Friedman, Heaney, Morales, Palenchar, et al. (2013), that measured the residential water use in 12 North American cities.

The pump settings in Pressure Zone 1 were adjusted to accommodate the new demand. Pumps that were previously shut off were turned on to ensure that all demand junctions in the intensification scenario either maintained the same pressures found in the expansion scenario or maintained a minimum pressure of 40 m (Great Lakes-Upper Mississippi River Board of State and Provincial Health and Environmental Managers, 2012). In addition, any pipe with a velocity exceeding 1.5 m/s
during hydraulic analysis (that was previously not observed in the expansion scenario) was upgraded to the next commercially-available size, until its velocity was below this maximum value.

An energy audit approach adapted from the work of Cabrera, Pardo, Cobacho, and Cabrera Jr (2010) was used to characterize the inputs and outputs of energy to each pressure zone based on the hydraulic modeling results. In this investigation, leakage was not considered and was not included in the hydraulic model. The energy flows into and out of a pressure zone are shown in Figure 4.3.

**Figure 4.3:** Schematic of energy inputs and outputs in each pressure zone (control volume).

The energy balance for each pressure zone is written as

\[ E_{\text{pump}} + E_{\text{reservoir}} = E_{\text{nextPZ}} + E_{\text{topography}} + E_{\text{pressure}} + E_{\text{friction}} \pm E_{\text{tank,filling/daining}} \]  (4.3)

The energy provided by the pumps \( E_{\text{pump}} \) and the reservoir \( E_{\text{reservoir}} \) were considered as energy inputs in Equation 4.3. For Pressure Zones 2, 2a, and 3, the reservoir was assumed to be the node (or nodes) connecting the pressure zone in
question with the adjacent pressure zone. This assumption was valid since the pressure zones are hydraulically isolated from each other except at the pumping stations, where water from the previous zone passes into the next zone. Energy outputs in each pressure zone consisted of the energy supplied to other connecting pressure zones ($E_{nextPZ}$), the energy supplied to the network nodes, and the energy lost to friction ($E_{friction}$) in the network pipes. The energy supplied to the network nodes of the distribution system was divided into two components: the mechanical energy needed to raise the water to the ground elevation of each node ($E_{topography}$) and the mechanical energy needed to provide a suitable pressure head at the node ($E_{pressure}$). The tank was also considered a source of energy input or output ($E_{tank;filling/draining}$), depending on whether the tank was draining or filling at a particular time step. Table 4.3 summarizes the equations used to calculate the energy inputs and outputs in the water balance of Equation 4.3.

Extended period simulations (EPS) lasting 24 hours were performed with EPANET2 to calculate the flow and head terms in the expressions of Table 4.3. A hydraulic time step of five minutes and a reporting time step of one hour was used. The energy inputs and outputs of Equation 4.3 were evaluated at each reporting time step and summed over the 24 hour period. The 24 hour diurnal pattern representing a day of service determined by the city was used in the simulation, with multipliers ranging from 0.5 to 1.7 for each hour.

A datum of 209 m (lowest ground elevation in the network located at the main pumping station) was used to evaluate the reservoir energy, topography energy, and tank energy terms in Equation 4.3. The use of a single datum for all three pressure
zones made it possible to consider the spatial context of the pressure zones – ac-
knowledging the relative distance of each pressure zone from the river source instead
of examining each pressure zone in isolation.

4.3.3 Embodied Energy Use Analysis

In the second scenario, the city follows an intensification policy whereby the pop-
ulation density within Pressure Zone 1 is increased as an alternative to developing
the urban area served by the network in Pressure Zone 3. The potential savings in
embodied energy achieved by eliminating the construction of water main stock in
Pressure Zone 3 was quantified using the approach of Prosser, Speight, and Filion
(2013). Here, the authors applied life cycle energy analysis (LCEA) to quantify the
embodied energy associated with ductile iron pipe replacement, as a function of pipe
length and diameter. The energy required per length of ductile iron pipe at various
commercially-available diameters ranged from 342 kWh/m for 150 mm pipe to 789
kWh/m for 400 mm pipe (Prosser et al., 2013). For the calculation, it was assumed
that all pipes in Pressure Zone 3 are ductile iron pipes, which is the current preferred
pipe material for the city.
Table 4.3: Energy components.

<table>
<thead>
<tr>
<th>Energy component</th>
<th>Equation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumping energy</td>
<td>$E_{pump} = \gamma Q_p H_p \Delta t$</td>
<td>$\gamma$ = specific weight of water</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$Q_p$ = flow supplied by pump</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$H_p$ = head supplied by pump</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta t$ = time interval</td>
</tr>
<tr>
<td>Reservoir energy</td>
<td>$E_{reservoir} = \gamma Q_{res} H_{res} \Delta t$</td>
<td>$Q_{res}$ = flow supplied by reservoir</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$H_{res}$ = head supplied by reservoir (relative to datum)</td>
</tr>
<tr>
<td>Energy to next pressure zone</td>
<td>$E_{next PZ} = \gamma Q_{cp} H_{cn} \Delta t$</td>
<td>$Q_{cp}$ = flow through pipe connecting to next pressure zone</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$H_{cn}$ = head of node connecting to next pressure zone</td>
</tr>
<tr>
<td>Topography energy</td>
<td>$E_{topography} = \gamma Q_d H_{elev} \Delta t$</td>
<td>$Q_d$ = demand at node</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$H_{elev}$ = elevation head at node (relative to datum)</td>
</tr>
<tr>
<td>Pressure energy</td>
<td>$E_{pressure} = \gamma Q_d H_{press} \Delta t$</td>
<td>$H_{press}$ = pressure head at node</td>
</tr>
<tr>
<td>Friction energy</td>
<td>$E_{friction} = \gamma Q_{pipe} H_l \Delta t$</td>
<td>$Q_{pipe}$ = flow through pipe</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$H_l$ = head loss in pipe, determined by the Hazen-Williams relationship</td>
</tr>
<tr>
<td>Tank energy</td>
<td>$E_{tank} = \gamma Q_{in/out} H_{t} \Delta t$</td>
<td>$Q_{in/out}$ = flow in or out of tank</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$H_{t}$ = head of water in tank (relative to datum)</td>
</tr>
</tbody>
</table>
4.4 Results and Discussion

4.4.1 Urban Form Characterization

The case study system used in this investigation is a clear example of how North American urban development progressed, as described in the work of Southworth and Owens (1993). Table 4.4 reports the connectivity index values for each pressure zone. Pressure Zone 1, which has the highest index value of 0.78, is a highly connected gridiron configuration with few cul-de-sacs developed before the 1950s. Pressure Zone 2 has a moderate index value of 0.59 because it is dominated by neighbourhoods developed from the 1950s to the 1990s with "warped parallel" and "cul-de-sac/loop" street topologies (Southworth & Owens, 1993) that contain more loops, curves, and dead-ends. These street geometries reduce the number of intersections, which is responsible for the lower connectivity. Similarly, Pressure Zone 3 has a moderate index value of 0.66 because it is dominated by cul-de-sac/loop-based neighbourhoods developed from the 1990s and onwards. The aerial images shown in Figure 4.4 depict this change in urban form across the three pressure zones in the case study system.

Table 4.4: Connectivity index value for each pressure zone.

<table>
<thead>
<tr>
<th>Pressure Zone</th>
<th>Cul-de-sacs</th>
<th>Intersections</th>
<th>Connectivity Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36</td>
<td>130</td>
<td>0.78</td>
</tr>
<tr>
<td>2 + 2a</td>
<td>65</td>
<td>92</td>
<td>0.59</td>
</tr>
<tr>
<td>3</td>
<td>51</td>
<td>100</td>
<td>0.66</td>
</tr>
</tbody>
</table>
4.4.2 Scenario 1: Historical Expansion - Early 1900s to Present

Figures 4.5 and 4.6 display the percentage breakdown of the components of input and output energy for each pressure zone over a 24 hour diurnal period. The actual energy values for the components of input and output energy can be found in Tables B.1 and B.2 in Appendix B.

Figure 4.5: Historical expansion (Scenario 1)–Percentage breakdown of input energy components for each pressure zone.
From Figure 4.5, it can be seen that the energy input in Pressure Zone 1 is mostly supplied by shaft work (pumping energy) as opposed to the reservoir energy from the existing head of the water source. This is expected as the system draws its water from a river and is located on the side of a valley, where the water source is the lowest point of elevation in the system. It should be noted that the more significant contribution of “reservoir” energy in Pressure Zones 2 and 3 is actually the energy delivered from the preceding pressure zones. Pressure Zone 2’s “reservoir” energy is actually the energy supplied from Pressure Zone 1. Similarly, the “reservoir” energy supplied to Pressure Zone 3 is sourced from Pressure Zones 1 and 2.

Figure 4.6 indicates that following the energy delivered to other pressure zones, the pressure energy component is one of the main contributors to energy use for all three pressure zones. This suggests that most of the energy input into the system reaches the end users. However, as seen in Table 4.5, the case study system operates with a significantly higher average head than the minimum criteria of 40 m and thus
has surplus pressure head under average demand conditions.

Table 4.5: Average surplus pressure head of each pressure zone.

<table>
<thead>
<tr>
<th>Pressure Zone</th>
<th>Average surplus pressure head (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td>2 + 2a</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>22</td>
</tr>
</tbody>
</table>

Another main contributor to energy use in both Pressure Zones 2 and 3 is the energy used to lift the water to locations at higher elevations (topography energy). Figure 4.6 shows that energy to lift water to higher elevations steadily increases from Pressure Zone 1 to Pressure Zone 3. These results suggest that for this particular case study system, there is an increasingly large “energy penalty” paid to lift water from the source (river) to the nodes further away, located at the points of highest elevation.

Figure 4.6 also suggests that the energy lost to friction dominates in Pressure Zone 1, but becomes less important in the more distant Pressure Zones 2 and 3. Since the water source is connected to Pressure Zone 1, water to meet the demands of the other two pressure zones must pass through Pressure Zone 1. Pressure Zone 1 thus features the largest flows, resulting in more significant friction losses. In addition, Pressure Zone 1, being the oldest urban area, contains pipes with the lowest Hazen-Williams C values, contributing to friction losses.

An additional point of consideration for the friction energy component is how flows are distributed within each pressure zone. In their study on the pumping energy use of neighbourhoods with different street topologies, Wong et al. (2015) found that neighbourhoods with low connectivity near their water supply connection
experienced larger friction losses. This was due to a combination of the high flow rates from the water supply connection and the lack of available flow paths because of low connectivity. To compare flow distribution, Wong et al. (2015) calculated each neighbourhood’s total “high flow pipe length” – the summation of the lengths of all pipes carrying high flows.

For this case study, total high flow pipe length was calculated for each pressure zone. A “high flow” was defined as a flow larger than one-fifth of the flow provided by the water source in the pressure zone. Two scenarios exist for each pressure zone – pump-dominated time steps (when water flows from a pumping station) and tank-dominated time steps (when water is supplied by a tank). Because the flow regime (direction of flow) remains the same for all pump-dominated time steps and for all tank-dominated time steps, only one (one hour) time step for each scenario was examined. Table 4.6 summarizes the total high flow lengths in each pressure zone, for both the reservoir-dominated and tank-dominated scenarios. The results do not indicate any clear differences between flow distribution in the pressure zones. Although Pressure Zone 1 has higher overall connectivity than the other pressure zones, flow distribution does not appear to improve in this pressure zone. One reason is that the areas where high flows are occurring (near the pumping station and tank) are not well-connected, despite Pressure Zone 1 having a well-connected gridiron pattern elsewhere. In addition, pipes in Pressure Zone 1 that have particularly low Hazen-Williams C values (e.g., C = 60-80), also happen to be the pipes carrying large flows, further increasing friction losses.

It should be noted that these observations are made for an energy profile where
Table 4.6: High flow pipe lengths in each pressure zone for a one-hour time-step.

<table>
<thead>
<tr>
<th>Pressure Zone</th>
<th>Flow regime</th>
<th>Total high flow pipe length (m)</th>
<th>Friction energy in high flow pipes (kWh)</th>
<th>% Total length</th>
<th>% Total friction energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pump</td>
<td>4,274</td>
<td>21.58</td>
<td>8</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>Tank</td>
<td>5,543</td>
<td>11.05</td>
<td>10</td>
<td>92</td>
</tr>
<tr>
<td>2</td>
<td>Pump</td>
<td>4,310</td>
<td>22.05</td>
<td>9</td>
<td>81</td>
</tr>
<tr>
<td></td>
<td>Tank</td>
<td>2,432</td>
<td>1.83</td>
<td>5</td>
<td>96</td>
</tr>
<tr>
<td>3</td>
<td>Pump</td>
<td>4,862</td>
<td>6.16</td>
<td>9</td>
<td>91</td>
</tr>
<tr>
<td></td>
<td>Tank</td>
<td>2,520</td>
<td>0.04</td>
<td>5</td>
<td>63</td>
</tr>
</tbody>
</table>

Friction is a relatively small fraction of overall energy use. Street topology played a large role in the neighbourhood scenarios previously examined by Wong et al. (2015) because the networks were assumed to be flat, and energy use was dominated by friction losses. The analysis on real-life pressure zones suggests that for this case study system and others like it, street topology may not play as significant a role, in light of more dominant factors such as the energy required to lift water to higher elevations.

However, aside from street topology, it is evident that other aspects of urban form do play an important role in affecting energy use. The case study system used in this investigation is a clear example of how a city and its water distribution network has been shaped by the urban development that occurred over more than a century. Urban growth after the Second World War in North America was characterized largely by outward expansion into greenfield areas, often in the form of low-density suburban neighbourhoods (Anderson et al., 1996). This expansion is clearly seen in the case study system, where urban areas in Pressure Zones 2 and 3 are largely residential-only and are noticeably lower in house density. This expansion occurred despite a significant increase in elevation away from the water source, and as seen in
the results presented earlier, a significant amount of energy is devoted to lifting and delivering water to these neighbourhoods.

An additional aspect of urban form that was not considered in this investigation (due to limited information) is the difference in per capita outdoor water use between pressure zones. Wong et al. (2015) examined outdoor water use as a function of irrigation requirements in their neighbourhood scenarios. It was noted that lower density neighbourhoods tended to have larger lawns, and thus, higher irrigation requirements. Pressure Zones 2 and 3 both contain lower density housing with larger lawns, which could result in more outdoor water use than houses in Pressure Zone 1. A higher per capita demand in Pressure Zones 2 and 3 would increase the volume of water that must be lifted and delivered to these zones, impacting both topography energy and pressure energy, both of which are significant contributors to overall energy use.

4.4.3 Scenario 2: Intensification in Pressure Zone 1

For the intensification scenario, Figure 4.7 shows the percentage breakdown of the energy output components, for a 24 hour diurnal period. The actual energy values for the components of input and output energy can be found in Tables B.3 and B.4 in Appendix B. These results are compared with those of the expansion scenario, found in Figure 4.6.

With the elimination of an entire booster pumping station, total energy use is significantly lower in the intensification scenario compared to the expansion scenario, decreasing from 6,600 kWh/day to 3,300 kWh/day. In addition, Pressure Zone 1’s
original pumping schedule did not require adjustments (no new pumps were turned on) because the existing excess capacity in the system was able to accommodate the new demand at the required minimum pressure. In more extreme cases of intensification, a trade-off may exist between the energy required to lift water to users in high-rise buildings and the energy required to pump water to neighbourhoods at the urban fringe. For example, a different pumping schedule in Pressure Zone 1 or booster pumps (Beveridge, 2007) might be needed in a case where buildings higher than ten storeys were constructed. However, it should also be remembered that expansion in this particular case study system also entails an energy penalty associated with pumping water to higher ground elevations.

From Figure 4.7, it can be seen that the energy make-up of each pressure zone is different from the expansion scenario. With one less pressure zone present, Pressure Zone 1’s energy profile is no longer dominated by the energy delivered to other pressure zones, decreasing from 56% to 23% of total energy output. Instead, a more
significant component of the energy output in Pressure Zone 1 is delivered to the end users, with the pressure energy component at 49% of total energy output. In addition, friction energy is no longer the next largest component (decreasing from 22% to 16% of total energy output) because the demand in Pressure Zone 3 is now met near the water source, reducing the presence of large flows traveling through Pressure Zone 1. In the same way, friction energy in Pressure Zone 2 is also reduced from 9% to 5% of total energy output because no water is being conveyed to the next pressure zone. A similar observation was made in the work of Filion (2008) – in comparing three different population distributions, it was found that a monocentric distribution, where most of the demand was situated near the reservoir, had the lowest energy requirements.

4.4.4 Embodied Energy Use Analysis

The embodied energy associated with the pipe network in Pressure Zone 3 was also quantified and totalled to 25.9 GWh. The embodied energy requirements for each pipe diameter class can be found in Table B.5 in Appendix B. In light of the magnitude of operational energy requirements for this case study system, a one-time embodied energy saving of 25.9 GWh is somewhat significant (25.9 GWh is roughly equal to ten years of operating energy for Scenario 1). However, as seen in the earlier analysis, the intensification scenario provides an illustration of the potentially more significant operational energy savings associated with intensifying instead of expanding a water distribution system.
4.5 Summary and Conclusions

This chapter examined the impact an urban area’s long-term development has on the energy use of its water supply and distribution system. Analysis was performed on the hydraulic model of a water distribution system in the Midwestern United States. The case study was found to follow the typical narrative of North American urban development in the twentieth century and the pressure zones defined in the water distribution system corresponded well to urban areas developed at different periods in history.

Energy use was compared between the three pressure zones through an energy balance approach adapted from the work of Cabrera et al. (2010) that identifies the different components of energy input and output in each pressure zone. Energy lost to friction was found to be a significant component of energy output in Pressure Zone 1 due to the large amount of water (high flows) that must be conveyed to the other two pressure zones. Pressure Zone 1 also covers the oldest urban area, and thus contains older pipes with lower Hazen-Williams C values, resulting in higher friction losses. Topography energy was found to be a major contributor to output energy in Pressure Zones 2 and 3. This is due to the sharp increase in ground elevation moving away from the river source.

An additional modeling investigation looked at the energy impact of an alternative development scenario, where urban growth is addressed by intensifying urban areas in Pressure Zone 1, instead of developing the third pressure zone. It was found that energy use in the intensification scenario was significantly lower compared to the expansion scenario because the majority of the system’s demand was served close
to the water source.

This investigation analyzes a case study system for the purpose of producing new knowledge on how long-term urban development can affect the energy use of a water supply and distribution system. Given more available information, the analysis of the current case study system could be expanded to look at the differences in per capita water use in each pressure zone. Future work could also expand this investigation by analyzing more real-life systems of varying sizes and degrees of complexity. However, the trends identified in this study will hold true across a large number of systems with a similarly variable topography and can be used to inform development plans for the cities of the future.

4.6 References


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Chapter 5

Summary and Conclusions

5.1 Summary

Water supply and distribution systems are important infrastructure components in many urban areas in North America, providing end users with water at an acceptable pressure and quality. A significant amount of energy is required to operate and maintain these systems (Goldstein & Smith, 2002; Sanders & Webber, 2012). Today, as their physical components reach or exceed their service life, existing systems in North America are faced with challenges in operating efficiently. In addition, as urban populations continue to increase (United Nations, 2014), drinking water systems must also accommodate potential increases in water demand linked to population growth.

Water distribution pipe networks are spatially linked to the road networks of urban areas. As a result, how urban areas have developed and continue to grow greatly influences the physical layout of their water distribution networks. This research examined the impact of urban form on the energy use of water supply and distribution systems through the analysis of neighbourhood scenarios characterized
by different combinations of street topology and population density. The effect of long-term urban development on the energy use of an actual, complex water supply and distribution system was also examined.

The literature review in Chapter 2 addressed the relatively unexplored connection between urban form and energy use in water supply and distribution systems. This link was examined through a review of research literature in three areas – urban morphology, sustainable urban forms, and the connections between urban form and water system design and performance. The findings from all three areas were consolidated in order to provide context for methodological frameworks and identify key variables of interest for further research.

Chapter 3 examined the embodied and pumping energy use of neighbourhood scenarios characterized by combinations of street topology and population density. The topologies were based on street patterns commonly found in North American cities. A second set of scenarios evaluated the pumping energy use of each neighbourhood scenario, accounting for the differences in outdoor water used for lawn irrigation at different population densities. Key findings included:

- Per capita embodied energy use was lower for gridiron neighbourhoods due to their shorter total pipe lengths.

- Per capita pumping energy use was strongly correlated to the connectivity of the area near the water source. In general, gridiron networks were well-connected near the water source and thus had lower per capita pumping energy use compared to the other neighbourhoods.
• Outdoor (irrigation) water use varies significantly between neighbourhoods of different densities and has a strong influence on pumping energy requirements.

• Although the investigation considered all possible combinations of street topology and population density, in reality, street topologies have their own “native” population densities. A gridiron neighbourhood tends to have a higher native population density, and thus has lower energy requirements due to both its topology and lower irrigation requirements.

• Neotraditional street topologies can potentially offer a lower energy alternative to conventional suburban neighbourhoods. However, the extent to which energy is reduced depends on whether higher densities and shorter block lengths are also incorporated.

Chapter 4 examined the relationship between urban form and energy use in water distribution systems at the scale of the city. In particular, the impact that long-term urban development had on a North American case study system was examined. For the system in question, it was found that changes in urban form corresponded well with the three pressure zones of the distribution system. The energy use of the three pressure zones was compared using an energy balance approach adapted from the work of Cabrera, Pardo, Cobacho, and Cabrera Jr (2010). An alternative development scenario was also examined, where the population density of the existing city core (nearest to the water source) was increased instead of expanding the urban fringe. Key findings included:

• As the case study system expands further away from the river source, there is
an increasingly large “energy penalty” paid to lift water from the river source to the areas of higher elevation.

• In the intensification scenario, more of the system’s demand was met near the water source, at lower elevation. As a result, friction losses due to large flows conveyed through Pressure Zone 1 were reduced, and a larger percentage of total energy output was available to provide pressure energy to end users.

5.2 Research Contributions

Three major research contributions to the study of water supply and distribution systems have been made in this thesis.

The first research contribution is the consolidation and organization of research literature from the fields of urban planning and civil engineering in order to establish the link between urban form and energy use in water supply and distribution systems. The combined findings of the literature showed that this link is greatly influenced by the social, political, and economic forces that determine how urban development occurs. From this understanding, key urban form variables that could affect the energy use of water distribution systems were identified.

The second research contribution is the production of new knowledge on how urban form variables such as street topology, population density, and per capita outdoor water use affects the energy use of water distribution systems at the neighbourhood level. The analysis was performed on neighbourhoods modeled after historical street layouts found in North America and shed light on how urban design choices made over the last century affect the energy use of water distribution systems.
The third research contribution is the production of new knowledge on how long-term urban development affects the energy use of an actual, complex water distribution system. In addition, the findings also contributed insight on how an alternative growth scenario (intensification instead of expansion) affects the energy use of the case study system.

5.3 Future Work

This thesis looked at the relationship between urban form and the energy use of water supply and distribution systems at two different scales – neighbourhood and city. Future research at the neighbourhood scale could be expanded by considering more urban form variables. The current analysis assumed that each neighbourhood was entirely residential, where in reality, different land use patterns exist in different neighbourhoods of a city. The influence of different diurnal patterns due to land use could be examined. The current analysis also assumed that no leakage occurred in the pipe networks. Since leakage is affected by both the length of the network and network pressure, future analysis could consider how differences in leakage volumes affect the energy use of the neighbourhoods.

Future research at the city-scale could be expanded in two ways. First, the analysis of the current case study system could be combined with additional city population data in order to also consider the differences in per capita water use in each pressure zone. Second, future work could broaden the scope of this research by examining and comparing more real-life systems of varying sizes and degrees of complexity.
5.4 References


Appendix A

Supplementary material for Chapter 3

Creation of neighbourhoods

Due to the higher diversity in land use in older city cores, purely residential gridiron neighbourhoods tend to be very small in size compared to warped parallel or cul-de-sac neighbourhoods. As a result, gridiron neighbourhoods were “enlarged” by replicating the original grid pattern multiple times. 750 lots served as a middle ground between the larger warped parallel and cul-de-sac/loop networks and the “enlarged” gridiron networks.
Table A.1: Total pipe length (m) for neighbourhoods at base, high, medium, and low densities.

<table>
<thead>
<tr>
<th>Neighbourhood</th>
<th>Total network length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base</td>
</tr>
<tr>
<td>GR-1</td>
<td>9,384</td>
</tr>
<tr>
<td>GR-2</td>
<td>9,124</td>
</tr>
<tr>
<td>GR-3</td>
<td>2,174</td>
</tr>
<tr>
<td>WP-1</td>
<td>12,529</td>
</tr>
<tr>
<td>WP-2</td>
<td>12,563</td>
</tr>
<tr>
<td>WP-3</td>
<td>6,002</td>
</tr>
<tr>
<td>CL-1</td>
<td>13,860</td>
</tr>
<tr>
<td>CL-2</td>
<td>15,039</td>
</tr>
<tr>
<td>CL-3</td>
<td>22,019</td>
</tr>
</tbody>
</table>

Table A.2: Indoor and outdoor water use (lpcd) for neighbourhoods at base, high, medium, and low densities.

<table>
<thead>
<tr>
<th>Neighbourhood</th>
<th>Indoor demand (lpcd)</th>
<th>Outdoor demand (lpcd)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Base density</td>
<td>High density</td>
</tr>
<tr>
<td>GR-1</td>
<td>262</td>
<td>49</td>
</tr>
<tr>
<td>GR-2</td>
<td>262</td>
<td>51</td>
</tr>
<tr>
<td>GR-3</td>
<td>262</td>
<td>28</td>
</tr>
<tr>
<td>WP-1</td>
<td>261</td>
<td>67</td>
</tr>
<tr>
<td>WP-2</td>
<td>260</td>
<td>51</td>
</tr>
<tr>
<td>WP-3</td>
<td>264</td>
<td>22</td>
</tr>
<tr>
<td>CL-1</td>
<td>263</td>
<td>95</td>
</tr>
<tr>
<td>CL-2</td>
<td>264</td>
<td>67</td>
</tr>
<tr>
<td>CL-3</td>
<td>260</td>
<td>134</td>
</tr>
</tbody>
</table>
Appendix B

Supplementary material for Chapter 4

B.1 Historical maps of case study city

The following maps are public domain images taken from the Historical Topographic Maps Collection produced by the United States Geological Survey (USGS). For more information, the online collection can be accessed at http://nationalmap.gov/historical/. For privacy, all references to major geographic locations have been removed.
Figure B.1: Case study city in 1908.
Figure B.2: Case study city in 1987.
B.2 Energy balance results for Scenario 1

Table B.1: Scenario 1–Components of input energy for each pressure zone, summed over a 24 hour simulation period.

<table>
<thead>
<tr>
<th>Pressure Zone</th>
<th>Pumping energy (kWh)</th>
<th>Reservoir energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2,320</td>
<td>130</td>
</tr>
<tr>
<td>2+2a</td>
<td>1,228</td>
<td>1,385</td>
</tr>
<tr>
<td>3</td>
<td>429</td>
<td>1,128</td>
</tr>
</tbody>
</table>

Table B.2: Scenario 1–Components of output energy for each pressure zone, summed over a 24 hour simulation period.

<table>
<thead>
<tr>
<th>Pressure Zone</th>
<th>Topography energy (kWh)</th>
<th>Pressure energy (kWh)</th>
<th>Friction energy (kWh)</th>
<th>Tank energy (kWh)</th>
<th>Energy to next zone (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>94</td>
<td>468</td>
<td>535</td>
<td>-33</td>
<td>1,385</td>
</tr>
<tr>
<td>2+2a</td>
<td>501</td>
<td>511</td>
<td>227</td>
<td>236</td>
<td>1,128</td>
</tr>
<tr>
<td>3</td>
<td>865</td>
<td>663</td>
<td>48</td>
<td>-17</td>
<td>N/A</td>
</tr>
</tbody>
</table>
B.3 Energy balance results for Scenario 2

Table B.3: Scenario 2–Components of input energy for each pressure zone, summed over a 24 hour simulation period.

<table>
<thead>
<tr>
<th>Pressure Zone</th>
<th>Pumping energy (kWh)</th>
<th>Reservoir energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2,149</td>
<td>128</td>
</tr>
<tr>
<td>2+2a</td>
<td>498</td>
<td>522</td>
</tr>
</tbody>
</table>

Table B.4: Scenario 2–Components of output energy for each pressure zone, summed over a 24 hour simulation period.

<table>
<thead>
<tr>
<th>Pressure Zone</th>
<th>Topography energy (kWh)</th>
<th>Pressure energy (kWh)</th>
<th>Friction energy (kWh)</th>
<th>Tank energy (kWh)</th>
<th>Energy to next zone (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>161</td>
<td>1,123</td>
<td>361</td>
<td>110</td>
<td>522</td>
</tr>
<tr>
<td>2+2a</td>
<td>501</td>
<td>508</td>
<td>50</td>
<td>-43</td>
<td>N/A</td>
</tr>
</tbody>
</table>

B.4 Embodied energy results

Table B.5: Embodied energy requirements for Pressure Zone 3.

<table>
<thead>
<tr>
<th>Pipe diameter</th>
<th>Total length (m)</th>
<th>Embodied energy (GWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150 mm (6-inch)</td>
<td>16,070</td>
<td>5.5</td>
</tr>
<tr>
<td>200 mm (8-inch)</td>
<td>17,833</td>
<td>7.5</td>
</tr>
<tr>
<td>250 mm (10-inch)</td>
<td>354</td>
<td>0.2</td>
</tr>
<tr>
<td>300 mm (12-inch)</td>
<td>16,613</td>
<td>9.1</td>
</tr>
<tr>
<td>400 mm (16-inch)</td>
<td>4,639</td>
<td>3.7</td>
</tr>
</tbody>
</table>

Total embodied energy 25.9