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The Effect of Urbanization on the Embodied Energy of Drinking Water in Tampa, Florida

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by

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DEDICATION

I dedicate this dissertation to my parents and my advisors. I am grateful for the unconditional love and support of my parents in obtaining this degree and (in life). I thank you for your patience in listening to my frequent calls airing my frustrations, and reinforcing me with your positive encouragement.

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ABSTRACT

Increasing urbanization has serious implications for resource and energy use. One of these resources is drinking water. The increased amount of impervious surfaces associated with urban development is responsible for increased runoff during rain events, which may have a negative impact on the quality of nearby bodies of water, including drinking water sources. The growing populations associated with urbanization require a higher water demand. In addition, urban drinking water systems use energy to collect, treat, and distribute a safe reliable effluent to users. Therefore, this study focuses on the degree to which urbanization influences the embodied energy of drinking water in the city of Tampa via three objectives: (1) determine the degree to which the embodied energy of drinking water treatment is influenced by water quality possibly caused by urbanization, (2) determine the influence of urban form on the embodied energy of water supply, and (3) determine the effect of the state of water infrastructure on the embodied energy of drinking water.

The influence of the water quality of the Hillsborough River Reservoir on the embodied energy of drinking water at the David L. Tippin Water Treatment Facility was determined and quantified via statistical analysis methods and life cycle energy analysis. Results show that energy due to electricity and fuel use (direct energy) is responsible for 63% of the embodied energy of drinking water treatment in the city of Tampa. However, the 37% of energy due to treatment chemical usage (indirect energy) is substantial and most influenced by influent water

quality. Two constituents, total organic carbon and conductivity, are responsible for influencing 14.5% of Tampa's drinking water treatment embodied energy.

The effect of smart growth on the embodied energy of water supply was studied via the comparison of four future development scenarios within the Tampa WSA. The water consumption was estimated for each scenario and integrated into EPANET, a water distribution modeling software. After running each scenario, the embodied energy was calculated. The smart growth scenarios had 1-4% higher embodied energies than the business-as-usual scenario (urban sprawl). This was due to the location of added demand relative to the location of the water treatment facility. Nevertheless, while smart growth does not inherently minimize the embodied energy of water supply, it can result in the minimization of per capita water use due to the addition of more multi-family homes.

About 16 pipe replacement scenarios were used to determine the degree to which the state of water infrastructure affects drinking water supply embodied energy. These scenarios were simulated using EPANET. The replacement of all pipes in the city of Tampa is estimated to result in an embodied energy decrease of about 20%. However, taking into account the energy use associated with pipe installation, only replacement of pipes that are older than 20 years with recycled ductile iron yields a net energy savings.

The results of these studies show the influence of the roles that influent water quality, future urban development and infrastructure condition play on the embodied energy of drinking water in the Tampa WSA. However, future studies could look more in depth into these relationships via more definitive studies on the effect of land use on the Hillsborough River, and expanding the future development scenario studies to the metropolitan scale.

CHAPTER 1: INTRODUCTION

1.1 Urbanization Trends and Implications

Current trends point toward an increasingly urbanized world. During the 20th century, the world's urban population increased eightfold. In 2008, the population was equally split between rural and urban dwellers. By 2030, 60% of the world's population is projected to live in urban areas. This threshold has already been surpassed in the US and Canada, where about 80% of the population lives in urban areas (World Water Assessment Programme, 2009). Ever-expanding city limits translate to changes in land use as more farmlands and unoccupied land are converted to residential, commercial, and industrial infrastructure. However, in the past 50 years, urban land use dynamics in the US have also changed as people have moved from highly dense communities to less dense suburban communities.

Increasing urbanization may also result in increasing resource consumption and effects to the environment. During the past 200 years, exponential increases in population have been accompanied by similar increases in energy, water, and land use (Zimmerman et al., 2008). In addition, domestic as well as commercial and industrial energy use, as well as transportation may result in increased greenhouse gases (Kennedy et al., 2009).

Urbanization's effect on nearby water resources and quality has also been widely studied. For example, past studies have shown that because of the predominance of impervious surfaces in urban areas, increased rainfall results in runoff to nearby bodies of water, thus increasing the loading of pollutants. As a result, watersheds with 10% impervious area have slightly impacted water bodies, while watersheds with 25% impervious area were found to not sustain normal ecosystem functioning that is supported by water quality (Pelley, 2004). Other research has also highlighted the negative impact of urbanization on nearby water quality. Tu et al. (2007) observed via statistical analysis an increase in conductivity in surface water near suburban Boston. Meanwhile, an Atlanta-based study that used geographically-weighted regression highlighted the positive correlation between population density and conductivity in the surrounding surface water (Peters, 2009).

Growing cities also will affect regional water demand. This is best illustrated by existing conflicts between water use for agriculture and for expanding urban areas. Outside of the city of Hermosillo, Mexico, increasing urban water demands have resulted in less water for farmers due to the reliance of both communities on the same underground aquifers (Diaz-Caravantes & Sanchez-Flores, 2011). However, other factors influence the consumption of water within cities. Economic growth over the past thirty years in the South Korean city of Taejeon has been correlated with a simultaneous increase in water demand (Yoo, 2007). An analysis of suburban areas near Barcelona, Spain by March and Sauri (2010) demonstrated that more sprawled cities are linked to increased household water use. Delving more deeply into this issue, these averages could be due to building type as a Portland-based study by Shandas and Parandvash (2010) estimated that industrial buildings and single-family homes have higher per capita water consumption on average than multi-family homes.

1.2 Drinking Water Management

Urban drinking water systems are usually composed of three stages: collection of a source water, treatment, and distribution (storage is considered a part of the distribution stage). Collection refers to the extraction of the water from the drinking water source, which can be groundwater or surface water. Once taken from the source, water is sent through a treatment plant where it goes through several processes to reach an adequate quality for consumption and use. The effluent is then transported to the users via a distribution system that consists of pipes, pumps, tanks, and valves.

All of these stages of the drinking water management system consume energy. For example, all stages require a degree of pumping (Filion et al., 2004; Friedrich et al., 2009). Water treatment facilities also use energy via mixing and, indirectly, through the addition of chemicals (Stokes & Horvath, 2010; Mo et al., 2011; Santana et al., 2014). In fact, several past studies have estimated the energy associated with drinking water management in Northern California (Stokes & Horvath, 2010), the island of Sicily (Del Borghi et al., 2013), the Sydney, Australia metropolitan area (Lundie et al., 2004), the city of Tarragona, Spain (Amores et al., 2013), and the cities of Kalamazoo, Michigan and Tampa, Florida (Mo et al., 2011). These studies estimated a wide range of energy values per unit water used (5.2 – 54 MJ/m^3) (which includes whether they accounted for both indirect and direct energy use). This difference may be due to several factors. For example, during the drinking water collection stage, the location of the water source can play a very significant role in energy usage. In California, large-scale water transport schemes that provide water to the southern region of the state are in part responsible for the 20% energy use of the water sector (Klein et al., 2005). During the treatment stage, a desalination plant uses about 10 times more energy than a conventional water treatment plant (Del Borghi et al., 2013). With respect to distribution, characteristics such as urban form as well as the pipe replacement rate have resulted in differences in energy use that range from 11-76% (Filion et al., 2004; Filion, 2008).

1.3 Two Urban-Water-Energy Pathways

As demonstrated previously, urbanization can affect source water quality and water use, and drinking water management requires energy through its various stages. However, past research has not explored the link between urbanization, drinking water, and energy use. Accordingly, this dissertation aims to explore this relationship via two pathways.

First, urban growth has serious implications for nearby water bodies. In many cases, the affected bodies of water may also serve as sources of drinking water. Further degradation of source water quality may influence the operation of a water treatment facility that relies on this source. These changes can definitely lead to differences in the amount of energy used. This relationship between urban development, water quality, and energy use comprises the first pathway investigated in this dissertation's research.

Urbanization, which affects the water quality of nearby water bodies, including drinking water sources, may also influence the energy associated with treatment and supply due to factors such as consumption and urban form. The buildings within an urban area drive the overall water demand. To satisfy a unit volume of this water demand, energy is required for its collection, treatment, and distribution. However, factors such as urban form and the state of the infrastructure play a role as cities with a more compact layout and newer infrastructure may consume less energy than cities characterized by more sprawl and deteriorating infrastructure. This urbanization-water-energy relationship is referred to as the second pathway in this dissertation's research.

1.4 Research Questions and Dissertation Synopsis

Based on the aforementioned two pathways, this dissertation aims to address the overarching research question: What is the effect of urbanization on the embodied energy of drinking water and supply? This question will be addressed via the following specific research objectives:

- Determine the influence of influent water quality on the energy use associated with the treatment of water in the City of Tampa Water Service Area (Tampa WSA).
- Determine how and to what degree different urban development projections affect the energy associated with water distribution in the Tampa WSA.
- Determine the effect of the infrastructure condition on the energy associated with drinking water treatment.

This dissertation is organized into six chapters. Chapter 2 is a summary of all of the previous background research that will set the context for this research. Chapter 3 addresses the first pathway by using statistical methods and life cycle energy assessment to determine how and to what degree the influent water quality of the Hillsborough River Reservoir (Florida) influences the energy use associated with operation and maintenance of the David L. Tippin Water Treatment Facility (Tippin WTF). Chapter 4 addresses the second pathway, by studying the degree to which future urban development scenarios such as smart growth and sprawl influence the energy used by distribution systems in the Tampa WSA. Chapter 5 looks at the contribution of the condition of the infrastructure to the embodied energy of water supply. Finally, Chapter 6 will include recommendations that will be made as well as suggestions for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Urbanization

The amount of land devoted to urbanization and the percent of the population living in urbanized areas are steadily increasing. During the 20^{th} century, the world's urban population increased eightfold. Currently, 54 percent of the population is classified as urban (United Nations, 2014). In North America, the urban majority threshold has already been passed as about 80% of the populations of Canada and the US live in urban areas. In addition, by 2030, 60% of the world's population is projected to live in urban areas (World Water Assessment Programme, 2009). These distributional changes translate into land use changes, as more farmlands and unoccupied land are converted to residential, commercial, and industrial land uses to serve these growing populations. In addition, in the past 50 years, urban land use dynamics in the U.S. have also changed as people have moved from highly dense communities to less dense suburban communities.

2.2 Water Quality Influenced By Urbanization

One of the determinants of surface water quality is the land that surrounds it. For instance, increased urbanization also means an increase in the amount of impervious surfaces. During rain events, debris, chemicals, and other constituents collected on the roads, parking lots and roofs are washed into the nearest river, stream, lake or other water body. Watersheds composed of 10% impervious area show degradation in water quality, while watersheds with 25% impervious area are unable to support basic ecosystem functions (Pelley, 2004).

Concurrently, inadequate wastewater treatment contributes to the degradation of urban streams (United Nations Environment Programme, 2002).

Past research has studied the influence of urbanization on receiving water bodies. Peters (2009) measured the impacts of urbanization on water quality in the Atlanta Metropolitan Area using data taken from 21 stream stations, each representing a watershed within the area of study. The results illustrate the diverse nature of pollution due to urbanization as nearby industries can be responsible for the presence of metals in some localized areas. Most urbanized watersheds shared in common a higher amount of runoff than their more pristine counterparts as well as elevated levels of metals such as copper (Cu), zinc (Zn), and lead (Pb). The relationship between development and heavy metals and runoff is also supported by Hertler et al. (2009), who conducted a study determining the effects of development (for tourism) on the water quality of La Parquera, a coastal zone in southwestern Puerto Rico. While the analyzed water body was a bay, the study still detected a relationship between development and heavy metals possibly due to runoff. In addition, development was also related to higher total suspended solids (TSS) values as well as phosphorus.

While the aforementioned studies indicate the distinct effect that urbanization has on the receiving water body's quality, they fail to take into account the spatial variation associated with urbanization. First, urbanization can occur in different contexts. In addition to Peters (2009), another Atlanta-based study supported this point using geographically-weighted regression to determine the effects of land use on water quality parameters (Tu, 2011). Data were taken from 81 sampling stations from 2000-2009 over a diverse range of watersheds in terms of level of urbanization. Results showed how relationships between urbanization and water quality changed based on the urban/rural gradient. Specific conductivity and urbanization had a significant positive correlation in less urbanized areas, while agricultural land use was found to be an important pollutant source in less urbanized areas.

There are also different modes of urbanization, which usually fall between compact development and urban sprawl. Tu et al. (2007) examined the evolution of urban sprawl on water quality in Eastern Massachusetts from 1971-2004. Average water quality values for conductivity, nitrogen and phosphorus species, dissolved metal ions, and dissolved and suspended solids were obtained from each decade for 37 sampling points. Geographic information systems (GIS) as well as population data were collected and then modified to create urban sprawl measurements such as population density; percentage developed land use; and per capita developed land use. Spearman's Rank analysis was subsequently used to detect any statistically significant relationships between degrees of sprawl and water quality. Overall, even though there was a general increase in specific conductivity, central, more densely populated areas were only associated with a small increases while suburban areas experienced larger increases in specific conductivity. A similar study was conducted by (Carle et al., 2005); however, in addition to taking density into account, other land use variables such as access to city services, amount of impervious area, as well as the structural properties of the buildings in each watershed were measured through statistical analysis (principal components analysis, PCA, and correlation analysis) to find correlations with water quality variables. The resulting significant correlations demonstrate that different types of urban indicators are related to different water quality parameters. For instance, total Kjeldahl nitrogen (TKN) was positively related to household density and recent rainfall, while total phosphorus was also related to household density and total impervious surface.

2.2.1 Indicators of Water Quality Influenced by Urbanization

The diverse nature of urbanization is reflected in the extra constituents that are discharged into the water after a certain watershed is urbanized. For example, elevated chloride levels in a New England watershed were significantly correlated to road density due to salt application during the winter (Rhodes et al., 2001). Meanwhile, increased alkalinity at a water quality station located in an urbanized watershed in Atlanta, Georgia suggests the effects of intensive construction with concrete (Peters, 2009). Therefore, urbanization indicators depend on different factors such as climate, location of the urban area, the degree and type of urbanization (Tu, 2011), as well as the presence of wastewater treatment infrastructure (Zeilhofer et al., 2011). Table 1 lists prominent water quality parameters and the studies that link them to urbanization.

Table 1 Urbanization-affected water quality parameters and corresponding studies

Constituent	Study
Biochemical Oxygen Demand	Lee et al., 2010; Tran et al., 2010; Tu, 2011; Zeihofer et al., 2011
Conductivity	Rhodes et al., 2001; Wenner et al., 2003; Kney and Brandes, 2007; Tu et al., 2007; Hertler et al., 2009; Peters, 2009; Ye et al., 2009; Thompson et al., 2010; Tran et al., 2010; Tu, 2011; Zeilhofer et al., 2011
Nutrients (Nitrogen, Phosphorus and Related Species)	Rhodes et al., 2001; Carle et al., 2005; Mehaffey et al., 2005; Tu et al., 2007; Coskun et al., 2008; Hertler et al., 2009; McMahon et al., 2009; Peters, 2009; Tong et al., 2009; Ye et al., 2009; Lee et al., 2010b; Wilson and Weng , 2010; Tu, 2011; Zeilhofer et al., 2011
Metals	Hertler et al., 2009; Lee et al., 2010b; Peters, 2009; Rhodes et al., 2001; Wilson and Weng, 2010

2.2.1.1 Biochemical Oxygen Demand, Chemical Oxygen Demand, Dissolved Oxygen

Two studies found positive correlations between urbanization and biochemical oxygen demand (BOD) and chemical oxygen demand (COD) values in surface water. For example, Lee et al. (2010) found a significant relationship between residential areas and BOD and COD concentrations in nearby streams. Zeilhofer et al. (2011) observed a positive correlation between urban areas in the Cuiaba region in Brazil and BOD and COD values. In this context, these increased values may most likely be attributed to inadequately treated or untreated wastewater discharges. Of course, COD and BOD are both inversely related to dissolved oxygen (DO), which is supported by the negative correlation between DO and urbanization. This relationship has been confirmed in other studies (Tran et al., 2010; Tu, 2011).

2.2.1.2 Nutrients

Due to the influence of fertilizer application, past studies have linked constituents such as nitrogen and phosphorus to agricultural development (McMahon et al., 2009; Ye et al., 2009; Lee et al., 2010; Tran et al., 2010). Other studies have shown that urbanization can be related to elevated nutrient levels. That is, residential area-predominant urbanization tends to be linked to this effect as fertilizers are used for lawns and/or domestic wastewater discharges are not adequately treated (Lee et al., 2010; Wilson & Weng, 2010). Non-specified urbanization has also been positively correlated with nitrogen and phosphorus species. For example, increased nitrate (NO_3) associated with urbanization has been observed in several studies (Rhodes et al., 2001; Hertler et al., 2009; Tong et al., 2009; Ye et al., 2009; Tu, 2011). However, according to Tu (2011), NO_3 contamination might also be due to fertilizer runoff since the correlation between urbanization and nitrate (as well as total nitrogen and nitrite) is stronger in suburban areas. A similar relationship with urbanization can be inferred for phosphorus as it has been linked with residential areas (Lee et al., 2010; Wilson & Weng, 2010), although other studies also link phosphorus with new non-residential development (Hertler et al., 2009) and general urbanization (Ye et al., 2009).

2.2.1.3 Metals

Previous research has also investigated the link between increased urbanization and elevated concentrations of metals. This relationship is logical given that metals are used in construction as well as in industry. The study by Peters (2009) shows levels of Cu, Pb, and Zn that exceed Georgia's state standards in most sampling stations in the Atlanta Metropolitan Area, which, for this study, were located in urban areas (Peters, 2009). Urbanized areas in southwest Puerto Rico were also associated with runoff containing heavy metals such as nickel (Ni) (Hertler et al., 2009). Meanwhile, Wilson and Weng (2010) were able to specifically relate commercial-industrial-transportation land uses to elevated cadmium (Cd), nickel (Ni), and Pb concentrations in nearby rivers and streams.

2.2.1.4 Conductivity

Even though the effect of urbanization can vary between places, there are some commonalities between the studies of urbanization effects on nearby bodies of water. Of the aforementioned studies, two have observed a positive correlation between conductivity and urbanization (Tu et al., 2007; Tu, 2011). One study has directly looked at the relationship between conductivity and urbanization and found that conductivity is positively correlated to the percentage of urbanized land use (Xinhao & Zhi-Yong, 1997). Nevertheless, since conductivity is a measurement of dissolved species in the water, there is a possibility that conductivity may be comprised of naturally occurring species. To respond to this uncertainty, Kney and Brandes (2007) and Thompson et al. (2010) devised methods that could indicate if a significant amount of conductivity was from anthropogenic sources, regardless of underlying geology and the alkalinity of the water.

2.2.1.5 Land Use and Water Quality of Drinking Water Sources

Like any other body of water near an area that has been urbanized, drinking water source quality is also influenced by nearby land uses. McMahon et al. (2009) analyzed the effect of land use changes on public service wells located in four different cities in the United States, each underlain by a distinct aquifer system. Several models were run in conjunction with each other to simulate the relationship between evolving land use patterns and NO_3 and tracers. The results of this research highlighted how location of certain land uses could slowly or quickly impact the water quality of these wells. Factors to consider were topography as well as geography in affecting the "water age" or the time for recharge from a certain area to reach a well. With respect to surface water, Baykal et al. (2003) conducted a study in the rapidly urbanizing Istanbul metropolitan area to determine the link between predominant surrounding land use and general reservoir water quality for the seven drinking water reservoirs located in the metropolitan area. Results showed that the most polluted reservoir was near land with the highest population density, urban land use, and ranked second in overall population in the watershed. In contrast, the reservoir with the best water quality was surrounded by land with the lowest population density, occupied land, and industrial land use.

More specific studies linking land use and reservoir water quality have also been carried out. For example, Coskun et al. (2008) used land use data from 1993-2006, water quality data, and Landsat images to determine the effects of land use on water quality of a drinking water reservoir and possible explanations. Results show a high percentage of population growth in the watershed as well as a high amount of industrial discharge to the reservoir. Spectral analysis of Landsat data using different bands also confirmed the extent of pollution throughout the reservoir. However, conclusions were based on the inference that urbanization was the cause of water quality deterioration. The study by Mehaffey et al. (2005) better confirms the effects of land use on water quality through use of statistical analysis that integrated water quality and land use data parameters from the mid 1970's to the late 1990's. The results more clearly illustrated the land use-reservoir water quality link showing the significant relationship between agriculture and total nitrogen as well as agriculture and urbanization and total phosphorus.

2.2.2 Water Consumption Influenced by Urbanization

2.2.2.1 Agricultural Water Use

There has long been a demonstrated link between land use and water consumption. Traditionally, this relationship has been analyzed through water use due to agriculture. Two world-scale studies have analyzed this relationship with respect to water source, crop requirements, and climate (Rost et al., 2008; Pfister et al., 2011). Pfister et al. (2011) illustrated this relationship by calculating the overall land and water stress around the world based on local climactic and water availability conditions and comparing the results to the crops grown in each geographic area. The study showed that a significant amount of crops are grown in water scarce regions (2011). (Rost et al., 2008) investigated agricultural water use by source, separating water for agriculture into two categories, blue water (irrigation from surface and groundwater aquifers) and green water (rainfall). A model was used to simulate water consumption based on local climactic and agricultural parameters around the world. Model outputs demonstrated that land cover change had a significant effect on the processes associated with agriculture such as increasing river discharge and a decrease in evapotranspiration. In terms of irrigation, half of global "blue" water was estimated to be drawn from nonrenewable bodies of water or aquifers (2008). Even different crop types and the presence of trees on a plantation can have an effect on the amount of water consumed through agriculture (Narain et al., 1998).

While it is known that agriculture land use consumes a significant amount of water, increasing urban populations nearby may be a source of competition for water resources. This dynamic has been studied in the area outside of the City of Hermosillo in Mexico, where growing urban water demands have come into conflict with traditional agricultural water demands. Through land use analysis and interviews with farm owners, the study has painted a picture of the increasing scarcity of water for agricultural use due to policies limiting the amount of water farmers could use and the expansion of wells for urban water consumption that affect existing wells used for agriculture. This has been reflected in the land use changes such as the diminishment of farmland, the growth of barren land, and the presence of “ranchettes”, which are somewhat similar to country vacation homes (Diaz-Caravantes & Sanchez-Flores, 2011).

2.2.2.2 Urban Water Use

Urban areas are generally composed of commercial, industrial, and residential land uses. The majority of studies on urban water use are primarily focused on the residential sector. To date, there are only a couple studies that focus exclusively on commercial and industrial water use. In fact, residential water consumption analysis has been used to determine the relationship between scale of urbanization, building characteristics, socioeconomic and demographic characteristics, and water consumption.

2.2.2.2.1 Commercial and Industrial Water Use

Within urban areas, commercial and industrial land uses are responsible for a significant amount of water consumption. For instance, a Portland-based study by Shandas and Parandvash (2010) found that commercial/industrial structures had the largest influence on total urban water use. However, water use within each commercial/industrial building can vary due factors specific to the building (i.e. number of employees). A Hawaii-based study found that the number of employees was positively correlated with the amount of water consumed, even though the amount of water consumed per employee decreased (Malla & Gopalakrishnan, 1999).

2.2.2.2.2 Urban Form and Water Use

At the city scale, urban form has been shown to affect water use. Densely populated cities generally consume less water per-capita. A study comparing the domestic water consumption patterns of municipalities in the Barcelona metropolitan area that resembled "compact" cities and "suburban" cities was conducted to determine how urban sprawl affects water consumption. The authors compiled socio-demographic data, population, climate, and water use data into an ordinary least squares regression model to determine any significant relationships. In all, suburbanization was linked to increased water use by smaller households, thus highlighting the influence of sprawl on urban water use (March & Sauri, 2010). Using density as a metric for development type, a similar Portland-based study, focusing exclusively on single-family homes, found a negative correlation between density and water consumption (Chang et al., 2010). In conclusion, these studies demonstrate the importance of planning in influencing water use. In fact, Chang et al. (2010) recommends the spatial considerations in planning can actually be helpful in implementing climate change adaptation with respect to the changing availability of water.

2.2.2.2.3 Demographic and Socioeconomic Factors

In addition to development type, demographic and socioeconomic considerations factor into the domestic water consumption rates. However, the influence of these factors on water use varies. Generally, economic growth and prosperity have been associated with increased water use. At the city scale, Yoo (2007) shows, through different statistical analyses, that urban water consumption has increased with increasing economic growth in Taejeon, South Korea from

1973-2001. Demographic factors have a more complex relationship with water use. At the household water use scale, one study found a negative correlation between education level and water consumption (Shandas & Parandvash, 2010). In a Metropolitan Barcelona-based study, there was a negative correlation between aging rate and water consumption, which could be explained by generational differences in terms of water conservation habits (March & Sauri, 2010). A Portland-based study found that socioeconomic factors (i.e. education level, salary, number of people in a household) have a significant statistical influence on the sensitivity of water use to climate (House-Peters et al., 2010).

2.2.2.2.4 Building Characteristics

The characteristics of the building or residence have been known to greatly influence water used. Past studies have shown that larger buildings generally are associated with more water use. Shandas and Parandvash (2010) considered type of building (commercial/industrial, single family residence, multi-family residence) as well as amount of land built on per unit parcel, and concluded that single-family residences (which are usually larger in size than multi-family residences) had a higher influence on total water consumption than multi-family residences. House-Peters et al. (2010) found that base water usage positively correlated to household size and that drought sensitivity was significantly related to structural variables. This link makes sense as houses with larger outdoor areas are more prone to use water for outdoor applications and respond to drought conditions or restrictions by moderating use (House-Peters et al., 2010). Nevertheless, a couple studies did note a negative correlation between water consumption and building age, which could be due to widespread retrofits of older houses with newer water-saving technologies or lack of in-ground irrigation (Palenchar, 2009; Chang et al., 2010).

2.3 Smart Growth

Urbanization is becoming a worldwide concern with respect to environment, and many areas in the US have responded by implementing a development paradigm called smart growth. This method of urbanization aims to have a minimal environmental impact as well as positive social impact. According to the Smart Growth Network (2006), smart growth is governed by 11 principles (Table 2). The first and most prominent example of smart growth implementation is in Oregon, with the passing of the Land Use Act in 1973. This legislation required that local governments designate urban growth boundaries that would accommodate future development for the next 20 years. Within these boundaries, land would be zoned for urban uses and densities, while outside, zoning would only be for agriculture and preservation of green space. In 1979, the city of Portland, Oregon implemented its urban growth boundary, and tasked the Metropolitan Service District (Metro) with its enforcement. Other states have also legislatively incentivized smart growth. In 1997, the state of Maryland designated growth areas to which the state would exclusively direct funds for infrastructure construction, maintenance, and repair. A year later, the state of New Jersey implemented programs aimed to protect farmland and green space, create a network of biking and walking trails, and promote increased downtown development (Urban Land Institute, 1998).

Table 2 A list of the 11 principles of smart growth (Smart Growth Network, 2006)

Smart Growth Principles
Mix land uses
Take advantage of compact building design
Create a range of housing opportunities and choices
Create walkable neighborhoods
Foster distinctive, attractive communities with a strong sense of place
Preserve open space, farmland, natural beauty, and critical environmental areas
Strengthen and direct development towards existing communities
Provide a variety of transportation choices
Make development decisions predictable, fair, and cost effective
Provide a variety of transportation choices
Encourage community and stakeholder collaboration in development decisions

2.3.1 Effects of Smart Growth Legislation

In 1997, Maryland passed legislation to incentivize smart growth. State funds used for municipal infrastructure were required to be used in Priority Funding Areas (PFAs). A few studies have investigated the effect of this legislation. Irwin and Bockstael (2004) developed a hazard model to determine how smart growth policy implementation affects land use. The study found that more stringent land management policies (i.e. 80% protected land requirement in rural development) actually promote more development within existing urban areas (38% of new construction urban) while weaker policies (50% protected land requirement) actually encourage sprawl (17% of new construction urban). Another study was done to assess the effect of Maryland's Priority Funding Areas (PFAs) legislation to determine its effect on the funding of water and sewer infrastructure. A logit model was used to analyze the factors (land market and fiscal variables) that influence investment in PFAs. Factors such as increased state funding and county affluence were more likely to incentivize project development within PFAs while areas deemed "tax rich" tended to fund more areas outside of PFAs (Howland & Sohn, 2007). Logit models were also used to measure the degree to which Maryland's Smart Growth legislation influenced urbanization pre and post-legislation. Overall, new developments were 2.3 times more likely to be located within PFAs while they were 0.6 times less likely to be located in Rural Legacy Areas (RLAs). In most counties, the post-legislation period increased the likeliness of new development to occur within PFAs (Shen & Zhang, 2007).

2.3.2 Smart Growth and GHG Emissions

The smart growth principles of compact building design, creating walkable neighborhoods, and providing a variety of transportation choices have the indirect effect of encouraging walking and public transit over personal car use. An added possible benefit is that the compact nature of smart growth has the secondary effect of less energy use via streamlined energy distribution systems (Straka, 2002). Thus, implementation of renewable energies is more feasible in smart growth communities. Nevertheless smart growth policies need to consider the context of the community with respect to energy usage such as the roof orientation to maximize the amount of solar energy that can be captured or requiring the installation of PVC piping connecting the roof to the basement of each dwelling for future rooftop energy systems.

A few studies have investigated the effect of smart growth on greenhouse gas (GHG) and other air emissions. Behan et al. (2008) ran an integrated transportation simulation model called IMULATE to model current and smart growth trends. While implementation of smart growth did not reverse the upward trends in fuel consumption and carbon monoxide emissions, compared to the control case, smart growth was projected to result in 25% less fuel usage and emit 30% less CO than the "base case." Hankey and Marshall (2010) compared the effects of different urban growth patterns on future vehicular GHG emissions based on data from about 146 U.S. cities. These scenarios were modeled via Monte Carlo analysis. Following a compact development growth paradigm resulted in a net decrease of about 17% in GHG emissions compared to the business-as-usual growth scenario. Lee and Lee (2014) used a multilevel structural equation model (SEM) to predict the GHG emissions of 125 U.S. cities under several future urbanization scenarios. The model predicted every 10% increase in population density would result in a 4.8% decrease in travel-related CO_2 emissions and 3.1-3.5% decrease in household-related CO_2 emissions. One paradigm, transit-oriented development (TOD), is also a means of implementing smart growth. Nahlik and Chester (2014) carried out a life cycle assessment (LCA) of TOD along two bus lines in Los Angeles. Their results found a relative decrease in environmental impacts such as energy use, GHG emissions, respiratory impacts, and smog formation.

2.3.3 Effect of Smart Growth on Water Quality and Water Use

The smart growth principle of “preserving open space, farmland, natural beauty, and critical environmental areas” not only has aesthetic merit, but may also minimize environmental impact, especially with respect to nearby water quality. Previous research has shown that watersheds with at least 10% impervious area have degraded water quality and increased sprawl would create 43% more runoff. Therefore it was recommended that regional planning should incentivize development in existing high-density areas or brownfields to minimize urban expansion (Pelley, 2004). The presence of septic tanks due to urban sprawl may also increase nutrient loading to nearby water bodies. Such is the case for Maryland and the Chesapeake Bay. The effect of Maryland’s PFA smart growth policy on the use of septic tanks was investigated by integrating PFA boundary, sewer, and septic tank data into a random-clumped binomial statistical model. Results showed that PFA policy had no effect on the use of septic tanks as from 1988-2003, the percentage of residences on a septic tank system increased from 25% to 38%. Location of new residences had the strongest effect on wastewater treatment system, as places built outside of the PFA were more likely to rely on a septic system (Harrison et al., 2012).

There have only been a couple studies that have looked specifically at the effects of smart growth on water use. In one case, “compact building design” and “walkable neighborhoods” presented a dilemma. Guhathakurta and Gober (2007) developed a linear regression model to explain water use throughout different areas of the city of Phoenix. While greater lot sizes and pool areas were associated with increased water use, a mean low temperature increase of 1°F was related to an increase in water usage of about 1.7 gallons per month (June 1998), thus highlighting a tradeoff between larger lots associated with suburban or peri-urban areas and the urban heat island effect in denser urban areas, containing smaller lot sizes. However, the study by Runfola et al. (2013) incorporated a linear regression that predicted water use based on land cover and household characteristic variables into an urban growth model called GEOMOD. Results showed that by focusing development near already developed areas under the “smart growth” scenario, annual water use would grow by 2.2% compared to the 7.7% net growth under a business-as-usual scenario.

2.4 Embodied Energy

The provision of safe, reliable drinking water requires the consumption of energy. This energy is used to extract water from the drinking water source (collection), treat the water to an acceptable standard (treatment), and distribute it to users (distribution). During collection, electricity is used for pumping water from a surface water reservoir or from a groundwater aquifer. Pipes, which require energy to construct, install, and maintain, are used to convey water from the source to the treatment (Filion et al., 2004; Baldasano-Recio et al., 2005). At the water treatment plant (WTP), water is sent through a process train to remove constituents to satisfy safe drinking water regulations. Conventional WTPs include the addition of chemicals and mixing (i.e. coagulation and flocculation, pH adjustment, ozonation, disinfection) and filtration (reverse osmosis, ultrafiltration, sand and granular activated carbon (GAC)) (Racoviceanu et al., 2007; Bonton et al., 2012; Amores et al., 2013; Del Borghi et al., 2013). Energy is used in treatment chemical extraction, production and transport to the plant. Electricity is used for pumping water throughout the process train and mixing water with treatment chemicals. The treated effluent is pumped, via water mains, through a distribution system, which is responsible for providing users a safe, reliable resource.

The embodied energy of drinking water is basically the sum of the energy used during collection, treatment, and distribution normalized by the amount of water produced. It is composed of two types of energy: direct and indirect. With respect to drinking water, direct energy refers to on-site energy use (i.e. electricity and fuel). Indirect energy is defined as the off-site energy use, such as chemical and building materials, which are produced and transported off-site (Table 3).

Table 3 Direct and indirect energy definitions for each stage of the drinking water treatment and supply process

Drinking Water Stage	Direct Energy	Indirect Energy
Collection	Groundwater Pumping Importation Surface Water Pumping	Pre-Treatment
Treatment	Pumping Mixing Advanced Processes (i.e. Ozonation)	Treatment Chemicals Treatment Materials (i.e. GAC)
Distribution	Pumping Installation Equipment Use	Pipe Materials

Embodied energy also relies on energy contributions from life cycle stages. Water collection infrastructure, water treatment plants and distribution systems all consume energy during construction, operation and maintenance, and decommission (Mo et al., 2010; Mo et al., 2011). Energy is needed to produce the construction materials as well as build with these materials (Baldasano-Recio et al., 2005). While the infrastructure is in use, electricity is used run pumps and processes, while energy is consumed in the production of treatment chemicals to remove constituents (Mo et al., 2010; Mo et al., 2011). And finally, deconstruction or decommissioning of the infrastructure requires transport energy for its disposal, and, if needed, energy for reprocessing if component materials are to be recycled (Filion et al., 2004).

2.4.1 Direct vs. Indirect Energy

Most drinking water embodied energy studies account for direct and indirect energy in their calculations. However, only four studies categorized embodied energy contributions based on the definitions of direct and indirect energy used here (Racoviceanu et al., 2007; Vince et al., 2008; Mo et al., 2011; Bonton et al., 2012). Direct energy contributions ranged from 33% to 91% of total embodied energy, while indirect energy contributions ranged from 9% to 67%. Scenarios with higher indirect energy values were either plants that included membrane treatment or surface-water based drinking water systems. Vince et al. (2008) modeled an ultrafiltration plant, while Bonton et al. (2012) modeled a nanofiltration plant. Both processes are energy efficient with lower direct energy values (0.32 and 0.54, respectively) than a conventional water treatment plant, which would explain the relatively high contribution of indirect energy. Conversely, while the city of Tampa relies on a conventional water treatment facility (with ozonation), the fact that its drinking water source is a surface water reservoir necessitates the addition of more treatment chemicals for removal of natural organic matter (NOM). As a result, indirect energy is responsible for about 54% of the total drinking water embodied energy for the city of Tampa (Mo et al., 2011).

2.4.2 Life Cycle Stages

One aspect of embodied energy calculation is determining the amount of energy used during construction of the infrastructure, its operation and maintenance, and its decommission. Life cycle assessment (LCA) is prominent method of estimating these values. In fact, of the thirteen studies reviewed, about ten were or included aspects of LCAs. Of those nine studies, three included all three life cycle stages, five excluded decommission, and three only accounted for operation and maintenance.

Many of these LCA studies share in common the inclusion of the operation and maintenance phase. This is due to relatively high contribution of this stage to the overall embodied energy. For example, Mo et al. (2011) found that operation and maintenance was responsible for about 95% of the total embodied energy of Kalamazoo's and Tampa's drinking water. Bonton et al. (2012) estimated that about 88% of a nanofiltration plant's embodied energy is due to operation and maintenance. The relatively low contributions of construction and decommission have been used to justify their exclusion from drinking water LCA studies (Racoviceanu et al., 2007; Amores et al., 2013; Del Borghi et al., 2013).

2.4.3 Drinking Water System Components and Their Contributions

There are three main energy-consuming components to a drinking water treatment and supply system: collection, treatment, and distribution. About half of the reviewed studies included all three drinking water treatment and supply steps, of which four only included treatment and three focused on water distribution.

Six studies measured separately the embodied energy of water treatment plants (Lundie et al., 2004; Racoviceanu et al., 2007; Vince et al., 2008; Bonton et al., 2012; Amores et al., 2013; Del Borghi et al., 2013). Embodied energy values ranged from 0.70 to 38.2 MJ/m^3. The large range in values is due in part to the different water treatment processes used in the studies. These included: conventional systems (Racoviceanu et al., 2007; Bonton et al., 2012; Amores et al., 2013; Del Borghi et al., 2013), desalination systems such as ultrafiltration reverse osmosis and multieffect distillation (Vince et al., 2008; Del Borghi et al., 2013), as well as nanofiltration (Bonton et al., 2012). Generally, desalination processes consumed more energy than conventional or ultra/nanofiltration plants (Vince et al., 2008; Del Borghi et al., 2013). However, membrane treatment plants were found to consume about 5% to 25% of the energy that conventional plants use (Bonton et al., 2012).

Water distribution system energy usage was estimated separately in five studies. The energy used to move water from the treatment plant to users varied from 0.1 to 11.7 MJ/m^3. Differences in embodied energy values between scenarios within the same study were due to factors such as urban form, population density, and pipe replacement rate (Filion et al., 2004; Filion, 2008). For example, Filion (2008) modeled theoretical urban distribution systems following grid (gridiron) wheel spokes (radial), and satellite configurations and then conducted a life cycle energy analysis for each scenario. Results showed that the radial configuration consumed the least energy overall, even when varying the population distributions throughout the nodes. In a few cases, higher population densities towards the urban core aid in decreasing the energy used by the distribution system overall. Another life cycle energy assessment study concluded that a pipe replacement rate of 50 years was optimum in terms of minimizing system energy use compared to alternative 10, 20, and 100 year scenarios (Filion et al., 2004).

Embodied energy of drinking water treatment and supply estimates ranged from 5.2-54.1 MJ/m^3. The large discrepancy in values is mainly due to the study by Del Borghi et al. (2013) as well as a scenario modeled in Amores et al. (2013). Both studies share in common the incorporation of the desalination process, which consumes about 8-10 times more energy per unit of water treated than conventional systems included in the same studies. The contribution of desalination also has a great impact on the overall embodied energy of drinking water treatment and supply. When drinking water systems rely on conventional/filtration systems, treatment is only responsible for 17-30% of the total embodied energy, while distribution is the greatest contributor (Lundie et al., 2004; Amores et al., 2013). However, if the drinking water treatment mix includes desalination, treatment becomes the greatest contributor. For instance, the scenarios in Del Borghi et al. (2013) show that treatment is responsible for 78-81% of total embodied energy. Meanwhile, a scenario by Amores et al. (2013) that included desalination, resulted in a contribution of 65% to Tarragona's drinking water embodied energy.

2.4.4 Factors Influencing Water Distribution

Age and environmental conditions both contribute to pipe deterioration in water distribution systems, resulting in pipe leaks. These leaks ultimately lead to extra water being pumped into the system. Aubuchon and Roberson (2014) quantified the embodied energy in these water losses via a survey sent to utilities throughout the United States. Based on the responses, water losses as well as electricity use by the water treatment plant were calculated. Overall, average water losses were valued at 1.4 MJ/m^3 of water lost.

One method of responding to pipe leaks is through the replacement of water distribution infrastructure (i.e. pipes). However, replacement has an associated energy cost due to production, transport, and installation in the distribution system. Therefore, frequent pipe replacement is not only expensive but also energy intensive. Filion et al. (2004) conducted a life cycle energy analysis (LCEA) on New York City's distribution system using equations accounting for pipe manufacture, installation, pumping, deterioration, replacement, and disposal. In this context, a 50-year pipe replacement rate was found to have the lowest associated embodied energy compared to replacement rates of 10, 20, and 100 years.

Urban form has also been shown to influence water distribution. Filion (2008) modeled the distribution systems of three theoretical cities: gridiron, radial, and satellite. For each "city", three distinct population distributions were applied: uniform, monocentric, and polycentric. An

LCEA was conducted for each scenario. Cities that followed a radial form (similar to European cities) had consistently lower embodied energies. Meanwhile, in some cases, a more pronounced population density towards the center of each city resulted in a lower embodied energy.

2.5 The Two Pathways of the Urban-Water-Energy Nexus

2.5.1 The Urbanization-Water Quality-Water Treatment-Energy Pathway

Past research has demonstrated a link between urban development and the water quality of nearby water bodies. Urbanization-influenced constituents include BOD, COD, nutrients (nitrogen and phosphorous), conductivity, and metals. In some cases, these affected water bodies also serve as sources for public water. Therefore, changes in water quality could affect operation of the water treatment plant. As drinking water treatment uses energy directly through pumping as well as indirectly through chemical and material additions, any alteration in the operation of the water treatment plant could have implications for energy use. To date, there has been no study that has investigated how and to what degree influent water quality (possibly due to urbanization) affects the embodied energy of drinking water treatment.

2.5.2 The Urbanization-Water Use-Energy Nexus

Past research has clearly demonstrated that drinking water, from its extraction to its provision at the tap, has an energy cost. Collection, treatment, and distribution all use energy to ensure that users receive a safe, reliable effluent. However, a substantial amount of this energy is due to distribution in water systems that rely on conventional treatment. Urban form, pipe age, and leakage are factors that have been shown to influence distribution system embodied energy. Therefore, smart growth, with adequate maintenance, may aid in the minimization of distribution system embodied energy. Previous studies have linked smart growth to relatively lower greenhouse gas emissions, water use, and its possible positive influence on nearby water quality.

However, there is a need for a study to address the possible influence of smart growth, as well as the state of the infrastructure, on the embodied energy of drinking water distribution.

CHAPTER 3: INFLUENCE OF WATER QUALITY ON THE EMBODIED ENERGY OF DRINKING WATER TREATMENT[1]

3.1 Abstract

Urban water treatment plants rely on energy intensive processes to provide safe, reliable water to users. Changes in influent water quality may alter the operation of a water treatment plant and its associated energy use or embodied energy. Therefore the objective of this study is to estimate the effect of influent water quality on the operational embodied energy of drinking water, using the city of Tampa, Florida as a case study. Water quality and water treatment data were obtained from the David L Tippin Water Treatment Facility (Tippin WTF). Life cycle energy analysis (LCEA) was conducted to calculate treatment chemical embodied energy values. Statistical methods including: Pearson's correlation, linear regression, and relative importance were used to determine the influence of water quality on treatment plant operation and subsequently, embodied energy. Results showed that influent water quality was responsible for about 14.5% of the total operational embodied energy, mainly due to changes in treatment chemical dosages. The method used in this study can be applied to other urban drinking water contexts to determine if drinking water source quality control or modification of treatment processes will significantly minimize drinking water treatment embodied energy.

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3.2 Introduction

Urban expansion, due to increasing population and affluence, has led to an increase in residential and commercial areas, a rising demand for energy and water, and consequently, increased greenhouse gas (GHG) emissions (United Nations Environment Programme, 2002; Baykal et al., 2003; Kennedy et al., 2009). In response, some cities have sought to minimize their energy use and carbon footprint through the adoption of carbon mitigation policies and energy-efficient strategies and technologies. For instance, in 2008, the mayors of more than 850 North American cities signed an agreement with the objective of decreasing CO_2 emissions to 1990 values by 2012 (The United States Conference of Mayors, 2008).

The water sector is one contributor to municipal energy use with water and wastewater treatment and transport being responsible for up to 44% of a city's energy cost (Yonkin et al., 2008; City of Bloomington, 2011). In addition, population growth and tighter water quality standards are projected to result in an additional 20% increase in water and wastewater energy usage by 2023 (Environmental Protection Agency, 2008a). Therefore water managers must strike a balance between providing sufficient safe water to users and minimizing energy usage, due to economic considerations and to lower their city's carbon footprint. Proposed responses to these challenges include demand management strategies such as incentives for water-saving technologies and conservation education to reduce water consumption, as well as supply management strategies such as non-potable water reuse (Stillwell & Webber, 2010).

One point of convergence between urban water management and energy use lies in drinking water treatment and supply. Generally, urban areas in the U.S. provide drinking water via a centralized water treatment plant that is connected to a water distribution system. To ensure a safe, reliable, and high-quality water to city residents, urban water provision makes use of different energy-consuming water treatment processes organized in a process train, typically including pretreatment, coagulation, flocculation, sedimentation, filtration, and disinfection (Crittenden et al., 2005).

One metric used to quantify the energy use of water infrastructure over its life cycle is embodied energy, defined as the direct and indirect energy needed to produce a unit volume of treated water. Direct energy refers to the onsite energy consumption and has been interpreted in previous research as the electricity and fuel consumed by a drinking water system for treatment process operation and pumping (Racoviceanu et al., 2007; Mo et al., 2011). Indirect energy is consumed offsite and has previously been defined as the energy associated with treatment chemical and material manufacturing and transport, "maintenance", and "engineering services" (Racoviceanu et al., 2007; Mo et al., 2011). City-scale drinking water embodied energy studies were conducted for Toronto (Racoviceanu et al., 2007), the cities of Tampa (Florida) and Kalamazoo (Michigan) (Mo et al., 2011), and a plant-level study focused primarily on a treatment plant in Durban (South Africa) (Friedrich et al., 2009). Embodied energy has also been determined for alternative water treatment schemes, such as desalination (Stokes & Horvath, 2009), as well as components of water treatment and supply infrastructure, including New York City's water distribution system (Filion et al., 2004).

Chemical use and electricity (mainly due to pumping and process operation) are known to be primary contributors to the embodied energy of water treatment and supply (Racoviceanu et al., 2007; Mo et al., 2011). However, external factors may determine their contributions. Regulatory policy has been proven to drive the addition of more unit processes and/or chemicals to ensure a continuous high-quality effluent (Reiling et al., 2009). Drinking water sources (i.e. groundwater vs surface water) differently affect the amount of pumping and chemicals needed for treatment (Mo et al., 2011). The production and transport of materials needed for the construction of unit processes and the chemicals needed for extra treatment require energy (Racoviceanu et al., 2007; Mo et al., 2011). Therefore, changes in influent water quality, possibly driven by urbanization and climate (Carle et al., 2005; Coskun et al., 2008; Peters, 2009; Whitehead et al., 2009; Wilson & Weng, 2010), may also affect embodied energy and associated carbon emissions. Nevertheless, there has been no study to date that analyzes how influent water quality specifically influences the embodied energy of drinking water treatment. The objective of this study is to understand how and to what degree influent water quality, possibly caused by increasing urbanization and/or natural seasonal patterns, impacts the operation of drinking water treatment processes, and consequently, the embodied energy of drinking water treatment. The embodied energy is based on a unit volume of water leaving the treatment plant. Since the focus of this study is the water treatment, indirect energy here is defined as the energy used in the production and transportation of treatment chemicals and materials used during the water treatment process. The procedure employed and results obtained could help stakeholders and decision makers assess if water quality source control or even the use of different treatment chemicals will aid in lowering the cost, embodied energy, and carbon emissions associated with drinking water.

3.3 Materials and Methods

3.3.1 Study Background

Tampa is a major city of the Tampa-St. Petersburg-Clearwater Metropolitan Area, which has a current population of about 2.8 million and has grown in population by about 40% in the past two decades (U.S. Census Bureau, 2001, 2012). As of 2010, Tampa had a population of about 336,000 inhabitants, a 10.7% relative increase from 2000 (U.S. Census Bureau, 2010).

Much of this population growth has driven urbanization. The expansion of land classified as urban within the Hillsborough River watershed has grown in the past decade, according to a multi-year comparison of land use GIS data provided by the Southwest Florida Water Management District (SWFWMD).

Tampa's water supply is primarily obtained from a reservoir on the Hillsborough River and is treated at the David L. Tippin Water Treatment Facility (Tippin WTF). The Tippin WTF, which produces potable water for about 588,000 consumers in Tampa and its outlying communities, has a maximum capacity of 120 million gallons per day (MGD) (450 ML/day), and currently treats an average flow of approximately 68 MGD (260 ML/day) (City of Tampa, 2012). Treatment steps include: pre-treatment, flocculation/sedimentation, ozonation, biological activated carbon filtration (biofiltration), and disinfection. Sludge mostly from the flocculation/sedimentation step and backwashing of the biofiltration basins is sent to thickeners and subsequently trucked about 0.4 mi (0.6 km) to a sludge processing facility for dewatering. Prepared sludge is then sent to a farm about 11 mi (17 km) from the plant. A more specific description of the water treatment facility is illustrated in Figure B-1 in Appendix B.

3.3.2 Data and Methods

The procedure described here consists of three main steps. First, water quality and water treatment data were collected and processed. Second, the operational embodied energy was calculated. Third, statistical methods were employed to ultimately determine the effect of water quality indicators on operational embodied energy. The following sections go into more detail about each step.

3.3.2.1 Data Collection and Processing

Reservoir water quality data (i.e., alkalinity, hardness, non-carbonate hardness, carbonate hardness, magnesium hardness, iron, threshold odor number (TON), total organic carbon (TOC), color, conductivity, and pH) were obtained from the City of Tampa Water Department for the years 2002-2010. Data were collected daily (i.e., Monday to Friday). Additional details about the water quality over the eight-year period can be found in Table B-1 in Appendix B.

Plant operation data were also provided by the City of Tampa Water Department. The data included electricity, fuel, chemical use, and sludge production by the Tippin WTF for the years 2002-2010. Electricity, fuel, and sludge data for the entire plant were based on monthly totals from past bills and reports. Chemical consumption and flowrate data were reported daily. Other operation variables (e.g., operation hours, and amount of water treated) were provided as needed.

Since water quality, sludge production, and chemical, electricity, and fuel usage values were collected at different frequencies for the years 2002-2010, all values were standardized to monthly amounts. Water quality values were averaged monthly. Chemical usage and sludge production values were obtained by dividing the total amounts used in a given month by the volume of treated water. Electricity and fuel usage were also normalized by monthly volume of treated water. Water quality parameters will be defined as water quality values, while chemical dosages, sludge production, and normalized electricity and fuel use values will be referred to as water treatment parameters.

3.3.2.2 Operational Embodied Energy Calculation

The operational embodied energy (E_O) is the sum of the direct and indirect energies used exclusively during the operation and maintenance life stage. As defined early, direct energy here refers to the energy used (electricity, fuel, etc.) at the plant, while indirect energy includes the energy used to produce and transport treatment chemicals and materials for the water treatment process (ferric sulfate, sulfuric acid, caustic soda, lime, liquid oxygen, etc.). This study focused on drinking water treatment discounting distribution system and sludge dewatering offsite. The construction stage was excluded due to its relatively low impact, as determined in previous research (Mo et al., 2010; Mo et al., 2011).

Equation (1) was used to calculate the monthly direct energy (E_D, MJ/m^3). The energy used in the production of electricity and fuel (P_E and P_F, respectively, MJ produced/MJ consumed) was multiplied by the electricity (E_E, MJ/m^3) and fuel use (E_F, MJ/m^3) values for each month and summed. The fuel was assumed to be diesel produced and sold in the US.

$$E_D = E_E(P_E) + E_F(P_F) \tag{1}$$

Indirect energy (E_I, in MJ/m^3 water treated) was determined using Equations (2) and (3).

$$\varepsilon = E_P + E_T \tag{2}$$

$$E_I = \sum \varepsilon D \tag{3}$$

In Equations (2) and (3), E_P (MJ/kg) equals the chemical production embodied energy, defined as the energy use from extraction of raw materials to chemical production. E_T (MJ/kg) is the energy use due to transportation of a quantity of chemicals from the point of manufacturing to the plant. For sludge, only E_T was calculated to account for its transport to the sludge processing facility. These terms are summed to obtain the energy factor (ε, MJ/kg). D is the chemical dosage (kg/m^3) or the amount of sludge produced (m^3/m^3).

E_P and E_T were estimated by carrying out a life cycle energy analysis (LCEA) that included extraction of the necessary materials for chemical production, processing, and transport from the production facility to the plant. SimaPro 7 databases (Amersfoort, the Netherlands) were used for nine chemicals' production processes. Dry and emulsion polymers, classified as organic, were not in the database and thus were modeled as "organic chemicals". Additional information on chemical distributors and manufacturers was obtained from the Tippin WTF's operations manager. Cumulative energy demand (CED) was used to quantify E_P and E_T, which were subsequently summed to calculate ε. Each chemical's ε was then multiplied by the monthly chemical dosage (D, in kg/m^3), resulting in a chemical-specific monthly energy value. For each month, the values for each chemical were added together to calculate the monthly indirect energy (E_I). The direct (E_D) and indirect energies were combined to estimate the embodied energy (E_0, MJ/m^3) for each month as follows in Equation (4):

$$E_O = E_I + E_D \tag{4}$$

3.3.2.3 Statistical Analysis

Water treatment systems are composed of interrelated treatment processes, which function based on the quality of the water they treat via complex physical-chemical dynamics. The operation of these systems is determined through empirical means (i.e. jar tests) and the internal water quality, which can vary based on the treatment step. Prior knowledge of causal relationships and a black-box method such as statistical analysis are a simple means of quantifying relationships that should ultimately determine the influence of influent water quality on the entire water treatment process train and subsequently the embodied energy.

Relationships between the recorded water quality parameters were analyzed to determine representative water quality indicators. If a group of water quality parameters is highly correlated, only one parameter needs to be selected as the representative indicator for the group. Therefore, a collinearity test was carried out using Pearson's correlation method to determine the relationships between the eleven monitored water quality parameters, and ultimately isolate water quality indicators. The significance and strength criteria of a Pearson's correlation factor ($r > 0.4$ or < -0.4, and P-value < 0.05) were used in this study.

A backward-elimination linear regression was performed using SAS software (Cary, NC). All water quality indicators and prior treatment parameters were set as the independent variables and a water treatment parameter as the dependent variable. For each regression, the R^2 value was checked to measure the accuracy to which the regression can predict the dependent variable. This value indicates the percentage of the variance that is explained by the regression. Resulting regressions, with R^2 values greater than 0.5 (50%), were deemed significant.

To determine how each contributing factor (independent variable) affects the water treatment parameter (dependent variable) in question, two relative importance calculation methods (product measures and relative weights) were used. A decision-making process was followed to estimate relative importance of independent variables (Figure S2 in SI). Product measures were calculated for each significant regression to test for "suppressor" variables. These independent variables with extremely low product measures (≤ 0.05) were eliminated and regressions were recalculated only including non-suppressor variables. Product measures were then calculated again to determine the contribution of each independent variable.

If product measure analysis was found to be an invalid test, relative weights analysis was carried out using an R-based code (http://relativeimportance.davidson.edu) provided online (Tonidandel & LeBreton, 2008). Any independent variables with insignificant relative weights were eliminated and the regression and relative weights recalculated. It is important to note that R^2 values do decrease with the elimination of insignificant variables. Nevertheless, initially significant regressions were not excluded if their recalculated R^2 values fell below 0.5. Relative importance values were compared with corresponding r-values in a Pearson's correlation matrix consisting of water quality indicator and water treatment parameter correlations to determine if independent variables also shared significant correlations with the dependent variable. Congruency between the Pearson's matrix results and the relative importance analysis denoted an acceptable regression.

R^2 values and relative importance were used to determine the degree of influence of water quality indicators on embodied energy values. Percent contributions of each water quality indicator to water treatment parameters were calculated considering both direct relationships and indirect relationships due to the sequence of the treatment train. For instance, an elevated influent total organic carbon (TOC) concentration requires a higher dosage of coagulant. If the coagulant is a weak acid, the acid dosage used for pH modification to ensure optimum flocculation will also be affected. Therefore, TOC directly influences coagulant dosage and indirectly affects acid dosage (Figure B-2 in Appendix B). The percent influence of TOC on embodied energy via coagulant dosage (C_{Coag}) is estimated by multiplying the relative weight contribution of TOC to coagulant dosage (R_{TOC}) with the percent contribution of coagulant to the overall embodied energy of the plant (P_{Coag}) (Equation (5)). The degree of influence that TOC has on embodied energy through its indirect relationship with sulfuric acid dosage, C_{SA}, is determined by the product of R_{TOC}, the relative weight contribution of coagulant to sulfuric acid dosage, R_{Coag}, and percent contribution of sulfuric acid to total embodied energy P_{SA} (Equation (6)). For each valid regression, this analysis was applied to each contributing water quality indicator. The percent contributions were then combined to determine the aggregated water quality contribution.

$$C_{Coag} = P_{Coag}(R_{TOC}) \tag{5}$$

$$C_{SA} = R_{TOC}\left(R_{Coag}\right)(P_{SA}) \tag{6}$$

3.4 Results and Discussion

3.4.1 Embodied Energy

The 2002-2010 average operational embodied energy of the Tippin WTF was estimated to be 7.17 MJ/m^3 of treated water. Figure 1 shows that 62.6% was due to direct energy. This contribution is primarily from the use of the high service pump for the transport of treated water through the distribution system (EPRI, 2000). The remaining 37.4% is due to indirect energy associated with treatment chemicals. Chemicals used in the flocculation/sedimentation and biofiltration unit processes combined are responsible for 75% of the total indirect embodied energy. Ferric sulfate, used in the flocculation/sedimentation step (Figure B-1 in Appendix B), requires 4.86 MJ/kg ferric sulfate produced and transported to the Tippin WTF, and is added at a relatively high average dosage of about 156 mg/L (Table B-2 in Appendix B). This ε value is low compared to alternative coagulants, such as aluminum sulfate (alum, 10.8 MJ/kg) and ferric chloride (17.7 MJ/kg). Caustic soda is the main reason for the high indirect energy consumption associated with biofiltration. This pre-biofiltration pH regulator has a high ε of about 26.9 MJ/kg caustic soda produced and transported. Nevertheless, the average dosage is about 41 mg/L which is lower than that of ferric sulfate. Despite biological activated carbon's (BAC) high ε value (67.1 MJ/kg), it is only responsible for 0.4% of the indirect operational embodied energy as there were only four months from 2002 to 2010 when it was replenished. Variation in production and transport embodied energies is due to different manufacturing processes and transportation distances for the chemicals and material mentioned.

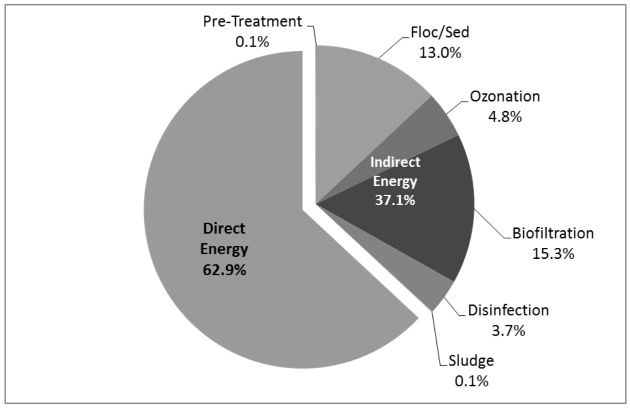

Figure 1 Breakdown of the total operational embodied energy for the David L. Tippin Water Treatment Plant.

Ozonation stands out as only contributing 5% to the total embodied energy and about 13.5% to total indirect embodied energy. Ozone is fed to the water treatment train as liquid oxygen, which has an ε value of 1.52 MJ/kg and a dosage of 65 mg/L. Much of the energy associated with ozonation is direct, as vaporizers and ozone contactors consume electricity (Crittenden et al., 2005).

In comparison to previous studies, the total embodied energy of the Tippin WTF (7.18 MJ/m^3) determined in this study falls between the estimates of two other studies of surface-water based systems: 2.6 MJ/m^3 and 10.3 MJ/m^3 (United Nations Environment Programme, 2002; Racoviceanu et al., 2007; Mo et al., 2011). Mo et al. (2011) was also a Tampa-based study and shares a similar direct embodied energy value to this study with a difference of only 0.3%. However, there is a contrast between the indirect energy values in all three studies. Mo et al. (2011) estimated a higher indirect energy contribution (53%) than direct energy to the total embodied energy. The study included water distribution as well as “engineering” and “consumer services”. Meanwhile, Racoviceanu et al. (2007) only observed a 6% indirect energy contribution. This can be explained by differences in site location, energy consumption of the high service pump in the plant due to different elevation, amount of upstream energy needed to produce electricity, energy calculation method, treatment processes, chemicals used, and the water source quality between this study and Racoviceanu et al. (2007).

3.4.2 Water Quality Influence on Water Treatment

The degree of interaction between influent water quality parameters was analyzed (results are presented in Table B-3 in Appendix B) to determine the appropriate water quality indicators for subsequent quantification of their influence on water treatment parameters. Pearson's collinearity test results narrowed the original 11 parameters to 4 indicators: total organic carbon (TOC), threshold odor number (TON), turbidity, and conductivity. TOC is strongly correlated with color (r=0.916). TON, which is the ratio of a sample of raw water and the non-odorous water needed to dilute it, is not correlated to any other parameter. Turbidity is only weakly correlated with conductivity (r=0.423) and is typically low (below 10 NTU) in the Hillsborough River Reservoir. Meanwhile, conductivity shares strong and moderate positive correlations with hardness, alkalinity, and pH (r=0.903, 0.733, 0.693, respectively). This type of relationship is expected as these parameters are related to the amount of dissolved ions in water. Local geology also plays a role because the Hillsborough River is underlain by limestone and dolomite, which are sources of calcium and manganese (Wolansky & Thompson, 1987). These minerals contribute to the water's hardness, alkalinity, and consequently, conductivity.

While the indicators are mostly unrelated, conductivity was still found to share a moderate negative correlation (r = -0.711) with TOC. This type of relationship is unique in that TOC in the Hillsborough River is generally derived from biomass and shares no physicochemical link with conductivity; therefore, they are treated as separate factors. However, climate may explain their correlation as both constituents are seasonally-influenced in this location. Conductivity values are generally higher during the dry season and diluted by increased rainfall during the wet season (43 inches of average monthly rainfall during the wet season, April to September, versus only 13 inches during the dry season, October to March). The contrary is true for TOC, which is transported via runoff from the river's source (i.e., the Green Swamp) during the wet season due to increased precipitation.[31]

The effects of the four water quality indicators and prior treatment chemicals on the dosages of chemicals used in each treatment process were estimated via linear regression, relative importance analyses, and Pearson's correlation (presented in Table 4). The water quality indicators TOC and conductivity have the strongest effect on chemicals used during flocculation/sedimentation (which is the first stage of treatment in most surface-water based plants). The highest R^2 values correspond to use of ferric sulfate (0.79) and sulfuric acid (0.75). These chemicals are also characterized by relatively high Pearson's r values (for ferric sulfate, TOC = 0.876; for sulfuric acid: conductivity = 0.789, ferric sulfate = -0.719), which denote strong linear relationships between influent water quality indicators and ferric sulfate and sulfuric acid dosages at the plant. In this location, ferric sulfate dosage is mainly driven by influent TOC concentration due to its role as a coagulant. Conductivity and ferric sulfate are the main drivers of sulfuric acid dosage, which is used for pH modification for optimum coagulation. Conductivity is strongly correlated to alkalinity, which necessitates a higher dosage of acid. Ferric sulfate is a weak acid and slightly lowers the pH, thus limiting acid dosage.

The fact that sludge production mainly results from flocculation and sedimentation is noted by its strong correlation with the coagulant ferric sulfate (r = 0.717). However, conductivity has a slightly stronger (negative) correlation (r= -0.793). This is most likely a seasonal, rather than physical-chemical relationship as more organic matter is present in the river due to runoff during the wet season, when conductivity is diluted.

The dosage of hydrogen peroxide is influenced in part by the influent TOC values and the dosage of liquid oxygen. Moderate correlations characterize these relationships. According to relative importance analysis results, liquid oxygen is the most significant contributor to hydrogen peroxide dosage and has the stronger correlation (r=0.528). Hydrogen peroxide's main use is to quench excess ozone (from liquid oxygen) post-ozonation. Conversely, TOC shares a weak, negative correlation with hydrogen peroxide. When ozone reacts with high amounts of TOC, there is less residual ozone, thus requiring less hydrogen peroxide to react with remaining ozone.

Table 4 Results of linear regression and relative importance analyses designating the water treatment parameters as dependent variables and influent water quality indicators as well as prior water treatment parameters as independent variables

Water Treatment Parameter	R^2 value	Relative Importance Method	Independent Variable	Relative Impact (Sum ≈ R^2)	Pearson's r
Ammonia	0.66	Regression	Chlorine	0.66	0.813
Caustic Soda	0.45*	Regression	Sulfuric Acid	0.45*	0.612
Ferric Sulfate	0.79	Regression	TOC	0.79	0.876
Sulfuric Acid	0.75	Relative Weights	Conductance	0.41	0.789
			Ferric Sulfate	0.34	-0.714
Hydrogen Peroxide	0.50	Product Measures	TOC	0.21	-0.443
			Liquid Oxygen	0.29	0.528
Sludge	0.65		Conductance	0.34	-0.793
			Ferric Sulfate	0.31	0.717

* The original R^2 value for the caustic soda dosage regression was 0.18. However, four outliers were identified due to the temporary inactivation of the ozonator. The values were eliminated and the regression was recalculated.

The weakest regression is associated with caustic soda (R^2 =0.45). This chemical is added after ozonation to raise the pH to about 7.0 for optimum biofiltration. Since sulfuric acid and caustic soda oppositely affect pH, their relationship is logical. The lower R^2 value may be attributed to the impacts of previous treatment steps. The flocculation/sedimentation stage significantly decreases the TOC and the pH (for optimum TOC removal). Lime is subsequently added to raise the pH to 6.0-6.5 prior to ozonation and to control bromate formation (Bales, 2012). Therefore, influent water quality is substantially different to pre-caustic soda addition water quality.

As expected, observation and comparison of the data in Table 4 highlights a decreasing influence of influent water quality on water treatment parameters the farther from the water intake point they are added. Figure 2 also illustrates this. TOC and conductance have a clearly observed effect on the dosages of ferric sulfate and sulfuric acid, as evidenced by their influences of 79% and 68%, respectively. This impact decreases post-flocculation/sedimentation stage as water quality influences 58% of sludge produced, 21% of the dosage of hydrogen peroxide, and about 31% of the caustic soda dosage. According to a meeting with the operations manager of the plant, post-flocculation/sedimentation water quality is consistent regardless of the seasonal variations of the influent water quality.

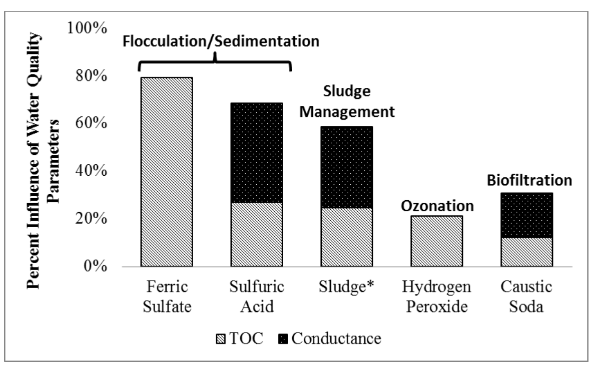

Figure 2 Impact of influent TOC and conductance values on chemical dosage. *Sludge collected from settled flocs and backwash from the biofiltration step

3.4.3 Influence of Water Quality on Embodied Energy

The contribution of the four representative water quality indicators (i.e. conductivity, TOC, turbidity, and threshold odor number (TON)) to the total operational embodied energy is illustrated in Figure 3. Turbidity and TON were found to have a statistically negligible effect on the total operational embodied energy. Influent TOC and conductivity combined are responsible for about 14.5% of the total operational embodied energy in the water treatment plant (about 40% of the indirect operational embodied energy). Of that, TOC is the largest contributor, responsible for 11% of total operational embodied energy, while conductivity only affects 3.5%. Increased TOC concentration in the influent requires higher dosages of ferric sulfate. Ferric sulfate usage is responsible for about 11% of the plant's total embodied energy. In contrast, conductivity is the main driver of sulfuric acid dosage, which partially influences lime and caustic soda dosages. However, sulfuric acid only accounts for about 2% of the plant's total operational embodied energy and has a relatively small embodied energy (2.13 MJ/kg acid produced and transported to plant).

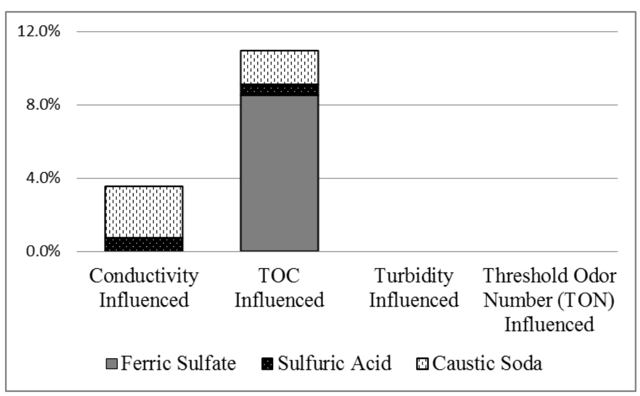

Figure 3 Percent influence of water quality parameters on total embodied energy

Conductivity's influence on embodied energy is mainly through caustic soda requirements. This pH regulation chemical has a relatively energy-intensive production process and is responsible for biofiltration's substantial contribution to the plant's total indirect embodied energy (Figure 3). Therefore, conductivity's relatively small influence on caustic soda dosage (19%) translates into an influence of 0.20 MJ/m^3 or about 2.8% of the plant's total operational embodied energy.

3.4.4 Seasonality

Seasonal processes tend to be significant drivers of TOC and conductivity values in the reservoir. As mentioned previously, maximum concentrations of TOC occur during the wet season while peak conductivity values are reached during the dry season. The average TOC from 2002-2010 during the wet season was about 14 mg/L, while during the dry season, it falls to 11 mg/L. The inverse is true for conductivity, which for the same duration has an average of 363 μmhos/cm during the dry season in contrast to a wet season mean of 331 μmhos/cm.

These fluctuations also translate into differences in the chemical embodied energy contributions. The total indirect energy values in the dry season are higher than those in the wet season principally due to caustic soda's high embodied energy. The embodied energy contributions of caustic soda and sulfuric acid (in most cases) follow a comparable trend (Figure 4). This resembles the seasonal dynamics of conductivity, which increases during the dry season and is diluted during the wet season due to increased precipitation. Conversely, the ferric sulfate embodied energy contribution is higher during the wet season than the dry season. This follows a similar seasonal pattern to TOC, which also has an elevated presence during the wet season because of mobilization of TOC in the watershed.

As a result of the influence of seasonality, the dynamics of the effect of influent water quality changes. For instance, from the wet season to the dry season, conductivity's contribution to total operational embodied energy increases from 3.3% to 4.1%, while TOC's influence drops from 11.7 to 10.4%.

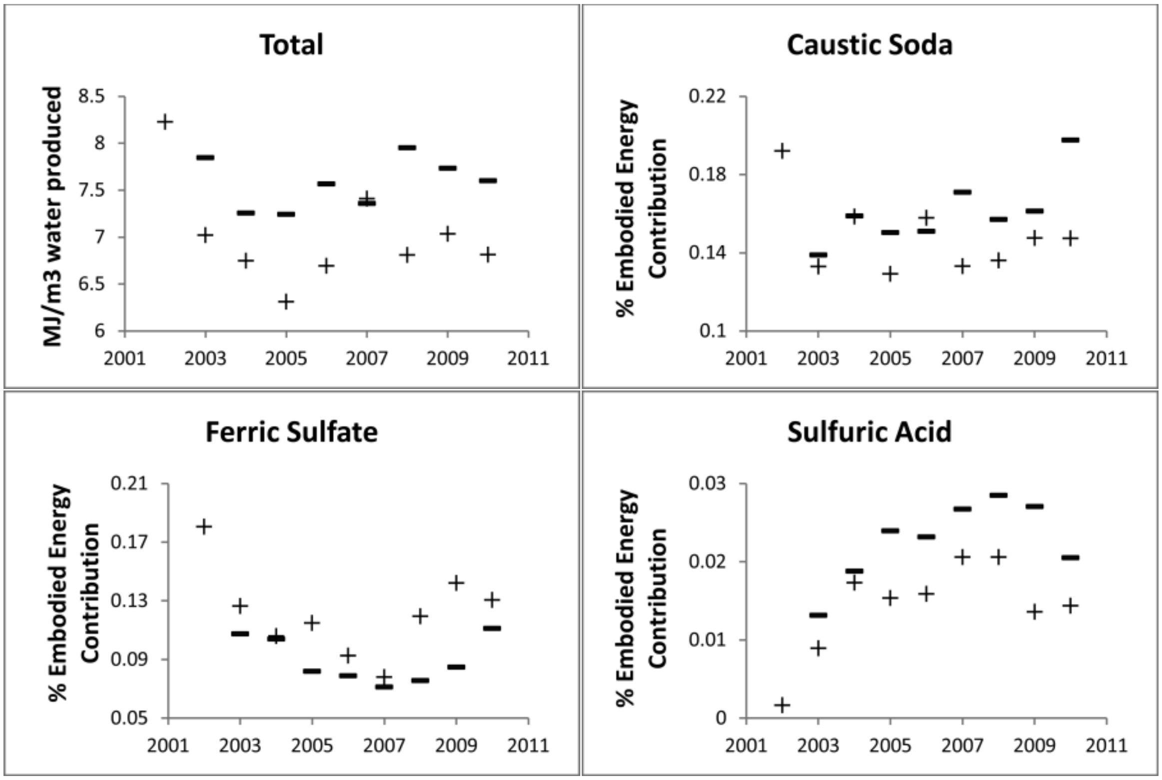

Figure 4 Wet and dry season comparisons of annually-averaged total embodied energy and percent-specific chemical indirect embodied energy contribution. (-) denotes dry season values, while (+) denotes wet season values

3.4.5 Other Possible Sources of Water Quality Changes

In addition to seasonality, geology and possibly land use contribute to the resultant water quality. In Tampa, an average hardness of 162 mg/L as $CaCO_3$ denotes very hard water. This is due to the geology underlying the Hillsborough River watershed where limestone and dolomite deposits occasionally come in contact with surface water (Wolansky & Thompson, 1987). Past research also suggests that land use plays an important role in altering the amounts of constituents in nearby bodies of water (Wang & Yin, 1997; Rhodes et al., 2001; Carle et al., 2005; Hertler et al., 2009; McMahon et al., 2009; Peters, 2009; Tong et al., 2009; Ye et al., 2009;

Lee et al., 2010; Tran et al., 2010; Wilson & Weng, 2010; Zeilhofer et al., 2011). According to a comparison of land use GIS data provided by SWFWMD, urban land use in the Hillsborough River has expanded over the past decade. The results of a Pearson's correlation test relating land use in the Hillsborough River sub-watershed area to corresponding annual averages of conductivity reveal a strong correlation (r=0.862). Similar relationships have also been seen in past research in other locations in the U.S. (Tu et al., 2007; Peters, 2009; Tu, 2011). Nevertheless, the effect of urbanization on conductivity in the Tampa Bay area is not fully conclusive due to lack of data.

3.4.6 Implications for Embodied Energy Minimization

Since influent water quality has a significant influence on the embodied energy of drinking water in Tampa, management of a watershed for water quality should be prioritized as an aid in minimizing costs, embodied energy, and carbon emissions. The two constituents that have the highest impact in this study area, TOC and conductivity, occur naturally and managers should be aware that climate change may partially influence future constituent trends. For example, according to the U.S. Global Change Research Program (2009), precipitation during the summer, winter, and spring in the Tampa Bay area is projected to decrease, which may result in lower TOC readings in the water (and less coagulant added) as well as an increase in conductance (increased sulfuric acid and caustic soda usage) due to lower stream flow. Also, increased urbanization in the watershed may also affect future TOC and conductance in the water. Though not a concern currently at this location, elevated TOC values have also been observed in urban streams that receive wastewater treatment plant effluent or runoff (Westerhoff & Anning, 2000; Sickman et al., 2007; Zeilhofer et al., 2011). However, it is important to note that TOC is a bulk measurement of organic compounds and its influence on water treatment may vary depending on the exact composition of these compounds. Meanwhile, urban expansion is associated with increased conductivity in surface water (Wang & Yin, 1997; Tu et al., 2007; Peters, 2009; Ye et al., 2009). Therefore, future plans for urban expansion and/or development may account for subsequent effects on the energy and carbon emissions associated with water supply.

In the case of water treatment in the city of Tampa, although most of the operational embodied energy is direct, influent water quality has a noticeable influence on the operational embodied energy through indirect energy. Flocculation/sedimentation-stage chemicals such as ferric sulfate and sulfuric acid are significantly affected by influent water quality. Their dosages are mainly influenced by TOC; however, the presence of conductivity additionally contributes in determining the dosage of sulfuric acid needed. Post-flocculation/sedimentation-stage chemicals, such as hydrogen peroxide and caustic soda, and sludge are also indirectly influenced by influent water quality. Overall, influent water quality affects about 14.5% of the total embodied energy.

Because there are many different configurations for drinking water treatment, the framework provided here for embodied energy estimation and supporting statistical analyses can be applied to other urban drinking water systems. Documented here is a procedure that will be able to estimate the influence of water quality and aid in determining if influent water quality is a significant factor in the total operational embodied energy of drinking water.

CHAPTER 4: THE EFFECT OF SMART GROWTH ON THE EMBODIED ENERGY OF WATER SUPPLY

4.1 Abstract

Cities are coming under increasing pressure to minimize energy use and greenhouse gas emissions. Consequently, drinking water utilities must improve the efficiency of their management systems while guaranteeing a clean effluent that satisfies drinking water standards. One possible solution is via smart growth, an urban development paradigm with the goal of reducing the environmental impact of urbanization. Therefore, this study aims to determine the effect of smart growth on the embodied energy of drinking water supply. Projected water use in Tampa's drinking water service area was estimated based on several urban growth projections. Then, each scenario's associated projected water consumption is integrated in an EPANET simulation of Tampa's water distribution system for the subsequent estimation of the embodied energies of drinking water distribution. Results show that smart growth has no exclusive influence on the embodied energy of water supply. However, location of added demand relative to the location of the water treatment plant has more of an influence on the operational embodied energy. Also, smart growth in the City of Tampa Water Service Area is responsible for a decrease in per-capita residential water and energy use of about 6-10% and 0.5-6.2% respectively. In conclusion, smart growth in areas near the water treatment facility may minimize water-related energy use.

4.2 Introduction

By 2050, the world's population is expected to reach 9.6 billion people with 60% living in cities (United Nations, 2010, 2013). This highly urbanized and increasingly affluent population will require more energy, land conversion, resource use, and agricultural development (Yeh & Huang, 2012). However, the most important resource needed by this growing urban population for overall community well-being is water. This explains the reliance of many cities on centralized water treatment and supply schemes composed of collection, treatment, storage, and distribution systems to satisfy water demands. All of these systems require energy, known as embodied energy, to provide a safe drinking water (Mo et al., 2011; Amores et al., 2013; Del Borghi et al., 2013; Santana et al., 2014). In response, cities and water utilities must confront the challenge of achieving availability, quality, and energy efficiency.

There are three main energy-consuming components to a water treatment and supply system: collection, treatment, and distribution (storage is considered a part of the distribution component). Past studies have estimated total the energy use of water treatment and supply systems at the regional (Del Borghi et al., 2013), metropolitan (Lundie et al., 2004), and municipal scales (Mo et al., 2011; Amores et al., 2013). Estimated embodied energies from these studies ranged from 5.2-54.1 MJ/m^3. Differences were mainly due to factors including the treatment process and piping distance. For instance, the desalination process consumes about 8-10 times more energy per unit of water treated than conventional systems included in the same studies making desalination responsible for about 65-81% of the total energy use in water management systems, where it is included (Amores et al., 2013; Del Borghi et al., 2013). Consequently, this contribution has a great impact on the overall embodied energy of water treatment and supply. However, when water systems rely on conventional/filtration systems, treatment is only responsible for 17-30% of the total embodied energy, making distribution the greatest contributor (Lundie et al., 2004; Amores et al., 2013). In the US, since centralized drinking water systems tend to rely on conventional treatment, distribution is most likely the largest contributor to overall embodied energy use.

Distribution systems usually follow roads, which explain the demonstrated influence of urban form on water distribution. Filion (2008) modeled the distribution systems of three theoretical cities: gridiron, radial, and satellite. For each "city", three distinct population distributions were applied: "uniform", "monocentric", and "polycentric". A life cycle energy analysis (LCEA) was conducted for each scenario. Cities that followed a radial form (similar to older European cities) as well as a higher population density in and near the center of each city resulted in lower embodied energies.

Smart growth is a development paradigm in which urban growth has a minimal environmental impact as well as positive social impact. It is governed by eleven principles as shown in Table 2 (Smart Growth Network, 2006). Past research has shown that smart growth can decrease negative environmental impacts. For instance, smart growth has been postulated to result in less energy use via streamlined energy distribution systems, which could aid in facilitating the implementation of renewable energies (Straka, 2002). Behan et al. (2008) used an integrated transportation simulation model to simulate current and smart growth trends and found that smart growth was projected to use about 25% less fuel and emit 30% less CO than the "base case." Hankey and Marshall (2010) modeled urban transportation scenarios and estimated a net decrease of about 17% in GHG emissions in the "smart growth" scenario compared to the business-as-usual growth scenario. Lee and Lee (2014) predicted, via a multilevel structural equation model, an accompanying 4.8% decrease in travel-related CO_2 emissions and 3.1-3.5%

decrease in household-related CO_2 emissions for every 10% increase in population density. The implementation of transit-oriented development (TOD) was studied by carrying out a life cycle assessment (LCA) of the areas surrounding two bus lines in Los Angeles and observed a relative decrease in environmental impacts associated with the TOD scenario, compared to the "business-as-usual" scenario (Nahlik & Chester, 2014).

Smart growth also has a relationship with water. Watersheds with at least 10% impervious area have been associated with degraded water quality and increased sprawl would create 43% more runoff (Pelley, 2004). Households built within existing urban areas are more likely to rely on centralized wastewater treatment systems (Harrison et al., 2012). However, only a couple studies were identified that looked specifically at the effects of smart growth on water use. Guhathakurta and Gober (2007) demonstrated, with a linear regression model, that greater lot sizes and pool areas (associated with sprawl) were associated with increased water use as well as temperature increases were related to increases in water usage. Runfola et al. (2013) incorporated a linear regression that predicted water use based on land cover and household characteristic variables into an urban growth model and showed that under the "smart growth" scenario, annual water use would grow by 2.2% compared to the 7.7% net growth under a business-as-usual scenario.

Water consumed at the tap incurs an energy cost, and in conventional water treatment and supply systems, the distribution system is responsible for a significant amount of this cost. Past research suggests that urban form can have an effect on the embodied energy of water, and smart growth serves as an alternative to the sprawl that has been a prominent mode of urbanization in the United States. There has also been no study identified that has observed how this urbanization paradigm may influence the embodied energy of an existing water distribution system. Therefore, this study compares the embodied energy of drinking water in four future water development scenarios, three of which incorporate smart growth within the city of Tampa, Florida.

4.3 Methods

4.3.1 Site Description

The City of Tampa Drinking Water Service Area (Tampa WSA) encompasses the political boundaries of the city of Tampa as well as certain outlying unincorporated communities (e.g., Town ‘n’ Country, Egypt Lake) (Figure 5). About 68 MGD of water is extracted from the Hillsborough River Reservoir, treated via the David L. Tippin Water Treatment Facility (Tippin WTF), and pumped through a 134,000-pipe distribution system to provide high quality drinking water to approximately 588,000 customers.

4.3.2 One Bay Development Initiative

One Bay is a consortium of public and private entities with the objective of encouraging development that incorporates the principles of sustainability. In 2007, over three hundred leaders were invited by One Bay to participate in a workshop called “Reality Check” to determine where future growth should take place in the Tampa-St. Petersburg-Clearwater (TSC) metropolitan area. In 2008, One Bay developed four future growth scenarios to simulate the effects of different development paradigms on land use, transportation, water use, employment, and housing. “Business as Usual” (BAU) is a continuation of current growth patterns. The “Preferred” scenario is the resultant plan of the “Reality Check” workshops. The “Compact” scenario projects more compact design via a clear preference for multi-family housing development concentrated in existing urban areas. Meanwhile, the “Green” scenario avoids construction in or near protected or sensitive areas. The latter three scenarios will be referred to as smart growth scenarios, as they result in an increased addition of multi-family households, and focus residential and commercial development within urban areas.

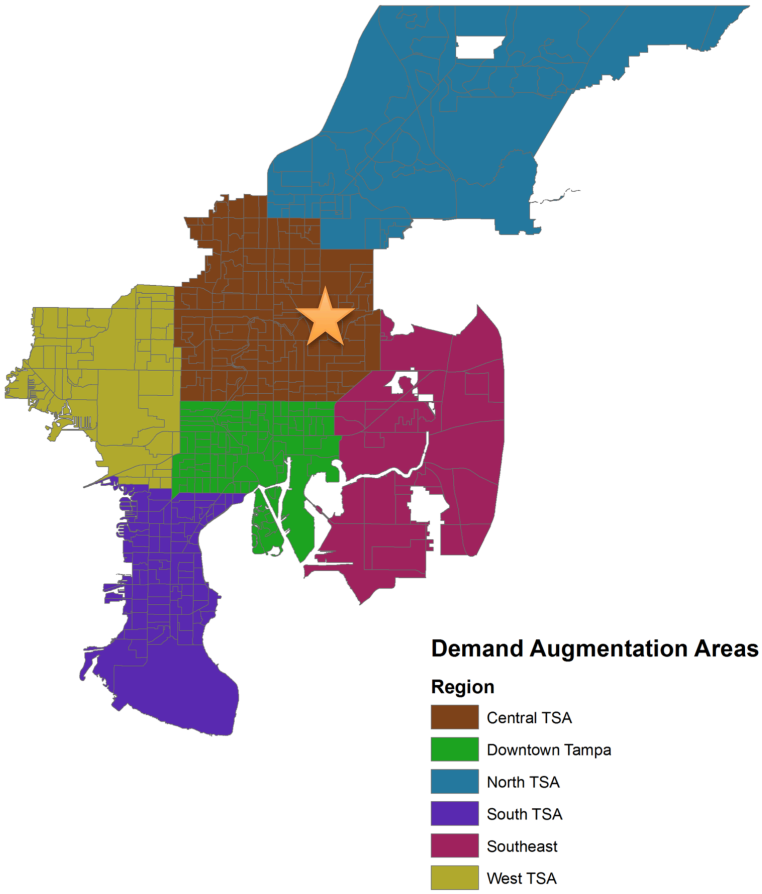

Figure 5 Extent of the Tampa Water Service area as well as regions within the area and the location of the David L Tippin Water Treatment Facility. The orange star indicates the location of the David L Tippin Water Treatment Facility

4.3.3 Data

4.3.3.1 Future Development Scenarios

The Tampa Bay Regional Planning Council (TBRPC) provided several GIS shapefiles that illustrate the future growth projections of the four growth scenarios outlined in the One Bay Initiative. The files were represented via a dot matrix with each "dot" representing a 39-acre area of land, containing the number of households and jobs that were projected to be added to the existing amount by 2050. Descriptions of each development scenario are presented in Table 5.

Table 5 Explanation of the different scenarios within the City of Tampa Water Service Areas modeled by One Bay Development Initiative

Name	Number of New Households	Number of New Jobs	2050 Population	Description
Business as Usual (BAU)	59,577	132,717	742,900	Growth projections based on current trends; Predominance of new single family home construction outside of urban areas
Preferred	208,881	353,655	1,131,091	Growth projections based on the consensus reached during the "Reality Check" workshops. Approved by municipal leaders, planners and other stakeholders. Increased development in existing urban areas. Increase in new multifamily home construction
Compact	208,410	348,288	1,129,866	The incorporation of compact design; Focus mainly on mixed-use multifamily construction; Development in existing urban areas
Green	169,824	287,538	1,029,542	Development is prohibited on or near protected or sensitive areas; Increased building of multi-family housing

4.3.3.2 Smart Location Database

Existing employment and household data were extracted from the Smart Location Database. This database is maintained by the Environmental Protection Agency (EPA) and was originally created to determine the "location efficiency" with respect to urban planning and transportation of communities throughout the United States (Ramsey & Bell, 2014). Information is aggregated at the census block group level and consists of data relating to density, mix of land uses, road density, and location of the population with respect to jobs and transportation. Housing unit and employment data were based on 2010 Census values.

4.3.3.3 Water Use

Current water use data was provided by Tampa Bay Water via a database called GOVNET (Clearwater, FL) (Table 6). This GIS database spatially organizes monthly water consumption of all accounts within the jurisdiction of Tampa Bay Water into a parcel-level shapefile. For the purposes of this study, the shapefile was clipped to the data within the boundaries of the Tampa WSA. Due to 2011 being the most recent year that data was collected for GOVNET, the monthly water consumption values for the year 2011 were summed for each account.

4.3.3.4 Water Distribution

A GIS shapefile of the Tampa WSA's distribution system was provided by the City of Tampa Water Department (Table 6). The shapefile contains the data for the approximately 134,000 pipes that make up the water distribution system. This data includes physical characteristics such as diameter, length, material, and the year the pipe was installed. For instance, pipes in the system range from 0.5 to 54 inches in diameter and is composed of 85% ductile iron pipes, 9% cast iron, 3% galvanized iron, 2% HDPE, and 1% PVC by length. In addition the Water Department also provided the locations of the three repump stations and one booster pump station.

Table 6 Data requirements to carry out research of this study

Type of Data	Source	Details
Land Use	Hillsborough County Property Appraiser	2011 Parcel level data with building and land characteristics
Water Use	Tampa Bay Water	GOVNET: 2011 Monthly water use for each account within the Tampa WSA in GIS format
Water Distribution	City of Tampa	GIS Shapefile of the Tampa Water Service Area distribution system
Future Development Scenarios	Tampa Bay Regional Planning Council	GIS Shapefile with areas where future residential and employment growth is projected to occur

4.3.4 Data Processing

4.3.4.1 Creation of the Base Hydraulic Model

The skelebrator tool in WaterGems (Exton, PA) was used to simplify the Tampa WSA distribution system shapefile from a network consisting of 134,000 pipes to just over 800 pipes. The skelebrator combines pipes that are in series or run parallel to each other to one equivalent pipe. Repump stations were excluded as they are mainly used for fire flows. However, the booster station was included as it is used to aid in the provision of water to the northern section of the Tampa WSA. In addition, pipes with a diameter of less than 8 inches were eliminated from the model for further simplification. The exclusion of these pipes should only minimally effect the embodied energy calculations. Next, the 2011 water consumption at each junction was incorporated into the hydraulic model in ArcGIS by aggregating the water consumption of the nearest parcels to each water distribution network junction via a proximity geoprocessing function. The resultant shapefiles with the junctions, pipes, pumps, and reservoir were then incorporated into an EPANET (Cincinnati, OH) file using the QGIS software plugin GHydraulics (Uelzen, Germany).

4.3.4.2 Scenario Creation

The future development scenarios provided by TBRPC have a region-wide scope including Hillsborough, Pinellas, Hernando, and Polk Counties. Each scenario projects a future population of about 7 million inhabitants in the entire Tampa Bay region. Therefore, each scenario GIS shapefile was clipped to fit the boundaries of the Tampa WSA. Each new household was estimated to contain 2.6 people based on the assumptions made by OneBay. The resultant scenarios project different future populations to be served by the city of Tampa Water

Department, given the assumption that the boundaries of the Tampa WSA do not change. Table 5 illustrates these differences.

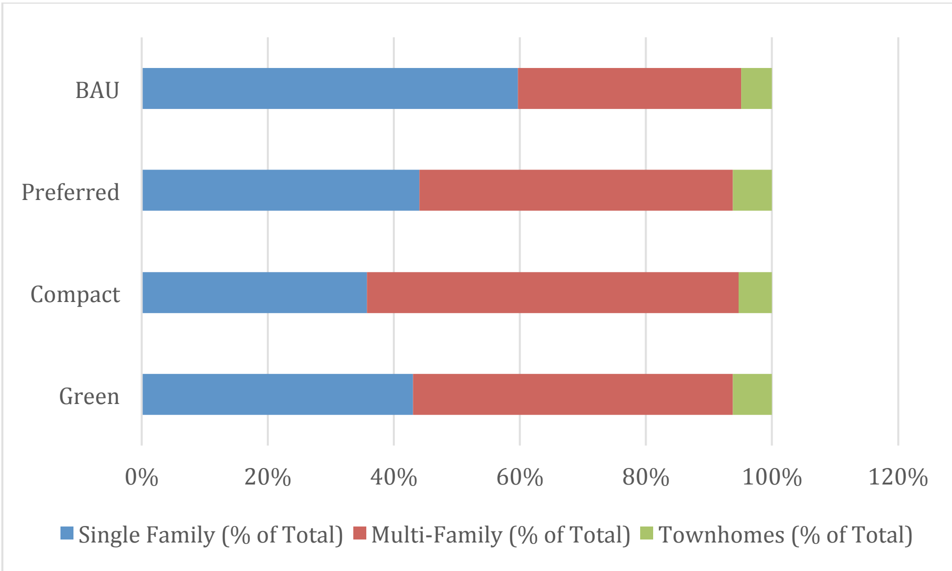

Figure 6 Household type composition for each future One Bay scenario within the Tampa Water Service Area

While the Preferred and Compact development scenarios add a similar amount of population to the Tampa WSA, BAU only adds 59,577 households, which is a little over a quarter of the amount added in the Preferred and Compact scenarios and about less than a third of the households added in the Green scenario. In addition to added population, the scenarios also have different future compositions of housing types (Figure 6). For example, in the BAU scenario, the majority of housing is single-family detached homes. In the other scenarios, multi-family homes and townhomes comprise the majority of all housing, reflecting a move towards compact design.

4.3.4.3 Water Consumption Projection

Future water consumption for the various development scenarios was estimated as the addition of the anticipated water consumption, due to new households and employment and the existing 2011 water consumption. An observation of average single-family home consumption values (in gallons per unit per day, GPUD) from 2002-2008 showed values stabilizing around an average of 254 GPUD (Hazen and Sawyer, 2013). Therefore, for the purposes of this study, the water consumption in existing households was assumed to not change from 2011 values, and any major changes would be from the addition of new households.

New household and employment water consumption values were separated into four categories: 1) single family household, 2) multi-family household, 3) townhomes, and 4) employment. Household water consumption data was obtained from the 2013 Tampa Bay Water Demand Management Plan (Hazen and Sawyer, 2013). This data was based on households within the boundaries of the City of Tampa. Multi-family household water consumption was estimated as the weighted average of buildings with less than 10 units, 10 or more units, and condominiums. The weights were determined by the composition of multifamily housing built from 2008-2012 (U.S. Census Bureau, 2013). Per-employee average daily water consumption was based on the estimations made by Nelson (2004). The water consumption values used for this study are illustrated in Figure 7.

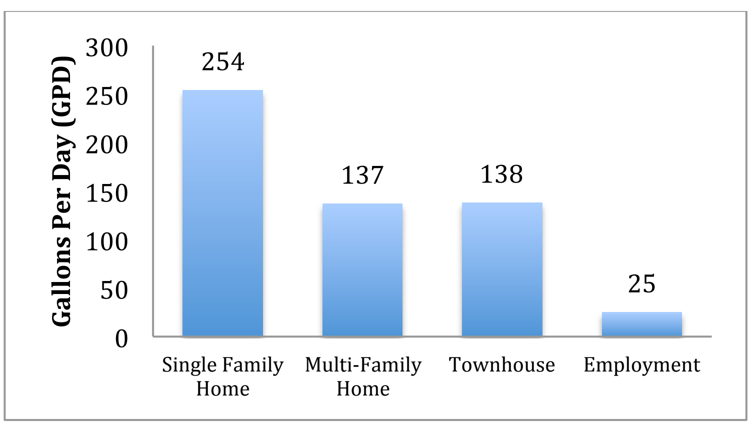

Figure 7 Per-household water consumption values for different households and employees within the city of Tampa. Note that 25 GPD for employment is per employee.

For the data points containing the number of added households and jobs in the shapefile for each scenario, the total new household water consumption was estimated using Equation (7).

$$W_R = (P_S C_S H) + (P_M C_M H) + (P_T C_T H) + (E C_E) \quad (7)$$

In Equation 8, W_R is the new household water consumption (in gallons per minute, GPM). P_S, P_M, and P_T are the percentages of added single-family households (SFH), multi-family households (MFH), and townhome households (TH), respectively. C_S, C_M, and C_T are the unitary consumption values for each SFH, MFH, and TH (GPM), respectively. H is the total amount of households added over the next 40 years. The employee water consumption (C_E, GPM) was based on the values from Nelson (2004) and assumed the same for all employment. It was multiplied by the amount of employment (E) for each data point. Once calculated, these points were summed at the nearest junction in the simplified hydraulic model. The new water consumption was then added to the existing water consumption at the same junction to create a hydraulic model for each scenario. The hydraulic model was exported to EPANET (Environmental Protection Agency, 2008b), a water distribution modeling software and then run (assuming constant demand for simplification purposes). The pumps were set at the lowest power to achieve a minimum pressure of about 50 psi at each junction.

4.3.5 Operational Embodied Energy Calculation

The operational embodied energy is defined as the energy associated with supplying a unit volume of water to users. In this study, this principally refers to the energy used to pump water throughout the distribution system per a unit volume of water used. EPANET was used to model each future water use scenario. After each simulation, the energy use per unit volume water consumed was obtained from EPANET's built-in energy analysis option. However, this value only accounted for the electricity used for pumping and not the energy used to produce the electricity. Therefore, energy use per volume of water was multiplied by an energy density of 3.49 MJ consumed/MJ produced, which is based on a cumulative energy demand analysis done in SimaPro (Amersfoort, The Netherlands) of the average mix for the United States. This same procedure was used previously to calculate the embodied energy contribution of electricity in the study by Santana et al. (2014). Annual per capita energy use and water use ware also estimated for each scenario. Per-capita water use was estimated by normalizing the total water demand in each scenario by the total future population. Per-capita energy use was estimated by multiplying the per-capita water use by the embodied energy. This metric was also used by Filion (2008) to compare the energy usage of different urban forms.

4.3.6 Demand Augmentation Analysis

To further determine the degree to which the embodied energy of drinking water is influenced by the location of extra demands, a demand augmentation analysis was conducted in which a total demand of 20 million m^3 of water per year was added over different regions of the city in addition to current demand. These regions are illustrated in (Figure 5). The operational embodied energy was calculated using the same methodology as that of the One Bay scenarios.

4.4 Results and Discussion

Figure 8 illustrates the operational embodied energies of each development scenario. Compared to 2011 embodied energy (Base, 3.30 MJ/m^3), all future development scenario embodied energies are projected to rise. The differences between the future development scenario embodied energy values seem minimal, as the largest difference (between the BAU and Preferred scenarios) is only about 4%. The Preferred scenario has the highest embodied energy, which is followed by the Compact, Green, and BAU scenarios, respectively. However, the small difference between these embodied energies could have a significant impact if water consumption is taken into consideration. For example, compared to the preferred scenario, the compact scenario consumes about 0.02 MJ/m^3 less energy. If both scenarios consume about 40 MGD, this translates into an annual difference of about 2.6 TJ, which is the equivalent of the yearly total energy consumption of 56 Florida households (Energy Information Administration, 2015).

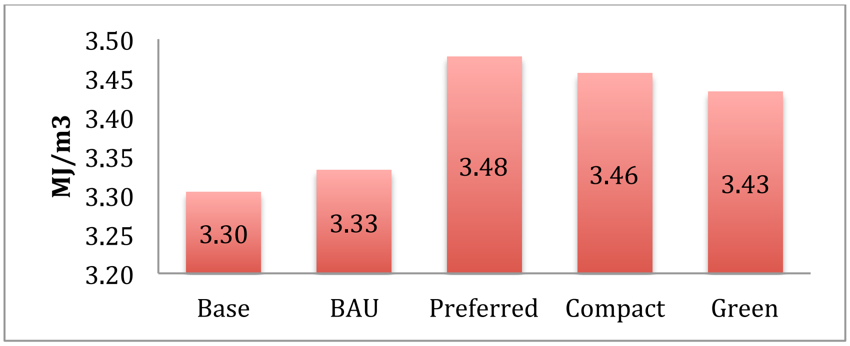

Figure 8 Operational embodied energy of water distribution in One Bay future development scenarios in the Tampa WSA

4.4.1 Spatial Distribution of Embodied Energy

The results of the demand augmentation analysis hint that location of extra demand may play a part in explaining the small differences between the future development scenarios. According to Table 7, increased demand farther away from the location of the water treatment plant raises the embodied energy of drinking water in the Tampa WSA by about up to 11%. The largest associated embodied energy value is associated with additional demand in West Tampa (3.71 MJ/m^3), which is followed by demand increases in South and North Tampa, while Central, Downtown Southwest Tampa have (5-10%) lower embodied energy values. The higher embodied energy values are mostly due to the extra energy needed to transport water a longer distance while ensuring a minimum pressure of about 50 psi.

Table 7 Embodied energy values of different demand augmentation scenarios

Region of Tampa	Embodied Energy (MJ/m^3)
Central	3.33
Downtown	3.38
North	3.50
South	3.52
Southeast	3.34
West	3.71

The percentage of added demand relative to the base 2011 demand for each future development scenario in each augmentation area is presented in Figure 9. The highest proportional increases in demand are in the Southeastern region and Downtown. The Southeastern section of the Tampa WSA is currently suburban in character, yet still has a fair amount of green space. Therefore, this is also prime land for future development, evidenced by the high demand increase percentages from 136-168%. Currently, the addition of more jobs and residences downtown also results in demand increases for each scenario that range from 63-168% of the 2011 demand. The lowest demand increase values are associated with South Tampa (0-45%). This area contains dense, historic neighborhoods that are generally built-out, which can explain the relatively lower amount of growth in demand in the area (Florida Center for Community Design and Research, 2015).

When comparing scenarios, demand increases in the smart growth scenarios (“Preferred”, “Compact”, and “Green”) tend to be higher than those of the BAU scenario. This can be seen in the West, Downtown, Central, and South regions of the Tampa WSA (see Figure 5). The main reason for this could be the quantity of households and jobs that are added to the WSA in the BAU scenario, which are about a quarter to one-third of that added to the smart growth scenarios (BAU scenario development is mostly outside of the Tampa WSA). Based on the results from the demand augmentation scenarios, the differences in the South and West regions of the WSA may be responsible for the relatively higher embodied energies in the smart growth scenarios compared to the BAU scenario. In the western region, the BAU scenario increases the demand by about 42%, which is substantially lower than the percentage increases associated with the smart growth scenarios (75-114%). In the southern section of the Tampa WSA, the BAU scenario adds almost no new housing or employment due to the lack of space for single-family homes. Nevertheless, the smart growth scenarios project demand increases of 41-45%, due to the addition of predominantly multi-family housing. The highest demand increases in the BAU scenario occur in Southeast with an expected demand increase of about 136% most likely due to the availability of land for development of single-family households. However, this increase is still smaller than the 139-160% increases associated with the smart growth scenarios. Also, based on the demand augmentation scenario, additional demand in the Southeast Tampa WSA has a negligible impact on the embodied energy.

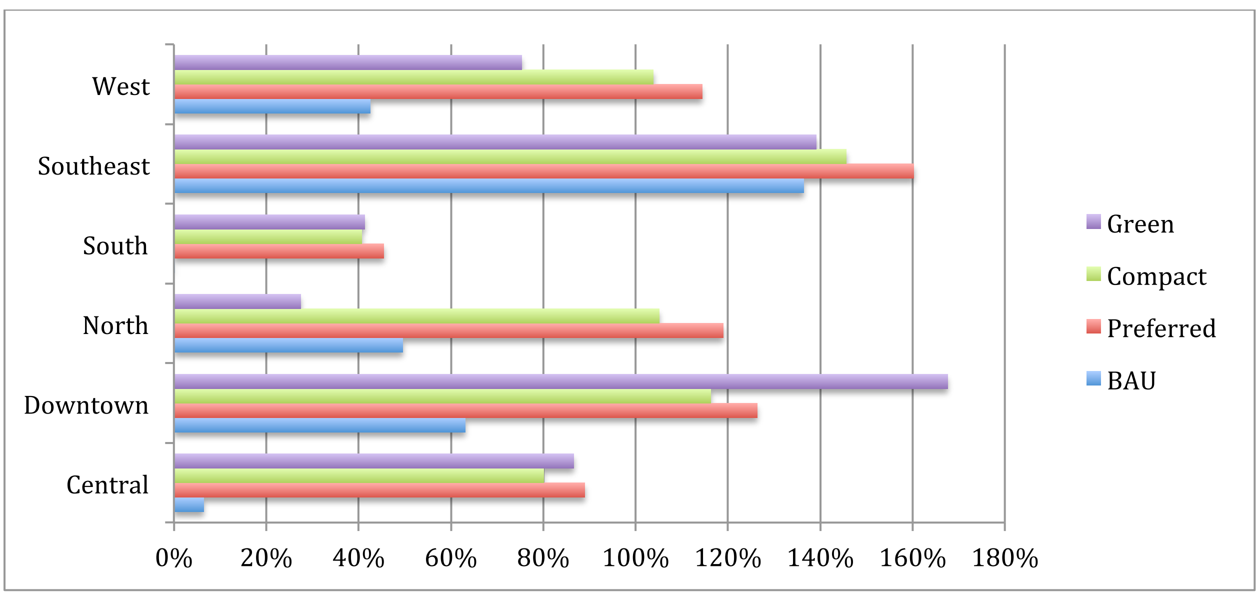

Figure 9 City of Tampa Water Service Area water demand percentage increases in each region by future growth scenario relative to 2011 consumption

Between smart growth scenarios, embodied energy differences may also be explained by the comparison of additional demands. For example, the Preferred scenario has consistently higher demand increases than the Compact scenario. This is mainly due to housing composition as both scenarios add a similar number of households and jobs in the same areas. In the preferred scenario, 50% of housing was classified as multi-family compared to the 59% of the Compact scenario. According to a report by Hazen and Sawyer (2013), in the city of Tampa, average multifamily housing water use is about 50% of that of single-family homes. The comparison with the Green scenario is more complex as the scenario projects the highest demand increase downtown (168%) while adding the least demand in the northern section of the Tampa WSA (27%). The lower embodied energy of the Green scenario compared to the Preferred and Compact scenarios may be attributed to the lower additional demands in the northern and western regions of the Tampa WSA, as overall embodied energies in these regions are more sensitive to additional demand.

4.4.2 Per-Capita Embodied Energy

Figure 10 compares the per-capita energy and water usages associated with water supply in the Tampa WSA. The per-capita embodied energy is defined as the product of the scenario's embodied energy and the per-capita water use. The Preferred scenario has the highest per-capita energy use (359 MJ/person/year) while having the second highest water usage (103 m^3/person/year). Conversely, the Compact scenario has the lowest per-capita energy and water usage (340 MJ/person/year, 98.6 m^3/person/year). The differences in both energy and water usage are minimal as the largest difference between value (Preferred vs. Compact) is about 5%. However, this comparison also shows how both energy density and water consumption influence per-capita embodied energy use. For instance, the difference between the Preferred and Compact scenarios is mainly due to household water consumption. About 36% of households in the Compact Scenario are single-family homes, compared to 44% in the Preferred Scenario. In Tampa, single-family homes use almost twice the amount of water as multifamily homes, thus translating into a lower per-capita water use, and subsequently, energy use.

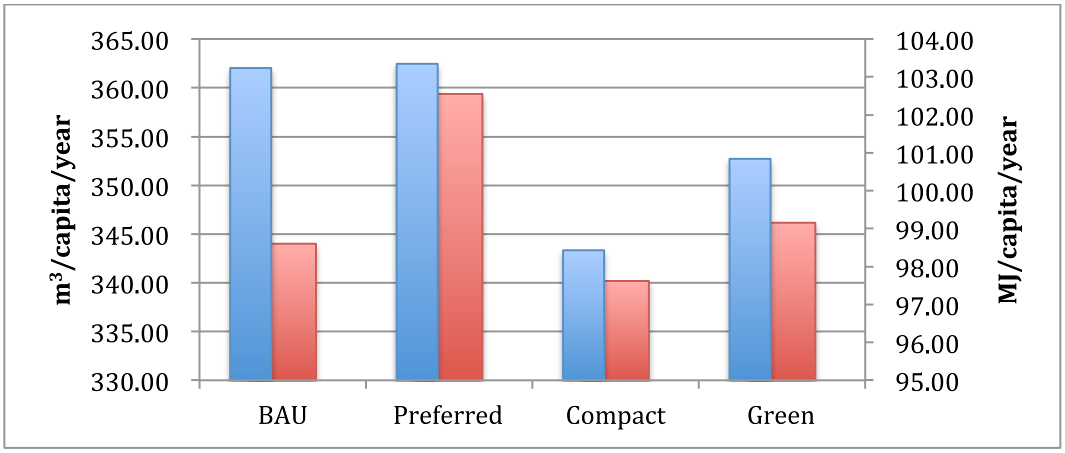

Figure 10 Per capita embodied energy (red) and water use (blue) by Tampa Water Service Area future development scenario

Another notable result is the BAU Scenario's relatively high per-capita water use (103 m^3/person/year) is slightly below that of the Preferred Scenario. This result is unexpected as about 60% of households in the BAU Scenario are classified as single-family, which on average consume about twice as much water as multifamily homes and townhouses, while the percentage is 44% for the Preferred Scenario. This discrepancy is attributed to the water consumption due to added employment. The new employment demand of the BAU scenario (4.6 million m^3/year) is only a little over 1/3 the amount of total demand from employment compared to the Preferred Scenario (12.2 million m^3/year) as shown in Table 8. Since the employment demand is also normalized by the total population, it is responsible for the higher per-capita water demand associated with the Preferred Scenario, and to a degree, with the lower relative decreases in per-capita water usage of the Compact and Green scenarios, compared to the BAU scenario. Smart growth scenarios project the concentration of more development in existing urban areas, hence the addition of more jobs within the Tampa WSA. By excluding new employment consumption (which ranges from 6-11% of total water consumption), the Preferred, Compact, and Green scenario per-capita water use values are 5%, 10 %, and 6% lower than the BAU scenario, respectively.

The BAU scenario also has the second lowest per-capita energy use (344 MJ/person/year). In this context, the relatively low embodied energy value associated with the BAU scenario (3.33 MJ/m^3) compensates for the higher per-capita water use value, thus resulting in a per-capita energy use for the BAU scenario that is lower than that of the Preferred and Green scenarios. Only the Compact scenario is lower by a percentage of about 1.1%. However, by excluding new employment water consumption, the BAU scenario maintains a higher per-capita energy usage compared to the Preferred, Compact, and Green scenarios which are associated with decreases of 0.5%, 6.2%, and 3.2%, respectively.

Table 8 Breakdown of the total water consumption associated with each scenario

	BAU	Preferred	Compact	Green
Base Demand (m^3/year)	55,536,026	55,536,026	55,536,026	55,536,026
New Employment (m^3/year)	4,584,293	12,215,904	12,030,518	9,932,099
New Single Family (m^3/year)	11,503,287	20,792,811	9,097,908	13,442,962
New Multi-Family (m^3/year)	5,005,380	25,868,104	32,810,104	22,862,566
New Townhomes (m^3/year)	76,078	2,473,386	1,763,136	2,044,757
Total Population	742,900	1,131,091	1,129,866	1,029,542

A previous study compared the energy use theoretical distribution systems of distinct urban forms (Filion, 2008). Each theoretical urban form scenario had an operational embodied energy (due to pumping) of about 468 MJ/person/year (assuming an energy density of 3.49 MJ/MJ). The total water consumption in each scenario was also the same, while differences were in the layout of the water distribution systems and the population densities at the consumption nodes (which drove water consumption). In contrast, each scenario in this study relies on the same distribution system layout, while the areas of increased water consumption were varied based on projected future water consumption patterns, resulting in different amounts of the total water use within the Tampa WSA.

4.4.3 Smart Growth and Drinking Water

In the case of the drinking water in the Tampa WSA, smart growth with respect to urban layout may or may not make a significant difference in terms of embodied energy. While the BAU scenario projects more single-family home development at the northern and eastern margins of the city, the increased consumption in these areas does not affect the overall embodied energy any differently than the smart growth scenarios, which estimate more growth in the southern and western parts of the Tampa WSA. More energy is needed to transport water to the northern, southern, and western regions of the WSA, which are relatively farther from the Tippin WTF. Therefore, the embodied energy value is sensitive to significant increases in development in the Southern region of the Tampa WSA. As a result, in terms of water distribution and the embodied energy of water, distance from the treatment plant plays a more important role than the implementation of smart growth.

With respect to water use, the Compact scenario modeled by One Bay shows a relatively lower per-capita water use energy use than the BAU scenario. This is primarily because of differences in composition of housing types and the amount of jobs added in each scenario. Generally, single-family homes consume, on average, twice the amount of water as multi-family households (254 vs. 137 GPUD). However, the number of jobs added moderates much of this decrease between scenarios. As a result, the Compact Scenario only projects a 5% decrease in per-capita water use, and a 1.1% decrease in per-capita energy use relative to the BAU scenario.

A more smart-growth-oriented planning paradigm that just focuses on residential water use for the Tampa WSA shows decreases in per-capita water and energy use, relative to the BAU scenario, up to about 10%, and 6.2 respectively. Therefore, the second principle of smart growth, compact design (see Table 2), must be aggressively implemented to residential water use so as to offset additional water use due to employment in order to minimize overall per-capita residential water and energy use. Even so, if the future population is the same for each scenario (742,900 people), the Compact scenario would yield a net residential water energy savings of 2.8 TJ/year. This is equivalent to the average yearly energy consumption of about 60 households in Florida (Energy Information Administration, 2015).While drinking water distribution is energy intensive and, in many conventionally based drinking water treatment systems, the highest energy contributor, when integrating the energy associated with indoor water use, the embodied energy is significantly lower. For instance, according to a report by the Energy Information Administration (EIA), the average household in Florida dedicates about 8.1 million BTU annually to water heating for uses that include showering, dishwashing and washing clothes (Energy Information Administration, 2013). Normalized by an average total household water use of about 199 gallons per day, the embodied energy of water heating is approximately 108 MJ/m^3 of total water used (heated and unheated). By integrating the results from this study and Santana et al. (2014), distribution and treatment together account for only 6% of the total embodied energy when including indoor water related energy use. Therefore, any improvement in the operational embodied energy of drinking water distribution will have only a minimal effect on the total embodied energy of drinking water. Still, a minimization in total water use due to smart growth may result in the avoidance of energy used to heat water. If each scenario results in the same future population (742,900 people), the Compact and Green Scenarios will avoid the use of 386 TJ and 192 TJ of energy per year due to heating, respectively. This savings is equivalent to the annual energy consumption of about 8,200 and 4,100 Florida households, respectively.

4.5 Conclusions

While smart growth has been shown to result in lower greenhouse gas emissions and in some cases less water use (Guhathakurta & Gober, 2007; Harrison et al., 2012; Runfola et al., 2013; Lee & Lee, 2014; Nahlik & Chester, 2014), in terms of water distribution energy use, smart growth has a minimal effect on the energy associated with drinking water treatment and supply. Instead, the distance of additional demand from the water treatment facility location plays a more prominent role in determining the embodied energy. Nevertheless, smart growth also results in possible water savings, as demonstrated by lower per-capita water consumption and energy use (Compact scenario) in development scenarios that tend toward smart growth due to housing composition. Hence, the second principle of Smart Growth (see Table 2) or compact development can result in a decrease in the energy, which can even be greater when taking into account the energy avoided by heating less water. Therefore, in order to maximize the energy savings from smart growth, proximity to the water treatment facility should also be considered in choosing the location of new development in addition to a radial water distribution layout.

CHAPTER 5: EMBODIED ENERGY SAVINGS THROUGH WATER DISTRIBUTION INFRASTRUCTURE MAINTENANCE

5.1 Abstract

In 2013, the American Society of Civil Engineers (ASCE) gave the nation's infrastructure a D. This low grade has serious implications not only for the safety of water infrastructure, but also the efficiency, as poorly maintained pipes require more energy to transport water. Therefore, this study aims to determine how operational embodied energy is affected by the condition of water distribution infrastructure in the city of Tampa Water Service Area. To carry out this study, the current water distribution system was modeled using GIS software and EPANET. Next, fifteen alternative pipe replacement scenarios were modeled and simulated. The embodied energies of all scenarios were compared. Results show that by replacing all pipes in the Tampa WSA, the embodied energy decreases by about 20%. When replacing categories of pipes per unit length, larger and older pipes save more energy. However, when incorporating the energy used to manufacture, transport, and install the pipes, pipe replacement with recycled ductile iron was able to yield a net savings in energy when replacing pipes over at least, 20 years old.

5.2 Introduction

In 2013, the American Society of Civil Engineers (ASCE) gave the nation's drinking water infrastructure a D grade due to its age and condition. Much of this infrastructure is nearing the end of its useful life. From the time the pipes, pumps, and tanks are installed, they begin a gradual deterioration process that results in a useful life of 15 to 95 years. In addition, it is estimated that there are 240,000 water main breaks per year in the US and in response, 4,000-5,000 miles of water distribution pipe are replaced annually (American Society of Civil Engineers, 2015).

Leakage, failure, and pipe deterioration in water distribution systems have a diverse range of causes. Gradual buildup of scale-forming deposits, such as calcium carbonate or aluminum silicate on the inside of pipes, can increase pipe roughness and thus constrict and even impede the flow of water (National Research Council, 2006). The water inside of the pipe and the soil surrounding the pipe can aid in corroding the pipe materials; thus, making them more prone to leaks (Reid, 2004). Operation of the distribution system can also play a role in causing wear and tear of the piping system. Sudden valve closures or pump deactivation can lead to drastic changes in pressure as well as water flow (known as water hammers). Cumulatively, these changes exert a strain on piping, causing cracking, leakage, and even failure (National Research Council, 2006).

Converting raw water from a groundwater or surface water source to a safe commodity that can obtained from a tap requires the use of pumps, treatment process equipment, chemicals, and distribution infrastructure, all of which consume energy (Baldasano-Recio et al., 2005; Ghimire & Barkdoll, 2007). This energy use that is derived from all these requirements is referred to as the embodied energy and consists of direct and indirect energy. Direct energy refers to the onsite energy usage, such as electricity use from pumping or fuel use from heating. Indirect energy use is defined as the “offsite” energy use (i.e. manufacturing of treatment chemicals and infrastructure materials) (Mo et al., 2011; Santana et al., 2014).

Previous studies have been able to quantify the drinking water embodied energies for different cities and regions. Lundie et al. (2004) conducted a life cycle assessment (LCA) for the Sydney, Australia metropolitan area drinking water system and estimated an energy use of about 5.2 MJ/m^3 water consumed. Mo et al. (2011) compared the drinking water embodied energies of Kalamazoo, Michigan and Tampa, Florida using a hybrid life cycle-input/output assessment and found values of 10.4 and 10.8 MJ/m^3, respectively. (Stokes & Horvath, 2010) used an energy and emissions estimation software called WEST to calculate an embodied energy of 5.4 MJ/m^3 for the region of Northern California. Amores et al. (2013) also used LCA to quantify different water management scenarios for the city of Tarragona, Spain and found that water-related energy use falls between 14.1-28.5 MJ/m^3. Meanwhile, the LCA by Del Borghi et al. (2013) estimated that the island of Sicily uses between 45.2-54.1 MJ/m^3 water used.

Drinking water management consists of three steps: collection, treatment, and distribution. Embodied energy contributions of each step depend on factors such as the water source, the treatment used, and the layout of the distribution system. Of the studies that have quantified the embodied energies of all three steps, distribution is responsible for most of the drinking water's embodied energy for systems reliant of conventional treatment systems (Lundie et al., 2004; Amores et al., 2013). However, when desalination is incorporated into the system, treatment becomes the highest contributor (65-81%) to overall drinking water embodied energy (Amores et al., 2013; Del Borghi et al., 2013).

Due to the significant energy consumption of water distribution systems, previous studies have also exclusively focused on their energy use. Lundie et al. (2004) estimated that distribution would require 3.6 MJ/m^3 water used. Meanwhile Amores et al. (2013) calculated that 7.7 MJ/m^3 would be needed for a 354 km distribution system in Tarragona (Spain). Studies have looked at the factors that affect distribution system energy use. Filion et al. (2004) carried out a life cycle energy assessment (LCEA), and compared the resultant embodied energies of New York City's distribution system based on pipe replacement schedules of 10, 20, 50, and 100 years. The study concluded that pipe replacement every 50 years results in the lowest embodied energy value (0.1 MJ/m^3 compared to 0.42 MJ/m^3 every 10 years). Another study observed the effect of urban form on embodied energies of theoretical water distribution systems and demonstrated that centrally dense, radially-oriented distribution systems consumed less energy based on a reduction in the energy used for pipe maintenance (Filion, 2008).

The most prominent cause of energy use in the water distribution system is pumping. According to Filion (2008), pumping was responsible for at least 83% of the total embodied energy in the theoretical water distribution systems modeled in the study. When pumping water from the plant to the user, the energy used by the pump must be enough to overcome the friction in the pipe, minor losses (i.e. bends and turns), elevation differences, and pressure maintenance within the system (Linsley et al., 1992). One study estimated about 85% of energy is used for pressure maintenance, while 7% is due to pressure reduction (i.e. valves and tanks), and 8% is due to friction and minor losses (Boulos & Bros, 2010).

An aging distribution system may affect the energy needed to transport water from the water treatment plant to the user. Pipes clogged with scale require more energy to overcome friction and ensure a minimum pressure. Corrosion of pipes may lead to increased water losses and means more pumping energy to maintain the same pressure. Over time, the occurrence of water hammers may cause more leaks throughout the distribution system. Therefore, an aging system not only translates into more water losses and inconveniences, but also more energy usage per unit volume of water used. This study will determine the effect of aging infrastructure as well as infrastructure improvements on the embodied energy of water in the city of Tampa and outlying areas. The results will be useful to water utilities to better understand the energy implications of maintaining water distribution infrastructure.

5.3 Materials and Methods

5.3.1 Site Description

This study focuses on the City of Tampa Water Service Area (Tampa WSA), which includes the city of Tampa as well as outlying areas. The water infrastructure of this entire geographic area is managed by the City of Tampa. Water is sourced from the Hillsborough River Reservoir and subsequently treated at the David L. Tippin Water Treatment Facility (Tippin WTF). The treated water is distributed to the approximately 588,000 users via a 134,000-pipe water distribution system.

5.3.2 Data Requirements and Processing of the Hydraulic Model

Water use, water distribution, and land use data were used to create the hydraulic model needed to simulate the Tampa WSA distribution system (Table 9). Water use data were obtained from Tampa Bay Water's GOVNET database. This database is used to track monthly water consumption for all of Tampa Bay Water's member jurisdictions including the city of Tampa (Florida). The City of Tampa also provided a geographic information systems (GIS) shapefile of the Tampa WSA water distribution system. In addition to the layout, the lengths, materials, and diameters of the pipes were included in the file.

The water distribution system GIS shapefile was exported from ArGIS (Redlands, California) to a water distribution modeling software called WaterGems (Exton, Pennsylvania) for the creation of a network of pipes and junctions. For the subsequent exportation of the distribution system file to EPANET (Environmental Protection Agency, 2008b), a water distribution system modeling software, the existing file must be simplified as large network files can significantly slow down the software. Therefore, the skelebrator tool in WaterGems was used to consolidate pipes running in series and in parallel to each other. Further simplification of the system was carried out by eliminating all pipes with a diameter of less than 8 inches due to the inability of the skelebrator tool to consolidate enough pipes to simplify the system to less than 1,000 pipes. Consequently, the water distribution system was simplified from 134,000 to about 900 pipes and about 669 junctions.

Table 9 Data needed to carry out study

Type of Data	Source	Description
Water Use	Tampa Bay Water	GOVNET, a spatially oriented database that tracks the monthly water consumption amounts of accounts within the jurisdictions of Tampa Bay Water
Water Distribution	City of Tampa	GIS file of the water distribution system for the City of Tampa Water Service Area
Land Use Data	Hillsborough County Property Appraiser	Parcel-level property data for all properties within Hillsborough County

Water consumption data were then added to the simplified distribution system file using ArcGIS. Using a proximity function in ArcGIS, the 2011 annual water use at parcels, representing accounts in GOVNET, was aggregated at nearby junctions in the simplified ArcGIS water distribution file. Water use data from this year was chosen as it is the last year for which the total annual water consumption data was collected. The resultant junctions, pipe, reservoir, and pump shapefiles were then combined and exported to the water distribution system modeling program EPANET (Cincinnati, Ohio). These demands were assumed to be constant for simplification purposes.

5.3.3 Pipe Roughness and Leakage Estimation

Due to the lack of the date of pipe installation within the base water distribution shapfile, pipe ages were estimated using parcel level land use data from Hillsborough County Property Appraiser (HCPA). The average actual age of all buildings was calculated within each 2010 census block group within the Tampa WSA. Pipes were then assigned ages based on the locations of their midpoints within the corresponding census block group boundaries. Using ArcGIS, the roughness was then calculated by integrating the pipe ages into an equation used by Filion et al. (2004) that linked pipe age to Hazen-Williams C-Factor, shown in Equation (8).

$$C = 18.0 - 37.2log\left(\frac{e_0 + \alpha t}{D}\right) \tag{8}$$

In Equation (8), C (unitless) is the Hazen-Williams roughness value, e_0 (mm) is the height of the wall roughness at time t=0, α is the wall roughness growth rate (mm/year), t (years) is the age of the pipe, and D (mm) is the diameter of the corresponding pipe. For the purposes of this study, e_0 was set to 0.18 mm and α was set at 0.16 mm based on suggestions by Walski and Sharp (1988). The system was assumed to be comprised of ductile iron piping because approximately 84% of the Tampa WSA distribution system piping was reported as ductile iron.

Pipe leakage is due to many factors including: age of the pipe, surrounding geology, connection to other pipes, and operation of the system. However, specific leakage information for each pipe in the Tampa WSA distribution system was unavailable. Therefore, a leakage allocation method designed by Ainola et al. (2000), for integration in EPANET, was used based on the assumption that leakage is mainly influenced by the age and diameter of the pipe as well as the pressure within the pipe. This explanation is feasible since deterioration-influencing factors (i.e. scale, corrosion, water hammers) are assumed to have a gradually larger effect on the system with time. In EPANET, the leakage at each junction (where demand occurs and pipes join) is calculated via the emitter coefficient. This method calculates the emitter value for each junction in the EPANET file.

To allocate leakage, first, all pipes were split at their midpoints by addition of A-junctions, where no consumption would occur. Demand junctions will be referred to as J-junctions. Next, the pipe diameter factor d (unitless) the pipe age factor (x, unitless) the pipe length (from the J-junction to the A-junction), L (m), and the pressure at the water use junction, I (psi), connected to the pipe were inputted into Equation (9) and summed for each junction via a MATLAB m-file. This resulted in the junction's leakage allocation number, Q^*, which is calculated as follows:

$$Q^* = \sum_{j=1}^{N_i} x_j L_j p_i \tag{9}$$

The Q^* value for each junction within the system was then summed and inputted in Equation (10) with the total leakage value, k (GPM), in order to calculate the leakage factor, c (unitless). For the purposes of this study, the k value was set to 17% of total flow based on a previous estimation of the Tampa WSA leakage rate (Gedalius, 2007).

$$c = \frac{k}{\sum Q^*} \tag{10}$$

Next, the values of L_j, d_j, a_j, and the resultant c values for each pipe j were multiplied. The resultant product was summed for all pipes j connected to J-junction i. The result was an emitter coefficient, E (unitless), for each junction i, where consumption occurs. This is illustrated by Equation (11).

$$E = \sum_{j=1}^{N_i} ca_j L_j \tag{11}$$

5.3.4 Scenario Creation and Embodied Energy Estimation

Sixteen pipe replacement scenarios were created based on replacement by pipe diameter and age. The scenarios were created to determine the significance in terms of embodied energy reduction of the replacement of certain pipe characteristics. The diameter-based scenarios were cumulative and non-cumulative, while the age based scenarios only accounted for replacement of pipes within certain designated age ranges. A MATLAB program was used to change the roughness of pipes that fulfilled the criteria in Table 10 to the roughness value of newly installed ductile iron pipe.

Table 10 Tampa Water Service Area pipe replacement scenario descriptions

Scenario	Description
Base	No pipe replacement
Over 40	Replacement of all pipes with a diameter of 40 in or over
Over 30	Replacement of all pipes with a diameter of 30 in or over
Over 20	Replacement of all pipes with a diameter of 20 in or over
Over 16	Replacement of all pipes with a diameter of 16 in or over
All New	Replacement of all pipes
<12	Replacement of all pipe with a diameter of 12 in or less
12-16	Replacement of all pipes with a diameter between 12 and 16 in
16-20	Replacement of all pipes with a diameter between 16 and 20 in
20-30	Replacement of all pipes with a diameter between 20 and 30 in
30-40	Replacement of all pipes with a diameter between 30 and 40 in
Over 20 years	Replacement of all pipes under 20 years old
20 to 40 years	Replacement of all pipes between 20 to 40 years old
40 to 60 years	Replacement of all pipes between 40 to 60 years old
Over 60	Replacement of all pipes over 60 years old

Each scenario was run in EPANET. Once finished, the pumping power was collected for each scenario and normalized by the base demand. The resultant energy per unit water use value was then multiplied by an energy density factor, taken from SimaPro (Amesfoort, the

Netherlands), which takes into account the upstream energy requirements to produce the energy needed for pumping, to estimate the operational embodied energy in the system. For the US energy mix, this value is 3.49 MJ/MJ produced. This method was also used to calculate the electrical energy use in the studies by Racoviceanu et al. (2007) and Santana et al. (2014).

5.3.5 Energy Payback Period

The energy saved by pipe replacement must also cover the energy used during the pipe replacement process for there to be a net benefit. The amount of time needed for the savings (due to less energy being used during operation) to equal the amount of energy used during pipe replacement is referred to as the Energy Payback Period or T_P (years). This estimation is presented in Equation (12):

$$T_P = \frac{E_F E_T E_I d}{W_c(E_E - E_N)} \tag{12}$$

E_F, E_T, and E_I refer to the pipe fabrication, transport, and installation energies (MJ/mi of pipe), respectively. These values are multiplied by the total distance of pipe that is being replaced (d, mi). Distances were obtained from the original water distribution system file provided by the City of Tampa Water Department, as it reflects the true amount of pipe replacement needed in each scenario. W_C is the volumetric water consumption in a year (m^3/year). E_E and E_N are the original and new (after pipe replacement) embodied energies (MJ/m^3). For the purposes of this study, the 2011 water consumption value was used as W_C, as this was the most recent year that GOVNET full year water consumption available.

5.4 Results and Discussion

A comparison of the cumulative pipe replacement scenario operational embodied energies by diameter is presented in Figure 11. This figure shows that by improving all of the pipes, the embodied energy can be lowered 3.99 to 3.26 MJ/m^3 (about 18%). By just updating all of the pipes with a diameter of 20 inches or greater, the embodied energy decreases from 3.99 to 3.73 MJ/m^3 (9% compared to the base case). Insignificant amounts of change in embodied energy are associated with the modification of all pipes with diameters higher than 30 or 40 in. This is possibly because in the "Over 40" scenario, only 28 pipe segments (3.7 miles of pipe) were changed, while in the "Over 30" scenario, about 116 pipe segments (11 miles) were modified out of a total of 1,969 segments (984 pipes) in the simplified network. This is comparable to the 474 pipe segments (31 miles of pipe) that were changed in order to obtain a difference of about 7% from the base "Real Age" scenario. A larger amount of replaced pipe segments would decrease the amount of leakage from the system, resulting in less energy losses and a lower embodied energy.

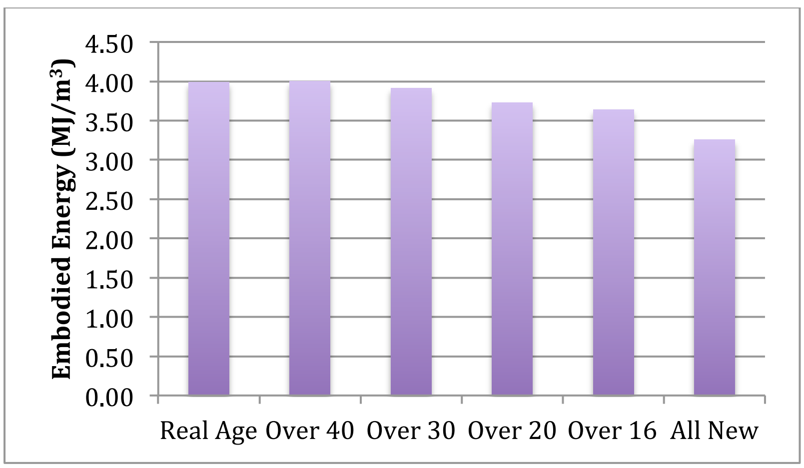

Figure 11 Comparison of operational embodied energies between cumulative pipe update scenarios

Most energy loss in the "Real Age" scenario is due to water losses from leakage. When the scenarios were run without incorporating leakage, the maximum embodied energy savings in the "All New" scenario was only 4%. Therefore, friction losses in the Tampa WSA account for only a small part of energy losses. This is supported by Boulos and Bros (2010), who estimated that only about 7% of total energy losses in a water distribution system are due to friction losses, compared to the 85% of losses due to the maintenance of pressure in the system.

Table 11 compares the resultant operational embodied energies after the replacement and modification of pipes within different diameter ranges. The largest decrease in embodied energy relative to the “Real Age” scenario is the replacement of all pipes under a diameter of 12 inches. In this case, almost half of the pipes in the simplified system are in this category. Therefore, the energy savings is due to the avoided combined leakages of this large amount of pipes in addition to friction, as smaller pipes tend to have higher headloss. The second largest embodied energy decrease (4%) is associated with the replacement of pipes within the 20-30 in diameter ranges. This is double the projected decrease in embodied energy associated with updating pipes with diameters of 12-16 in. The primary reason for this discrepancy is leakage as the model calculates that leakage is more likely to increase with pipes with a larger diameter.

Table 11 Comparison of operational embodied energies of the Tampa Water Service Area with respect to replacement of pipes within designated diameter ranges

Pipe Diameter Range (inches)	Operational Embodied Energy Value (MJ/m^3)	Pipe Energy Savings ($kJ/m^3/mi$)
D <12	3.64	5.45
D 12 to 16	3.90	3.94
D 16-20	3.91	7.76
D 20-30	3.83	7.56
D 30-40	3.93	8.06
D >40	3.95	9.44

Normalization of embodied energy savings by pipe distance helps show the relative impact of each pipe segment. For instance, the replacement of a 1500-ft segment of pipe with a diameter between 30 to 40 inches and an average flowrate of about 2800 gallons per minute (GPM) could translate into an energy savings of 13,000 MJ per year, which is about one-fifth the yearly consumption of a household in Florida (Energy Information Administration, 2015). According to Table 11, the replacement of pipes with larger diameters implies higher energy savings. This prevents a higher leakage volume, as pipes with larger diameters are prone to a larger volume of leakage when failure occurs.

Pipe replacement scenarios by pipe age indicate that the greatest embodied energy savings are associated with replacement of all pipes between 20-40 and 40-60 years old (Table 12). This is mainly an issue of quantity, as 37% of pipes in the project are within each age range. However, normalization of embodied energy savings by pipe length shows that replacement of pipes over 60 years old have the largest energy savings per mile of new pipe added. This is explained by the increases in roughness as well as vulnerability to leakage or failure associated with older pipes. Both of these characteristics of pipe deterioration require increased pumping energy due to higher friction in the system and possible water losses, respectively. Therefore, the older the pipe being replaced, the more embodied energy savings due to the gradual increase in energy used to transport water through the pipe as the pipe ages.

Table 12 Comparison of operational embodied energies by pipe replacement scenario by age

Pipe Age Range (years)	Embodied Energy (MJ/m^3)	Pipe Replacement Savings (kJ/mi)
Y <20	3.93	2.82
Y 20-40	3.72	5.77
Y 40-60	3.70	6.07
Y >60	3.88	7.87

In theory, the replacement of the oldest and largest pipes (by diameter) results in the greatest energy savings per unit length of pipe. Based on the leakage model, older pipes not only have higher friction factors, but are also more prone to leakage and eventual failure. Therefore, more pumping energy is required to not only overcome the friction within the pipe but also compensate for the water lost to leakage. In terms of pipe size, larger pipes, when they crack or fail, tend to leak higher volumes of water, resulting in more lost energy. Taking this into account, Figure 12 shows the areas that would be most advantageous to improve from an embodied energy saving prospective. The census block groups highlighted in red contain pipes that are over 60 years old and have a diameter of 30 in or higher. These pipes are located in the middle of the Tampa WSA near the Tippin WTF and are most likely responsible for transporting large amounts of water from the plant to the downtown Tampa, and Southern and Western sections of the Tampa WSA. This consists of 8 miles of pipe total, which could mean a total decrease of about 62.4 kJ/m3, which would mean a 2% decrease in the embodied energy value from the base scenario.

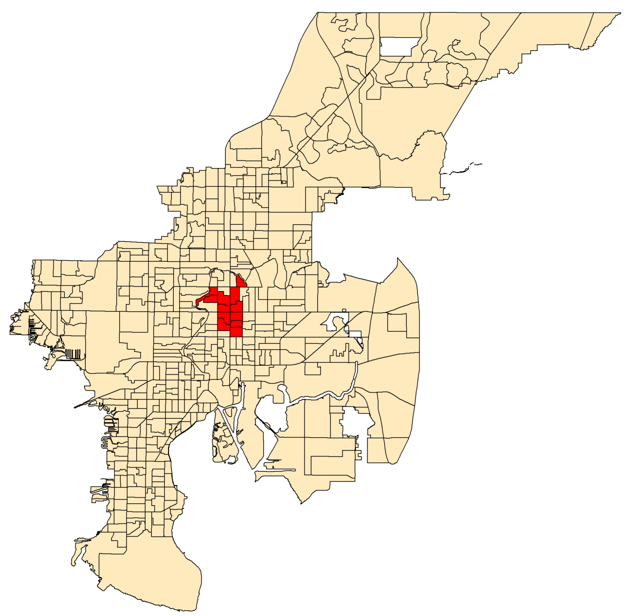

Figure 12 Census block groups with pipes that are over 60 years old with diameters of at least 30 inches in the City of Tampa Water Service Area

Results of a spatial embodied energy analysis (see Appendix C for more details) show the importance of distance from the water treatment facility compared to age of the pipes in terms of determining the embodied energy (Figure 13 A and B). The highest decreases in embodied energy when comparing the "Real Age" and "All New" scenarios are located in several census block groups located close to downtown Tampa and in the western part of the Tampa WSA. While these census block groups are not far from the Tippin WTF (approximately 14.5 km), they are located in areas where the buildings are generally older. The southern region of the Tampa WSA reports the highest decreases generally. In addition to being an area with older infrastructure, it is also located far from the water treatment plant. As a result, any deterioration in pipes in this area will be amplified by higher energy use needed to supply water to the area based on the location of the area relative to the water treatment facility. However, in the areas surrounding the water treatment plant (6 km radius) and the southeastern corner of the Tampa WSA, the decrease in embodied energy is the lowest despite the older average age of the pipes in certain census block groups. This shows that places located closest to the water treatment facility can withstand a higher degree of deterioration compared to those located farthest from the plant.

Compared to the "Real Age" scenario, all pipe scenarios incur an embodied energy savings. For instance, after one year of operation, energy savings ranged from 1.9 to 40 TJ of energy. This is the equivalent of the annual energy usage of 42 to 870 houses in Florida (Energy Information Administration, 2015). However, this energy usage does not take into account the energy used during the fabrication, transport, and installation of the new pipe. Therefore, assuming that all new piping is ductile iron, pipe embodied energy values were taken from a study by Baldasano-Recio et al. (2005), which estimated the embodied energy and greenhouse gas emission values of 3-meter pipe sections of concrete, PVC, HDPE, and ductile iron pipe lengths. For the purposes of this study, pipe replacements were assumed to be exclusively with either non-recycled or recycled ductile iron. Embodied energies of (including fabrication, transport, and installation) were 157 and 47 MJ/in of pipe, respectively. Consideration of these values was included in the estimation of the energy payback period. Figure 14 compares the payback periods (in years) of the different pipe replacement scenarios, when the piping is replaced with non-recycled and recycled ductile iron. Replacement of pipes with recycled ductile iron results in a shorter payback period than replacement of all pipes with non-recycled ductile iron. This is explained by the fact that upstream processes for recycled ductile iron consume about 70% less energy than those for non-recycled ductile iron.

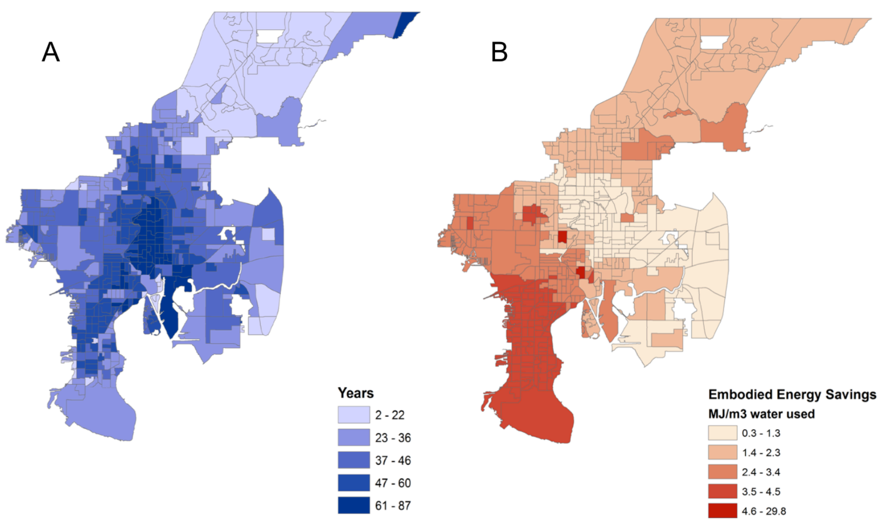

Figure 13 (A) Actual age of buildings and (B) embodied energy change (between “Base” and “All New” scenarios) by census block group in the Tampa Water Service Area

In terms of replacing pipes based on diameter, all energy payback periods, for recycled ductile iron, were less than 5 years with the exception of the D < 12 scenario (25 years). However, the scenarios with shorter energy payback periods also result in smaller decreases in embodied energy compared to the “Real Age” scenario. For example, updating all pipes with a diameter of 20-30 inches with recycled ductile iron results in a decrease in the overall embodied energy of the system by 4% with an energy payback period of about 2.5 years. This is in contrast to replacing all pipes with a diameter of less than 12 inches, which results in a lower embodied energy by about 9%, yet takes about 25 years to energetically amortize.

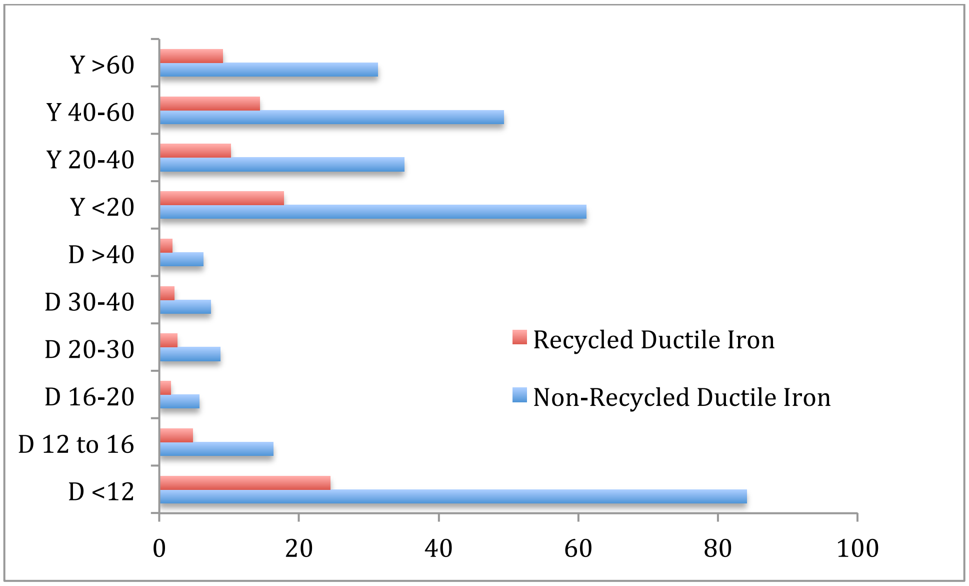

Figure 14 Energy payback periods (in years) of different pipe replacement scenarios

Age based pipe replacement scenarios generally have larger payback periods due to the amount of piping that is being replaced. However, the energy payback period needs to be less than the age of pipe being replaced for there to be a savings. For instance, the savings incurred by the replacement of 20-year old pipe must compensate for the energy used for installation of new pipe material in less than 20 years. This is the case for scenarios that replace pipe older than 20 years old. The shortest energy payback period is due to the replacement of pipe older than 60 years old, which is about 9 years. Nevertheless, there is still an energy savings when replacing pipes that are between 20-40 (10 years) and 40-60 (14 years) years old. In both these scenarios, the accompanied embodied energy decrease is 7%, which is significant.

5.5 Conclusion

Replacing water distribution infrastructure not only better ensures a safe, reliable effluent, but also can save energy in many cases. This is mainly due to the avoided leakage and, in smaller part, to friction associated with the installation of newer pipes. The energy impact of pipe replacement is also influenced by characteristics such as pipe diameter, pipe age, as well as the quantity of pipes being replaced. Older pipes are more vulnerable to failure through the gradual effects of scale, which can increase roughness, and corrosion, which can lead to leakage and even failure. Larger pipes, when they do leak, are more prone to leak higher volumes of water. Therefore, on replacement-by-distance basis, the replacement of older pipes with larger diameters yields the largest benefit.

Theoretically, replacing all of the piping in the City of Tampa Water Service Area results in an 18% decrease in the operational embodied energy (3.99 to 3.26 MJ/m^3). Based on one year of operation, this translates into a savings equivalent to the annual energy use of up to 870 Florida households. However, infrastructure improvement comes at a great energy cost. Pipe fabrication, transport, and installation are energy intensive. Therefore, when considered, replacement can end up consuming more energy than the energy saved by improving the infrastructure, resulting in a net energy loss. However, factors such as the diameter, the age, and the material being used to replace the distribution system infrastructure may help decrease the energy payback period, thus resulting in a net energy savings. For instance, from an energy perspective, the replacement of pipes older than 20 years old will have a 9 to 14-year energy payback period.

While the replacement of older pipe with recycled ductile iron yields a net energy savings, this may not be the case economically. Therefore, future studies should investigate the economic cost of improving water distribution infrastructure, mainly with respect to age, as replacement of all piping within a certain diameter would be unrealistic. The results from this and the proposed study should aid in determining an optimum pipe replacement schedule that ensures low embodied energies for distribution system operation and pipe fabrication, transportation, and installation; meanwhile minimizing the cost of this infrastructure improvement plan's implementation.

CHAPTER 6: CONCLUSIONS AND FUTURE RESEARCH RECOMMENDATIONS

The objective of this study was to understand how and to what degree urbanization affects the energy associated with water treatment and supply, otherwise known as drinking water embodied energy. A survey of the literature identified two pathways through which urbanization can affect the embodied energy of water supply. In the first pathway, urban development negatively affects the water quality of nearby bodies of water. If one of these water bodies is a drinking water source, the change in quality will influence a change in the operation of the water treatment facility, and consequently, the associated energy use of the water treatment system. In the second pathway, urbanization drives water demand, which has an energy cost, via the collection, treatment, and distribution system. Because water distribution systems run parallel to roads, urban form may also influence how distribution systems use energy due to factors such as distance and demand. Based on these pathways, these were the specific research objectives:

- Determine the effect of influent water quality on the embodied energy of drinking water treatment.
- Determine the effect of smart growth on the embodied energy of water supply.
- Determine the effect of infrastructure condition on the embodied energy of water supply.

6.1 Conclusions

Chapter 3 determined how and to what degree does the influent water quality influence the embodied energy of drinking water treatment in the city of Tampa. Statistical analysis and life cycle energy analysis were used to carry out his study. The embodied energy of water treatment in the city of Tampa was estimated to be 7.1 MJ/m^3. About 37% of this embodied energy was indirect or due to energy used for the manufacturing and transport of the treatment chemicals used in the process train. Influent water quality only affected the indirect energy or the energy used for water treatment chemical manufacturing. More specifically, constituents such as total organic carbon (TOC) and conductivity were responsible for influencing about 14% of the total embodied energy of the David L. Tippin Water Treatment Facility.

Chapter 4 addressed the second pathway relationship via a study on how smart growth influences the energy use associated with water supply or distribution. Four future urban growth scenarios for the City of Tampa Water Service Area (Tampa WSA) were simulated in a water distribution system modeling software to ultimately estimate and compare their associated embodied energies. The results obtained from this study showed only small differences between the future development scenarios. These differences were mainly due to the location and relative quantities of extra demand. For instance, the scenarios that simulated smart growth had higher embodied energies due to their larger demand increases (relative to 2011 demand) in areas that were farther away from the water treatment plant. Nevertheless, aggressively applied smart growth scenarios did result in less per-capita water usage. Also, when only taking residential water consumption into account, the Business as Usual scenario had the highest per-capita water and energy use. In summary, while smart growth can minimize overall and residential water usage, it has no observed influence on embodied energy. Instead, embodied energy is more sensitive to the location of added demand relative to the water treatment plant.

Chapter 5 documented a study that was carried out by modeling a simplified version of Tampa's water distribution system. Pipe ages and roughness were integrated into the model by estimating the average ages of the buildings in the immediate areas of the pipes. Leakage was integrated based on a leak allocation estimation method that assumed leakage water dependent on characteristics such as pipe diameter and age. Pipe replacement scenarios were simulated and their embodied energies were compared. By replacing all of the pipes in the system, the embodied energy of water supply decreased by about 18%. Most of this decrease was due to the amount of leakage avoided as opposed to the friction in the piping system. However, pipe replacement has an energy cost associated with the fabrication, transport, and installation of pipe segments. Therefore, the energy incurred by installation of ductile iron pipe, from recycled material, for pipes that were older than 20 years could be compensated by the yearly energy savings in 8-15 years, which is less than the age of the pipes being replaced.

6.2 Recommendations for Future Research

6.2.1 Urbanization and Water Quality

This dissertation has shown that influent water quality does influence the embodied energy of drinking water treatment. However, this study was unable to explain the urbanization-water quality dynamics within the Hillsborough River Reservoir Watershed. A preliminary analysis comparing water quality data and land use data within the watershed shows a correlation between conductivity and the percentage of urban land area. This relationship has been observed in previous studies. However, (1) land use and water quality dynamics are locality specific and (2) this data is inconclusive due to lack of data points. Therefore, the Hillsborough River Reservoir water quality and the land uses within the surrounding watershed need to be further monitored in order to ensure that this relationship is statistically significant. This type of study can also be expanded to other cities and metropolitan areas that rely on surface water treatment.

Another theme that arose while researching the relationship between influent water quality and drinking water treatment was the issue of climate change. According to Bales

(2012), total organic carbon (TOC) originates in the green swamp and is present in elevated concentrations in the Hillsborough River Reservoir due to its mobilization during Tampa's rainy season (May-October). TOC was also one of the main constituents of concern for the City of Tampa Water Department. Due to this constituent's natural presence in the water, climate change, possibly more than urbanization, may affect its presence in the water. Therefore, there is a need for studies to be conducted that observe or model current or future trends in drinking water source quality and determine how much climate change influences these trends. The methods outlined in Chapter 3 can also be applied to other drinking water treatment contexts and even treatment trains to quantify the degree to which the embodied energy of drinking water is affected by climate change.

6.2.2 Urbanization and Water Use

Smart growth in itself does not have an influence on the embodied energy of water supply (at least in the City of Tampa Water Service Area). However, there were a few limitations to the study: (1) future water consumption was based on the assumption that all single-family, multifamily, and townhouse households have the exact same consumption habits; (2) the general layout of the distribution system was maintained, meaning no new piping was laid out for Tampa's future residents; (3) the study did not include the entire area that was modeled by the OneBay future development scenarios.

To calculate future water consumption within the Tampa WSA, the assumption was made that all future households will consume the same based on housing category (i.e. single-family, multifamily, and townhouse). However, there are other factors that influence household water use including: lot size, house size, the number of residents, income, etc. One means of more accurately predicting future water use would be to rely on more localized averages for household water use. Average household consumption could be estimated at the census block, census block group, or even census tract level. This would reflect the different socioeconomic and demographic factors that influence water use. For instance, per-capita water use is higher in the affluent neighborhoods in the southern and northern regions of the Tampa WSA. Therefore, given the generally positive correlation between income and water use, a single-family house added in the southern or northern parts of the Tampa WSA will most likely use more water than a household in the central region of the Tampa WSA. This additional water consumption can then be added to the base model and the future growth scenarios can be re-run and compared with the study documented in this dissertation.

Location of demand relative to the water treatment is a significant determinant of the embodied energy of drinking water distribution. However, the addition of new pipe and extension of a municipality's water service area may also influence the embodied energy. The study in Chapter 4 assumed no change in the boundaries of the Tampa WSA and the structure of the distribution system, while modeling urban growth. In reality, cities also grow horizontally. This means a possible expansion of the borders of a water service area (WSA) due to annexation of new lands and the laying down of new piping to provide water to the residents in this newly acquired area. For this reason, there is need for another study to be carried out that determines and compares the embodied energies of future development, while incorporating the possible annexation of new land as well as the addition of new piping. This research could be carried out (1) by using existing urban growth models to predict future development and modifying the distribution system to ensure that water is transported to these new development areas; (2) by obtaining future growth scenarios and water distribution and use data from a planning commission and municipal water department, respectively; or (3) by the development of an urban growth model that automatically determines the layout of the additional piping for the distribution system.

Chapter 4 mainly focused on the Tampa WSA, yet the OneBay future development scenarios encompassed the entire Tampa-St. Petersburg-Clearwater metropolitan area. By expanding the scale of the study from just Tampa to the metropolitan scale, future growth scenarios can be more fairly compared, as each scenario adds the same amount of households and jobs throughout the area. By expanding the study area, embodied energy will also have to include the collection, treatment, and distribution stages (as different communities will rely on different water sources and treatments. Households that are not on centralized drinking water systems would be assumed to be served by wells (thus energy values for well water extraction will be estimated). Other alternate treatment scenarios, such as the inclusion of water reuse and desalination can be incorporated in the study as water reuse has been shown to result in lower GHG emissions and most likely result n an energy savings (Cornejo et al., 2014). The results from this study could be used by all member jurisdictions in the metropolitan area.

6.2.3 Smart Growth and the Water Energy Nexus

While the effect of smart growth on water distribution embodied energy has been studied, there has still been no study to date that has specifically investigated the current or future effects of smart growth on nearby water quality, especially if the body of water is a drinking water source. This type of study could be carried out through the use of land-use water quality models as well as future development scenarios provided by consortia such as OneBay, planning commissions, or existing urban growth simulation software. In fact, this research could incorporate the scenarios modeled by OneBay to ultimately determine the overall impact of smart growth on drinking water embodied energy via water quality and water consumption at the metropolitan scale.

6.2.4 Infrastructure Condition and Embodied Energy

The results of Chapter 5 have shown that distribution systems that run on newer pipes use less energy per unit volume of water transported. Even taking into account the upstream energy usage of pipe manufacturing, transport, and installation, depending on the pipe material used, utilities can avoid energy use. However, a savings in energy terms does not mean a savings in the economic sense. Therefore, a future study should integrate the economic cost of pipe maintenance as well as the economic savings due to energy efficiency to determine if the cost of infrastructure maintenance may also result in net economic savings due to avoided energy use.

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APPENDIX B: SUPPORTING INFORMATION FOR CHAPTER 3

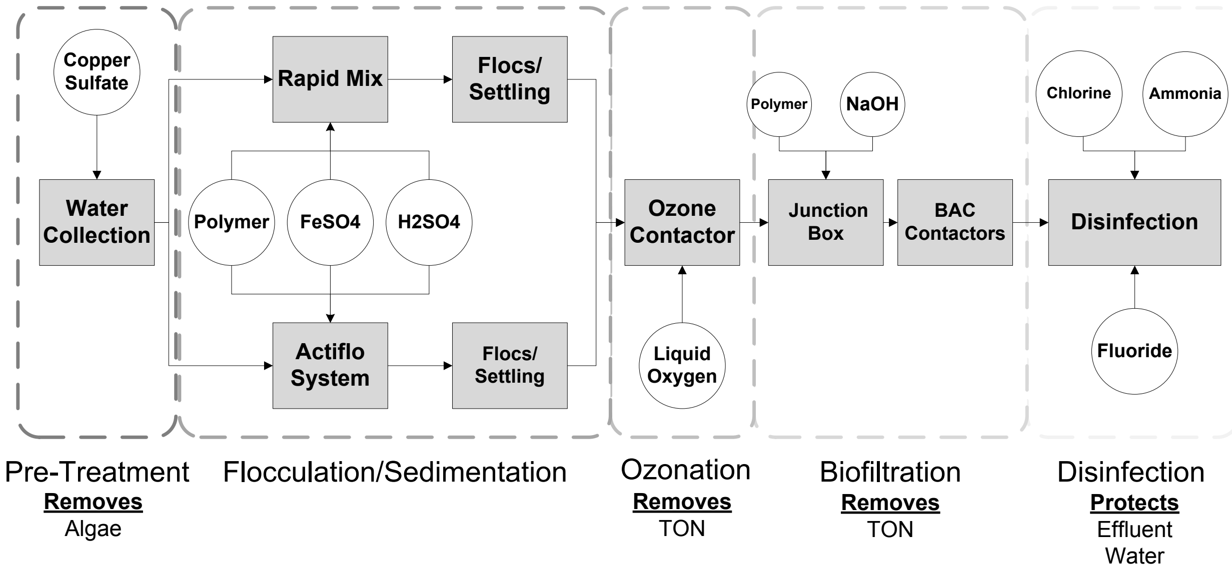

Figure B-1 Layout of processes at David L. Tippin Water Treatment Facility (Tampa, FL)

Table B-1 Hillsborough River Reservoir water quality parameters measured prior to jar testing at the David L. Tippin Water Treatment Facility (Tampa, FL)

Constituent	Range	Unit of Measurement
Alkalinity	26.6-154	mg/L as $CaCO_3$
Calcium Hardness	55.2-196	mg/L as $CaCO_3$
Color	20.2-292	PCU
Conductivity	161-547	µmohs
Hardness	60.8-235	mg/L as $CaCO_3$
Iron	0.01-0.57	mg/L
Magnesium Hardness	5.75-51.9	mg/L as $CaCO_3$
Non-Carbonate Hardness	7.05-102	mg/L as $CaCO_3$
pH	6.9-8.4	N/A
Total Organic Carbon (TOC)	3.10-36.4	mg/L
Total Organic Nitrogen (TON)	3.0-37.6	mg/L

Table B-2 Table comparing the average dosages and the embodied production and transport energies of all water treatment chemicals used in the Tippin WTP

	Average Dosage (mg/L)	**Embodied Energy (MJ/kg)**
Ammonia	1.505	42.084
Carbon	0.007	69.070
Caustic soda	40.685	26.948
Chlorine	8.643	22.707
Copper sulfate	0.158	34.795
Ferric sulfate	155.786	4.861
Hydrofluoric Acid	0.604	15.989
Hydrogen Peroxide	0.674	24.920
Lime	30.009	8.120
Liquid Oxygen	64.622	1.529
Dry Polymer	0.414	65.218
Emulsion Polymer	0.043	66.218
Potassium Permanganate	0.006	25.269
Sand	2.770	0.187
Sulfuric acid	61.839	2.135

Table B-3 Pearson's Correlation matrix quantifying the degree of correlation between tested water quality parameters. Numbers on the top are Pearson’s r values, while numbers on the bottom are α-values. Bolded values denote significant correlations.

	COLOR	TOTAL ALKALINITY	TOTAL HARDNESS	pH	NC HARDNESS	CA HARDNESS	MG HARDNESS	CONDUCTANCE	TURBIDITY	TON	TOC
COLOR	1.000	**-0.738**	**-0.779**	**-0.809**	**-0.598**	**-0.782**	**-0.502**	**-0.703**	-0.302	0.174	**0.918**
		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL ALKALINITY	**-0.738**	1.000	**0.865**	**0.773**	**0.480**	**0.883**	**0.518**	**0.733**	0.107	-0.037	**-0.704**
	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00
TOTAL HARDNESS	**-0.779**	**0.865**	1.000	**0.800**	**0.853**	**0.973**	**0.734**	**0.903**	0.330	-0.134	**-0.768**
	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
pH	**-0.809**	**0.773**	**0.800**	1.000	**0.602**	**0.797**	**0.542**	**0.693**	0.305	-0.197	**-0.793**
	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00	0.00
NC HARDNESS	**-0.598**	**0.480**	**0.853**	**0.602**	1.000	**0.787**	**0.752**	**0.821**	**0.465**	-0.195	**-0.616**
	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00	0.00
CA HARDNESS	**-0.782**	**0.883**	**0.973**	**0.797**	**0.787**	1.000	**0.559**	**0.897**	0.292	-0.121	**-0.772**
	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00	0.00
MG HARDNESS	**-0.502**	**0.518**	**0.734**	**0.542**	**0.752**	**0.559**	1.000	**0.606**	0.319	-0.129	**-0.494**
	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00	0.00
CONDUCTANCE	**-0.703**	**0.733**	**0.903**	**0.693**	**0.821**	**0.897**	**0.606**	1.000	**0.423**	-0.206	**-0.711**
	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00
TURBIDITY	-0.302	0.107	0.330	0.305	**0.465**	0.292	0.319	**0.423**	1.000	-0.176	-0.359
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00
TON	0.174	-0.037	-0.134	-0.197	-0.195	-0.121	-0.129	-0.206	-0.176	1.000	0.118
	0.00	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00
TOC	**0.918**	**-0.704**	**-0.768**	**-0.793**	**-0.616**	**-0.772**	**-0.494**	**-0.711**	-0.359	0.118	1.000
	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	

$$r = \frac{\sum\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\left[\sum\left(X_i - \overline{X}\right)^2 \sum\left(Y_i - \overline{Y}\right)^2\right]^{1/2}} \tag{B-1}$$

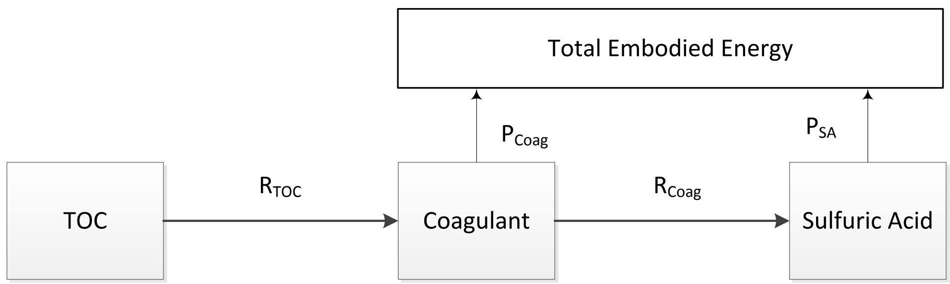

Figure B-2 Diagram of the relationships between relative importance values with respect to water quality and water treatment parameters

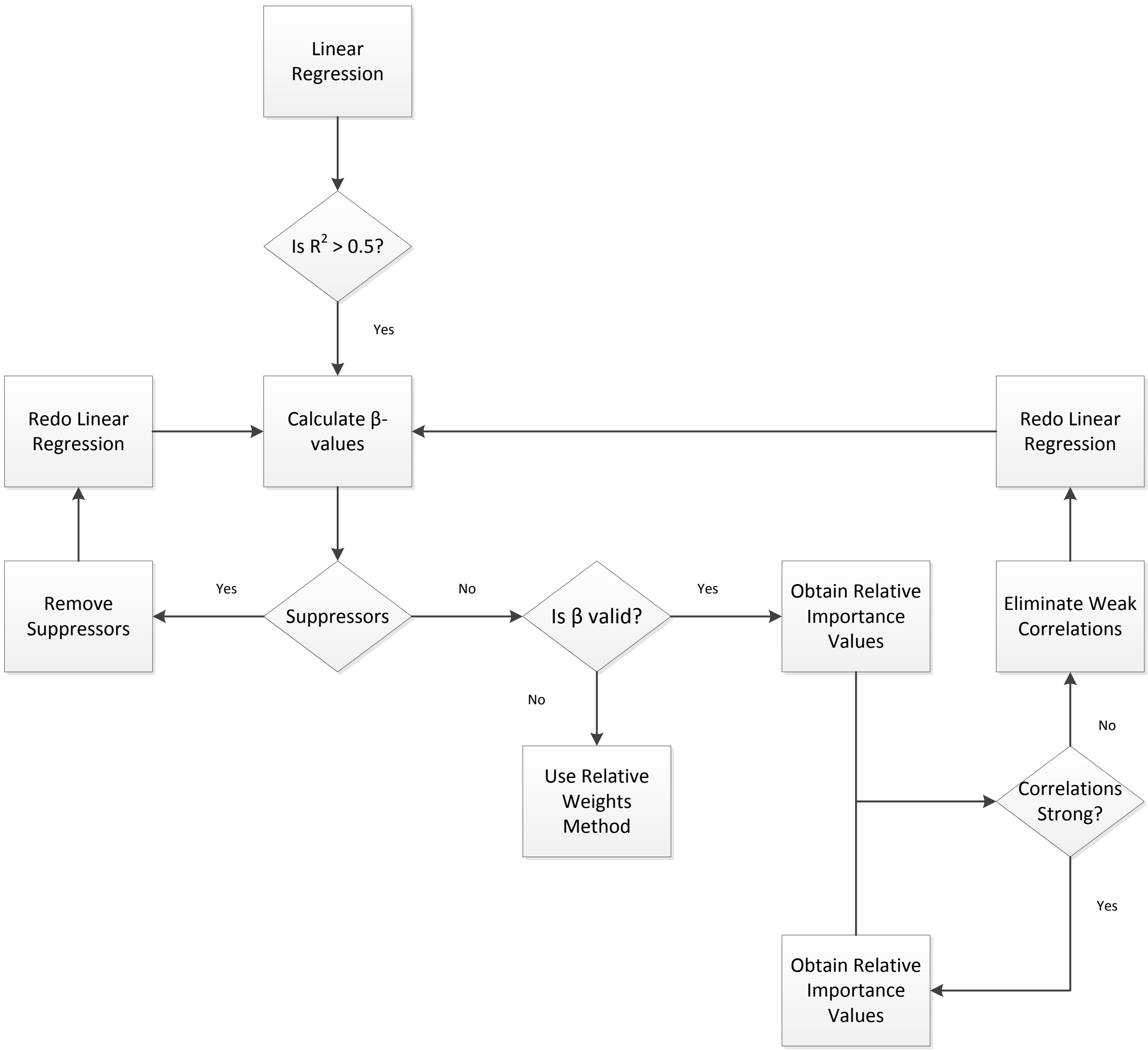

Figure B-3 Decision process tree used for relative importance calculations

APPENDIX C: EMBODIED ENERGY AT EACH JUNCTION IN THE NETWORK

C.1 Background

Power, P, is calculated using the equation below.

$$P = \delta Q h \tag{C-1}$$

where:

P – Power (hp, kW)

δ – Unit weight of water (lb/gal)

Q – Flowrate (gal/min, MGD, m^3/d)

h – Head (ft)

Head is the sum of friction head (h_f, ft) and pressure head (h_p, ft).

$$h = h_f + h_p \tag{C-2}$$

Energy, E, is calculated using the equation below.

$$E = Pt \tag{C-3}$$

where:

E – Energy (kWh, lb-ft, MJ)

t – Time (s, h, min)

Q is calculated as the volume of water, V, divided by time, t.

$$Q = \frac{V}{t} \tag{C-4}$$

where:

V is volume (gal, m^3)

Energy can then be calculated by the equation below.

$$E = \delta V h \tag{C-5}$$

C.2 Application

The data in Table C-1 and Table C-2 will be added to Figure C-1 below.

Table C-1 Junction information to be input into EPANET

Junction	Elevation (ft)	Demand (gpm)
J1	120	600
J2	120	400
J3	120	400
J4	120	300
J5	120	500
J6	120	300
J7	120	700
J8	120	700

Table C-2 Pipe characteristics information to be input into EPANET

Pipe	Diameter (in)	Length (ft)	Roughness
P1	12	500	100
P2	12	500	100
P3	12	500	100
P4	12	500	100
P5	12	500	100
P6	12	500	100
P7	12	500	100
P8	12	500	100
P9	12	500	100

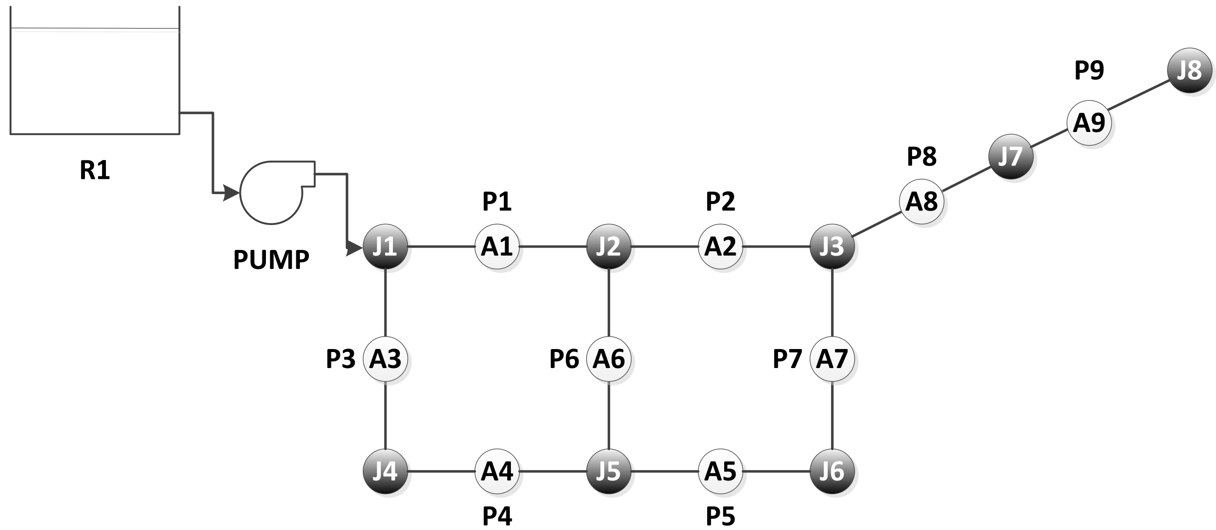

Figure C-1 Pipe network setup used for EPANET model

At each pipe in Figure C-1, an additional junction was placed starting with the letter "A". This junction is located at the same elevation and has no demand. The pump was set to a constant power of 275 kW. The duration of the simulation lasted 72 hours. The resultant head values, pressures, traces, flows, velocities and unit head losses were averaged over the 72-hour period.

Source tracing was done for every "A" junction. A table was created including the "A" junctions (see attached excel file) the destination "J" junctions (or "Users"), the flow percentages, the pipe length, the unit headloss (ft/kft) for each pipe, the friction loss (ft), the junction or user demand (gpm), the demand through the corresponding pipe, the ratio of flow for each user, and the allocated energy (Watts). The given values were the percent tracing (P, percentage), the pipe length (L, ft), and the unit headloss (f, ft/kft).

C.2.1 Friction Loss

Friction loss (h_f, ft) was calculated by multiplying the pipe length by unit headloss as shown in the equation below.

$$h_f = f\left(\frac{L}{1000}\right) \tag{C-6}$$

C.2.2 Pipe Demand Flow

Pipe Demand Flow (D_{Pn}) is defined as the amount of water demand at a certain junction that flows through a designated pipe. It was calculated by multiplying the demand by the trace flow percentage.

$$D_{Pn-k} = P_{n-k} D_k \tag{C-7}$$

where:

n – Pipe

k – Node or Junction

D_{Pn-k} – Demand at node k that flowed through pipe n (gpm)

P_{n-k} – Percentage flow through node k that has passed through pipe n

D_k – Demand at node k (gpm)

C.2.3 Demand Flow Ratio

The demand flow ratio, $P_{Q(n-k)}$, is the percentage of total flow through pipe n that is consumed at junction k. It is calculated by dividing the pipe demand flow by the sum of all pipe demand flows for a single pipe.

$$D_{Pn} = \sum_{k=1}^{j} D_{P(n-k)} \tag{C-8}$$

$$P_{Q(n-k)} = \frac{D_{P(n-k)}}{D_{Pn}} \tag{C-9}$$

where:

j – the total number of junctions/nodes in the network

C.2.4 Pipe Energy Cost

The pipe energy cost, W_n, is calculated by multiplying the friction head loss, total flow through the pipe and the unit weight of water together. This will result in a power amount.

$$W_n = \delta g D_{Pn} h_f \tag{C-10}$$

where:

W_n – Pipe Energy Cost (Watts)

δ – unit weight of water (3.7854 kg/gal)

g – gravity (9.8 m/s)

C.2.5 Allocated Power

By multiplying the pipe energy cost to the demand flow ratio, the amount of power (used for a certain pipe) allocated to each junction or allocated power (W_{n-k})can be calculated. The final value will be in Watts.

$$W_{n-k} = P_{Q(n-k)} W_n \tag{C-11}$$

Finally, the allocated power value will be summed for each junction to determine the allocated junction power, W_k (kW).

$$W_k = \sum_{n=1}^{z} \frac{W_{n-k}}{1000} \tag{C-12}$$

where:

z – number of pipes in the network

C.2.6 Friction Embodied Energy

By modifying the energy equation above, W_k can be converted to energy by assuming the system is running for one hour. This energy value is then normalized by the water consumption in an hour. This yields the embodied energy E_f.

$$E_f = \frac{W_k t}{60 D_k} \quad \text{(C-13)}$$

where:

E_f – Friction embodied energy (kWh/g or MJ/m^3)

t – time duration (h)

C.2.7 Pressure Head Embodied Energy

When the model is run, EPANET automatically calculated the pressure head, h_p (ft), at each junction. The junction with the lowest head is found. This can be converted into energy my modifying the energy equation above and normalizing it by the consumption that takes place at each node in an hour, thus estimating the pressure head embodied energy, E_P.

$$E_P = \frac{\delta V_k h_{pk}}{V_k} = \delta h_{pk} \quad \text{(C-14)}$$

where:

E_p – Pressure head embodied energy (kWh/gal, MJ/m^3)

V_k – Volume of water consumed at node k in an hour

h_{pk} – Pressure head at node k

C.2.8 Total Embodied Energy

With the E_f and E_p values, the embodied energy, E (MJ/m^3), can be calculated.

$$E = E_f + E_p \quad \text{(C-15)}$$